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Intercropped Macadamia and Coffee in Agroforestry System in Zambia: a Case Study

István György DEÁK[a, b*] – Sándor HORVÁTH[c]

[a] University of Sopron, Sopron, Hungary
[b] Ministry of Agriculture, Hungary
[c] MAVAD CAMPUS, Sopron-Gyomaendrőd, Hungary

Deák I.Gy. 0009-0002-1626-2948, Horváth S. 0009-0000-5402-7602

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ABSTRACT

This study examines the economic performance of an agroforestry system applied in Africa and complementary insights into its social and ecological implications, focusing on the intercropping of macadamia (*Macadamia integrifolia*) and Arabica coffee (*Coffea arabica*). The research was conducted on a 1.6-hectare area at Pamo Mangala Farm in Zambia between 2021 and 2024. During the study, we assessed and compared the effects of different planting systems on farm productivity, including homogeneous and heterogeneous layouts. The results show that intercropping can increase farm profitability through production diversification while supporting sustainable farming practices; it may also have positive effects on local employment and environmental conditions.

TANULMÁNY INFÓ

Kulcsszavak:
Fenntartható mezőgazdaság
Ökológiai hatás
Gazdaság jövedelmezősége
Vidéki foglalkoztatás
Heterogén hálózat

KIVONAT

Makadámdió és kávé köztes termesztése agroerdészeti rendszerben Zambiában: esettanulmány. Tanulmányunk egy Afrikában alkalmazott agrárerdészeti rendszer gazdasági teljesítményét vizsgálta, miközben annak társadalmi és ökológiai vonatkozásaira is betekintést nyújtott, a makadámdió (*Macadamia integrifolia)* és az arabica kávé (*Coffea arabica*) köztes termesztésére fókuszálva. A kutatás a zambiai Pamo Mangala Farmon zajlott egy 1,6 hektáros területen 2021 és 2024 között. A vizsgálat során különböző ültetési rendszerek — beleértve a homogén és heterogén elrendezéseket — gazdasági teljesítményét és termelékenységre gyakorolt hatását értékeltük és hasonlítottuk össze. Az eredmények azt mutatják, hogy a köztes termesztés a termelés diverzifikálásán keresztül növelheti a gazdaság jövedelmezőségét, miközben támogatja a fenntartható gazdálkodási gyakorlatokat; emellett feltételezhetően kedvező hatással van a helyi foglalkoztatásra és a környezeti állapotokra is.

*Corresponding author: istvan.gyorgy.deak@gmail.com; H-3214 NAGYRÉDE, Atkári u. 65, Hungary

1 INTRODUCTION

Mounting environmental, social, and economic pressures have made agricultural diversification and sustainability critical imperatives in Sub-Saharan Africa. Declining soil fertility, erratic rainfall patterns, deforestation, and market volatility pose increasing challenges to smallholder farmers in Zambia. Such systemic vulnerabilities call for innovative land-use models combining productivity with resilience. One promising strategy is agroforestry, which integrates trees and perennial crops into agricultural systems to provide multiple outputs and ecosystem services (Garrity, 2004).

Intercropping is a form of agroforestry in which two or more crops are cultivated in proximity. It can contribute significantly to sustainable agricultural intensification. It can also improve resource use efficiency, reduce pest and disease pressure, and enhance system-level resilience (FAO 2020). In this context, the intercropping of macadamia (*Macadamia integrifolia*) and coffee (*Coffea arabica*) represents a high-potential model that aligns with Zambia's adaptation goals, livelihood diversification, and sustainable land management.

Coffee is a globally significant export commodity and a key source of rural income in many parts of Africa. However, its monocultural cultivation has led to ecological imbalances and increasing susceptibility to climate stress, pests, and diseases such as coffee leaf rust (Bunn et al. 2015). Macadamia is a climate-resilient, nitrogen-demanding perennial tree that can improve soil organic matter, reduce erosion, and sequester carbon, while also offering strong market potential due to growing global demand for tree nuts (Leakey – Asaah 2013; Dawson et al. 2014). Integrating macadamia and coffee crops can potentially enhance land-use efficiency and deliver synergistic economic, ecological, and social benefits, including increased income stability through diversified revenue streams, improved soil health via organic matter inputs from macadamia litter, and microclimatic buffering that can protect shade-sensitive coffee plants from temperature extremes (Lemos – Ribeiro, 2024). Additionally, intercropping systems can strengthen community resilience, generate local employment, and foster farmer engagement with sustainable practices (Mbow et al., 2014).

Previous studies have demonstrated the effectiveness of agroforestry systems in similar tropical environments. For example, intercropping coffee with shade trees in Central America improved yields and quality while enhancing biodiversity and carbon sequestration (Soto-Pinto et al., 2000). Integrating legumes and high-value trees in Malawi and Kenya increased household incomes and soil fertility (Ajayi et al., 2007; Kuyah et al., 2019). Such examples highlight the relevance and replicability of agroforestry models for Zambia, particularly in regions with similar agroecological zones.

This study investigates the economic, social, and ecological implications of a small-scale intercropping trial involving macadamia and coffee in Zambia. Conducted between 2021 and 2024, the present study combines empirical data collection with a multidisciplinary analytical framework and evaluates whether this system can provide a scalable and sustainable agroforestry model for smallholder farmers in Zambia and beyond.The study objective was to evaluate the viability of intercropping macadamia and coffee under Zambian conditions from two perspectives:

- Economic viability (input costs, revenues, net profit)
- Social acceptability (labour requirements, resilience).

The study addressed the following key research questions:

1. Can intercropping macadamia and coffee increase profitability compared to monocultures?
2. How does macadamia–coffee intercropping affect labour demand and employment patterns?

2 MATERIALS AND METHODS

2.1 Trial design

The field trial was performed at Pamo Mangala Farm in Zambia, on a dedicated experimental plot covering 1.6 hectares in the Miombo Woodland. The study area is at 11°08′00.0″ S, 31°26′28.2″ E in northern Zambia *(Figure 1).* The plot is in Zambia's Northern Province, a region characterized by a warm temperate climate and dry winters. The area receives between 800 and 1,200 mm of rainfall annually, in a single rainy season extending from November to March. Mean annual temperature is approximately 22 °C, creating conditions suitable for both coffee and macadamia cultivation (FAO 2020).

Figure 1. Location of the experimental plot (Google Earth)

The soil of the experimental area is typical Miombo woodland soil, classified predominantly as sandy loam to loamy sand Ferralsols, with low inherent fertility. Baseline soil sampling before establishment indicated acidic conditions (pH 5.2–5.6), low organic matter content (below 2%), and limited available nitrogen and phosphorus, which are characteristic of many smallholder and commercial farming areas in central and northern Zambia. Soil texture and structure were uniform across the experimental blocks, allowing for valid comparisons among planting systems.

The trial plot was systematically subdivided into four equal blocks, each measuring approximately 0.4 hectares. The subdivision was specifically designed to enable a rigorous comparative analysis of different cropping systems under similar environmental and soil conditions. Each of the four blocks was assigned a distinct planting system, facilitating direct comparison of their agronomic performance, economic viability, and ecological impacts.

The initial planting of all plots was conducted between 2019 and 2020, using one-year-old healthy seedlings sourced from certified nurseries. In total, 1,300 coffee seedlings and 300 macadamia seedlings were planted across the experimental area, distributed according to the designed spacing for each cropping system. This setup allowed for sufficient sample sizes to assess growth rates, yield, and other parameters over the multi-year trial period.

The experimental design ensured consistency in soil preparation, fertilization, irrigation, and pest management practices across all blocks to minimize confounding factors and isolate the effects of the planting systems on performance outcomes.

2.2 Data collection

Data collection spanned agronomic, economic, and socio-ecological domains. The following parameters were measured:

- Agronomic: Yield estimates were conducted twice a year.
- Economic: Input costs (labour, seedlings, fertilizer, irrigation), yield per hectare, market prices, gross and net revenue (World Bank 2022).

2.3 Data analysis

Quantitative data were analyzed using descriptive statistics and inferential techniques, such as ANOVA, T-test, and regression analysis, to identify differences between systems.

2.4 Description of planting systems

This study evaluated four distinct planting systems to compare the agronomic, economic, and ecological performance of macadamia and coffee when grown separately and together under different spatial arrangements. Each system was designed to reflect both practical farming considerations and the potential for mechanization, yield optimization, and sustainable land use.

Homogeneous macadamia (8×4 m)

In this monoculture system, macadamia trees were planted with a spacing of 8 meters between rows and 4 meters within rows. This spacing was chosen to accommodate the large mature canopy size of macadamia trees and to allow sufficient sunlight penetration and air circulation, both essential for healthy growth and nut production. The 8×4-meter configuration was specifically designed with future mechanization in mind, providing enough room for machinery, such as tractors, to move through the orchard. The wide spacing also aimed to reduce competition for nutrients and water among trees, which is vital given macadamia's deep-rooting characteristics.

Homogeneous coffee (2×1.5 m)

The coffee monoculture system followed a traditional layout with coffee seedlings planted 1.5 meters apart within rows and 2 meters between rows. This spacing is typical for manual coffee plantations, enabling workers to access the plants for routine maintenance activities such as pruning, pest control, and harvesting. The relatively narrow 1.5-meter spacing within rows and between plants restricts the use of large-scale mechanized equipment, making this a labour-intensive system. The 2×1.5-meter spacing strikes a balance between maximizing the number of coffee plants per hectare and maintaining manageable plant productivity. The configuration supports high-density coffee planting while allowing adequate airflow and sunlight penetration.

Intercrop sparser coffee (8×3×1×1×3 m)

The modified intercrop system featured macadamia trees planted at a spacing of 8 meters between rows and 4 meters within rows, maintaining the layout necessary for mechanized operations. Within the 8-meter space between macadamia rows, coffee seedlings were arranged in a 3×1×1×3-meter pattern: the first coffee plant was located 3 meters from the base of the macadamia tree, followed by two coffee plants each spaced 1 meter apart, and then a 3-meter gap before the next macadamia tree *(Figure 2).*

This specific configuration allowed for three coffee trees per inter-row space, evenly distributed to avoid excessive competition while optimizing light availability. The 4-meter spacing between macadamia rows remained unchanged, ensuring continued access for tractors and machinery. Despite the relatively dense coffee planting, mechanized maintenance (e.g., mowing and spraying) was still feasible, while coffee management and harvesting were expected to remain largely manual due to the crop's structural and spatial characteristics.

This layout was designed to enhance land-use efficiency, support diversified production, and maintain operational flexibility in a mixed perennial cropping system.

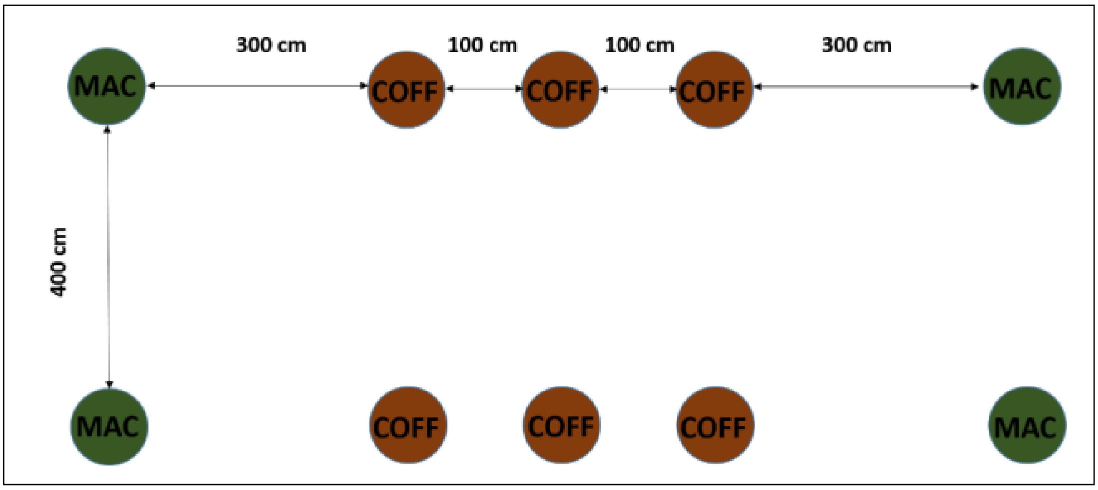

Figure 2. Sparser intercrop (Deák, 2020)

Intercrop with denser coffee (8×3×4×1 m)

This variant of the modified intercrop system was based on the initial layout where the macadamia spacing of 8×4 meters remained unchanged, yet the spacing between coffee rows was reduced. Specifically, an additional row of coffee was inserted between each existing pair of rows, effectively halving the inter-row distance for coffee to 1 meter. As a result, a coffee row was planted every 2 meters, significantly increasing the number of coffee plants per hectare compared to the original setup. The denser configuration precludes machine use; only manual maintenance and harvesting are feasible *(Figure 3)*. While this layout aims to enhance coffee yield by utilizing space more intensively, it also brings increased labour demands and the need for more careful management of competition among coffee plants for light, water, and nutrients.

The above system represents a shift in priority from mechanization toward maximizing planting density and potential productivity within the available area.

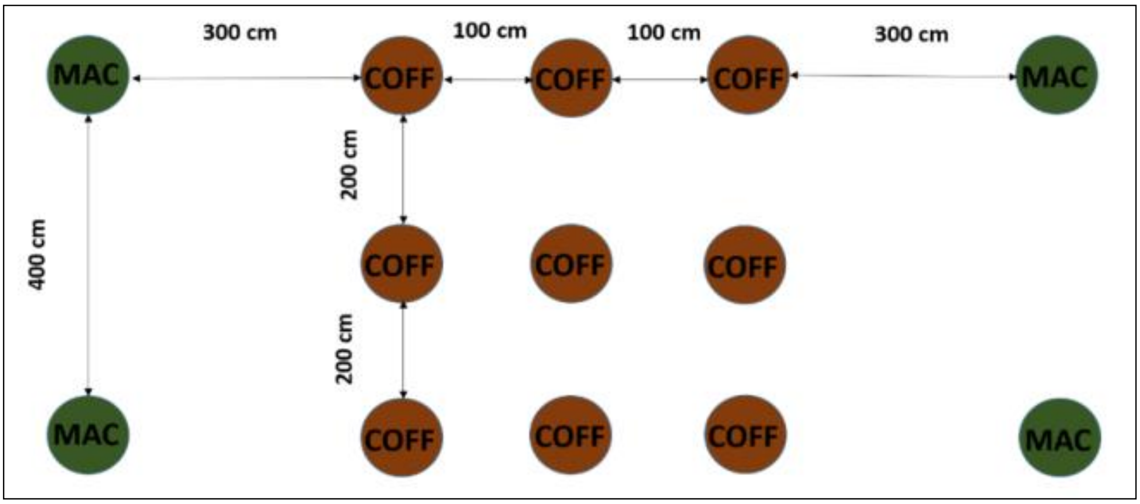

Figure 3. Denser intercrop (Deák, 2020)

2.5 Labor and material costs

Labour and material costs were monitored and recorded throughout the entire production cycle. These activities require varying levels of labour input depending on the cropping system and crop density.

Labor costs

Labour was identified as a significant component of total production costs. Labour intensity fluctuated across the different cropping systems, with the highest demands observed in the dense intercropped blocks, due primarily to the need for more frequent and meticulous management practices in systems where two crops are grown simultaneously and require additional care, such as timely pruning to avoid competition, more complex weed control, and coordinated harvesting schedules. Monoculture systems, especially homogeneous coffee plots, showed lower labour intensity as operations tend to be more straightforward with less complexity in crop management.

Labour activities throughout the production cycle included

- Planting: Manual planting of seedlings, which required careful spacing and depth adjustments to optimize growth conditions for both coffee and macadamia, especially in intercropped plots.
- Weeding: Regular manual weed removal was necessary to minimize competition for nutrients and water, with intercropped systems requiring more labour due to the complexity of managing two crop species growing in proximity.
- Pruning: Pruning was essential to maintaining optimal plant health and productivity. Coffee plants required routine pruning to enhance yield and quality, while macadamia trees demanded selective pruning to manage canopy structure and sunlight penetration.
- Harvesting: Harvest timing varied between crops and systems. Coffee harvesting is labour-intensive because ripe berries need to be selectively picked, whereas macadamia harvesting involves collecting nuts. Intercropping added complexity as coordination of labour was needed to avoid damaging either crop.
- Material Costs: Material inputs included essential components necessary for successful crop establishment and maintenance:
- Fertilizers: A mix of fertilizers—synthetic NPK (nitrogen, phosphorus, potassium) fertilizers, organic compost, and lime—was applied to improve soil fertility, support healthy crop growth, adjust soil pH, and enhance nutrient availability. The fertilizer

application rates were managed to meet the nutritional requirements of each cropping system.

- Pesticides and Organic Treatments: Crop protection strategies involved conventional pesticides and organic treatments to control pests and diseases. Organic treatments were favoured in the intercropped system to maintain ecological balance and protect beneficial insect populations.
- Irrigation: Irrigation for all experimental plots was sourced from a nearby natural stream. Irrigation was implemented across the study area using simple, low-input methods, reflecting local farming practice and the absence of mechanized irrigation infrastructure.
- Watering methods depended on plot accessibility and field conditions but included manual hose-based irrigation, bucket watering, or small-scale surface flooding. Simple gravity-fed drip lines were used to distribute water along crop rows in some plots; however, such systems operated without pumps or mechanical components.

The irrigation equipment required no capital investment or energy input. Consequently, irrigation did not incur equipment-related or water-related costs. Manual labour was the only input associated with irrigation, which covered water extraction from the stream and its application to the crops. Irrigation frequency and duration were adjusted according to crop type, plant developmental stage, and prevailing weather conditions.

2.6 Yield estimates and revenue projections

The yield estimates and revenue projections were developed based on observed growth patterns of coffee and macadamia trees in the trial, as well as on extensive market research on local commodity prices. Yield estimates were derived from systematic field observations conducted within the experimental plots, including regular assessments of tree growth parameters (such as plant height, canopy development, and bearing status), and recorded harvest quantities once production commenced. For coffee, yield measurements were based on harvested coffee cherry weight per plant and extrapolated to a per-hectare basis, while macadamia yield estimates relied on nut-bearing observations and harvested nut-in-shell weights. Revenue projections were calculated by combining these empirically observed yield data with average local prices. The analysis accounted for the typical maturation timelines of two crops, seasonal variability, and expected agronomic improvements over time.

Coffee yield projections:

Coffee plants generally require a few years after planting before they reach stable production levels. This study projected coffee yields to stabilize by the third year of growth, which corresponds to 2024 in the timeline. Coffee plants mature sufficiently during this growth period and produce consistent yields of coffee cherries each season. Early years showed lower output due to immature plants, while post-year-three yields were expected to remain relatively steady. Yield stabilization allows for more accurate revenue forecasting.

Macadamia yield projections:

Macadamia trees have a longer juvenile phase than coffee and typically reach their peak production several years after planting. Macadamia nut yields were projected to peak in 2026, the fifth year in our study. Peak production years are critical for ensuring the economic viability of macadamia orchards and heavily influence long-term revenue potential. The projected yield trajectory was modelled based on agronomic data and corroborated by local industry expertise.

Revenue calculations:

Revenue estimates were calculated by multiplying the expected yields by prevailing local market prices for coffee cherries and shelled macadamia nuts. The prices were sourced from reputable industry reports and market analyses to ensure realistic financial projections:

- Coffee cherries were valued at approximately 3.00 USD per kilogram, reflecting 2023 market prices.
- Shelled macadamia nuts commanded a higher price point of about 8.00 USD per kilogram.

The price points were applied uniformly across the cropping systems to maintain comparability, recognizing that fluctuations in market demand and quality could influence actual revenues. Revenue projections considered yield variability over the years, seasonal harvest volumes, and the respective contributions of each crop in intercropped systems.

3 RESULTS

3.1 Economic analysis

Between 2022 and 2026, the financial performance of the homogeneous coffee, homogeneous macadamia, and intercropping denser and spacer cropping systems showed clear divergence in efficiency and profitability trends *(Table 1).*

In 2022, all systems operated at a net loss. Coffee and macadamia monocultures generated limited revenues that could not offset initial establishment and input costs. While requiring the highest initial investment, the intercropped systems produced comparatively higher income, resulting in the lowest financial loss of the three, indicating early advantages in combined output and land-use efficiency.

In 2023, input costs began to stabilize, while yields—particularly from coffee—improved across all systems. Despite ongoing losses, the intercropped system further narrowed its financial deficit, reinforcing its greater short-term viability. Macadamia continued to mature slowly, while coffee systems struggled to achieve profitability due to modest market returns.

By 2024, the intercropped system approached financial break-even, benefiting from cumulative coffee yields and reduced operational costs. Macadamia monoculture also showed signs of financial improvement, though it still lagged. The coffee-only system remained the least profitable, hampered by market volatility and limited diversification.

In 2025, projections indicate a major turning point: the intercropped system is expected to reach a stable net profit for the first time, supported by consistent coffee output and early-stage macadamia harvests. Macadamia monoculture is also projected to enter positive financial territory. Coffee-only systems continue to reduce losses but remain economically less competitive.

By 2026, both macadamia and intercropped systems are forecast to achieve reliable profitability, with the intercropped models maintaining the strongest financial position overall. Its staggered yield cycles, shared inputs, and more efficient land use contribute to a superior long-term economic outlook.

Overall, these results confirm that despite higher early-stage costs, intercropping provides the most resilient and profitable model over a five-year horizon.

Table 1. Annual Financial Progression of Cropping Systems (2022–2026)

Year	System	Input Costs (USD)	Revenue (USD)	Net Profit (USD)
2022	Homogeneous Coffee	1,990	50	-1,940
	Homogeneous Macadamia	1,994	0	-1,994
	Intercrop Sparse Coffee	1,850	497	-1,353
	Intercrop Denser Coffee	1,900	500	-1,400
2023	Homogeneous Coffee	2,000	63	-1,937
	Homogeneous Macadamia	1,700	700	-1,000
	Intercrop Sparse Coffee	1,900	1,447	-453
	Intercrop Denser Coffee	1,800	1,900	100
2024	Homogeneous Coffee	2,000	299	-1,701
	Homogeneous Macadamia	1,600	1,700	100
	Intercrop Sparse Coffee	1,900	2,447	547
	Intercrop Denser Coffee	1,700	2,600	900
*2025	Homogeneous Coffee	2,000	800	-1,200
	Homogeneous Macadamia	1,400	2,200	800
	Intercrop Sparse Coffee	1,900	2,867	967
	Intercrop Denser Coffee	1,600	3,400	1,800
*2026	Homogeneous Coffee	2,000	1,300	-700
	Homogeneous Macadamia	1,300	2,500	1,200
	Intercrop Sparse Coffee	1,900	3,100	1,200
	Intercrop Denser Coffee	1,500	4,200	2,700

**Note: Table for 2025 and 2026 are projections based on observed trends and current market conditions.*

3.2 Social and ecological impacts

Qualitative observations and field-level assessments indicated a clear overall advantage of intercropped macadamia–coffee systems compared to monoculture production. Several recurring patterns were identified across the study period.

- **Income diversification** emerged as a key social benefit of the intercropped system. The simultaneous production of two high-value crops reduced dependence on a single commodity, thereby lowering exposure to price volatility and localized yield losses. This diversification contributed to greater income stability, particularly in years characterized by fluctuating market conditions.
- **Soil quality and moisture retention** were consistently more favourable under intercropping. Improved canopy structure and increased organic matter inputs supported better soil structure and enhanced moisture conservation, leading to visibly healthier soil conditions compared to monoculture plots.
- **Reduced production risk** was another notable advantage. The intercropped system demonstrated higher resilience to climate-related disturbances, such as drought stress or pest pressure, as reduced performance of one crop could be partially compensated by the continued productivity of the other (Smith – Mwamba 2023).

Although intercropping required higher total labour inputs from a social perspective, labour demand was more evenly distributed throughout the year. This more balanced seasonal labour requirement contributed to steadier employment opportunities, which is particularly relevant in rural areas where seasonal underemployment is common.

While the intercropped system required more labour overall, this demand was spread more evenly across the year, which contributed to steadier employment opportunities for local labourers. This year-round labour distribution was particularly appreciated in communities where seasonal unemployment is a recurring challenge.

3.3 Statistical analyses

3.3.1 Analysis of economic performance differences between cropping systems (ANOVA)

An analysis of variance (ANOVA) was applied to compare net profit outcomes among the four cropping systems—homogeneous coffee, homogeneous macadamia, sparse intercropping, and denser intercropping—over the 2022–2026 period *(Table 2).*

Accordingly, the null hypothesis, assuming equal mean net profitability across all systems, was rejected. These findings confirm that cropping system choice has a measurable and meaningful impact on farm-level economic outcomes, justifying further pairwise comparisons and trend analyses.

Table 2. ANOVA results for net profit differences among cropping systems

Source of variation	SS	df	MS	F	p-value
Between groups	20,745,200	3	6,915,067	8.72	0.002
Within groups	12,693,800	16	793,363		
Total	33,439,000	19			

The ANOVA results indicate statistical differences among the cropping systems ($F = 8.72$, $p = 0.002$). Therefore, the null hypothesis that all cropping systems generate equal average net profits can be rejected.

These findings confirm that the choice of planting system influences economic outcomes.

3.3.2 Comparison of net profitability between cropping systems (t-test)

Coffee Monoculture vs Macadamia Monoculture: The comparison of cumulative net profits over the study period shows that both monoculture systems remained economically constrained. Coffee monoculture generated persistent losses throughout the period, while macadamia monoculture showed gradual improvement and reached profitability only in later years. Statistical testing did not indicate a difference between the two monocultures over the full period ($p > 0.05$), reflecting their similarly delayed economic returns during the establishment phase.

Coffee monoculture vs. intercropped systems: t-test results reveal a statistical difference between coffee monoculture and both intercropped systems ($p < 0.05$). Intercropping substantially reduced early-stage losses and achieved positive net profits earlier, highlighting the clear financial advantage of diversification compared to coffee monoculture alone.

Macadamia monoculture vs. intercropped systems: The comparison between macadamia monoculture and intercropped systems did not yield statistical differences over the full period ($p > 0.05$). While intercropping showed faster profitability onset and higher cumulative gains, macadamia monoculture displayed a converging profitability trajectory by 2025–2026.

Overall, intercropping performs better than coffee monoculture while remaining statistically comparable to macadamia monoculture in terms of long-term net profitability.

Pairwise comparisons were conducted using independent sample T-tests to identify which systems differ *(Table 3)*.

Table 3. Pairwise comparison of cropping systems (t-test results)

Comparison	Mean difference (USD)	t-value	p-value
Coffee vs. Macadamia	1,317	1.42	0.17
Coffee vs. Sparse intercrop	2,437	3.18	0.01
Coffee vs. Denser intercrop	3,534	4.06	0.00
Macadamia vs. Sparse intercrop	1,120	1.21	0.24
Macadamia vs. Denser intercrop	2,217	2.05	0.06

The results show statistical differences between coffee monoculture and both intercropped systems ($p < 0.05$), while differences between macadamia monoculture and intercropped systems are not statistically significant at the 5% level.

3.3.3 Temporal trends in net profit across cropping systems: regression analysis

Linear regression analysis was conducted using annual net profit data from 2022 to 2026 to assess economic trends for each cropping system *(Table 4)*.

Table 4. Linear regression models for net profit trends

System	Regression equation	R^2
Homogeneous Coffee	$y = 310x – 2560$	0.89
Homogeneous Macadamia	$y = 800x – 2400$	0.94
Sparse Intercrop	$y = 640x – 1960$	0.91
Denser Intercrop	$y = 1020x – 2700$	0.96

- *Homogeneous Coffee*
  Displays a modest positive trend of approximately +310 USD/year, indicating gradual improvement. However, net profit remains negative throughout the study period, underscoring structural economic limitations.
- *Homogeneous Macadamia*
  Shows a strong upward trend of approximately +800 USD/year, transitioning from early losses to sustained profitability by 2025.
- *Intercrop Sparse Coffee*
  Exhibits a steady positive trend of approximately +640 USD/year, outperforming both monocultures during most of the period.
- *Intercrop Denser Coffee*
  Demonstrates the strongest performance with an annual increase of approximately +1,020 USD/year, achieving the highest profitability by 2026.
  Across all systems, intercropping—particularly in denser configurations—reaches profitability earlier and with greater efficiency than monoculture systems *(Figure 4)*.

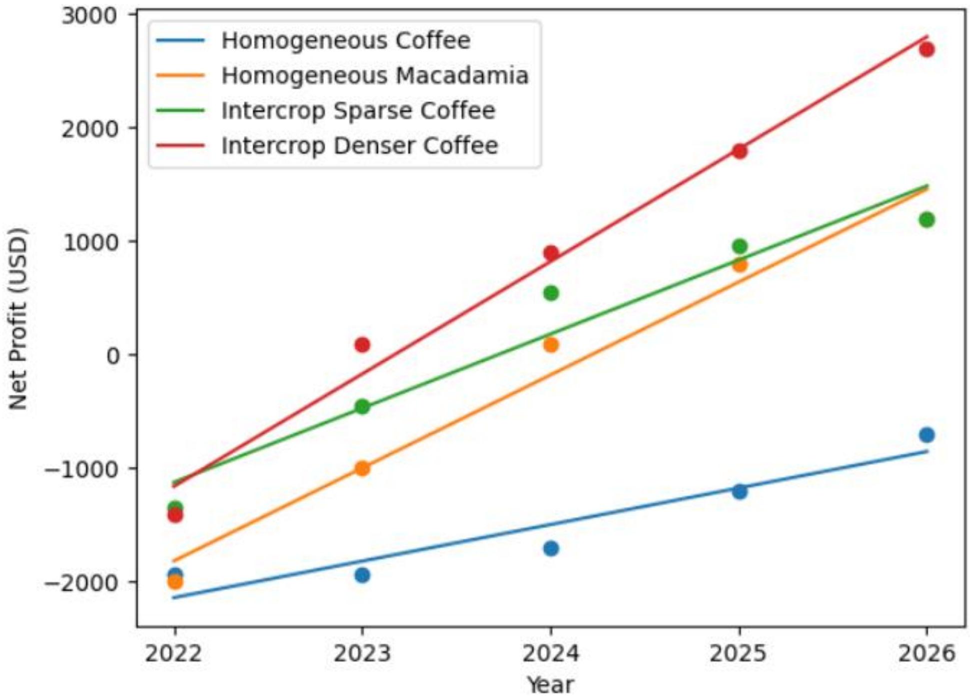

Figure 4. Regression analysis of net profit (values in USD, see also Table 4.)

4 DISCUSSION

4.1 Economic viability of intercropping systems

The economic analysis covering the 2022–2026 period clearly demonstrates the financial advantages of intercropping macadamia and coffee. Cumulative net profits amounted to approximately 4,100 USD for the denser intercropping system and 900 USD for the sparse intercropping system, compared to −7,480 USD for coffee monoculture and −894 USD for macadamia monoculture.

These results confirm that intercropping substantially mitigates establishment-phase losses and accelerates the transition to profitability. The denser intercropped system, in particular, maximized income diversification and land-use efficiency, leading to superior economic performance.

The findings are consistent with previous studies. Perdona et al. (2015) reported improved cash flow stability and economic resilience in macadamia–coffee intercropping systems in Brazil. Taken together, the results suggest that intercropping represents a financially robust and risk-reducing production strategy under small- to medium-scale African farming conditions.

However, several studies caution against overgeneralizing these benefits across contexts. Evidence suggests that the economic performance of agroforestry and intercropping is highly conditional on enabling environments—particularly reliable market outlets, supportive policies, and strong advisory/extension and technical support—without which financial gains may remain limited or uncertain (Thiesmeier – Zander, 2023; Tranchina et al., 2024). In smallholder settings, adoption and sustained performance can also be constrained by high upfront establishment costs, limited access to capital, and exposure to market uncertainty and commodity price volatility, which can erode profitability even when biophysical outcomes are positive (Stroesser et al., 2018; Abdul-Salam et al., 2022). In our case, early coffee revenues helped mitigate macadamia's delayed income stream, confirming the value of revenue diversification. However, this advantage is highly dependent on access to reliable markets and processing infrastructure, which are often lacking in rural Zambia.

4.2 Labour dynamics and employment implications

Intercropping led to increased labour demand across seasons, especially during periods of overlapping coffee harvest and macadamia maintenance, consistent with findings that intercropping systems can require higher labour inputs throughout the growing season than sole crops in diversified smallholder farming contexts (Thierfelder et al., 2024).

While this labour demand offers employment opportunities in regions with high rural underemployment, its sustainability is questionable. Glover (2020) argues that high labour requirements can be a disincentive in smallholder systems with limited mechanization and training. Similarly, observed that without clear labour scheduling and management capacity, intercropping systems may exacerbate organizational inefficiencies.

Therefore, realizing the employment potential of such systems will require parallel investments in labour training, cooperative work arrangements, and possibly community mechanization hubs.

4.3 Socioeconomic considerations

The intercropped system offers clear potential for improving long-term rural livelihoods. However, significant socioeconomic barriers to adoption remain. High initial investment requirements, lack of access to credit, and limited extension support are major obstacles.

In addition, traditional risk-averse behaviours and preferences for short-cycle crops discourage investment in systems with delayed returns. Glover et al. (2020) emphasize that such transitions require not only technical training but also behavioural change interventions and strong cooperative networks.

The perception of macadamia and coffee as export-oriented "elite" crops further compounds these barriers. Creating inclusive value chains and promoting local processing could improve acceptability and ensure broader participation.

4.4 Trade-offs and limitations

While the benefits of intercropping are substantial, our findings highlight several compromises:

- Labour coordination becomes more complex, especially during overlapping management.
- Pest and disease management requires broader expertise.
- The data stem from a 1.6 ha trial area and only a 5-year period, which limits scalability and long-term conclusions.

Moreover, profitability projections are sensitive to market fluctuations, climate variability, and farmer behaviour—factors that often fall outside the scope of short-term (Zida et al., 2021).

5. CONCLUSIONS

In addition to aligning with broader agroecological and climate adaptation goals, intercropping macadamia and coffee can enhance financial returns, ecological resilience, and employment generation. However, success is conditional on strong support systems: farmer training, market integration, financial services and possibilities, and policy alignment. Future research should prioritize long-term trials and explore diversification under varying socioeconomic and ecological conditions.

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