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RESEARCH ARTICLE

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Integrating indigenous crops in agroforestry systems: Lesser yam and teak mixed systems are more profitable than monocultures in Indonesia

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Societal impact statement

Major staple crops are often introduced and cultivated in monocultures. Yams are staple crops native to the majority of low- and middle-income countries and can provide an alternative to introduced staple crops. [Correction added on 9 January 2026, after first online publication: In the preceding sentence, stable has been corrected to staple in this version.] We showed that lesser yams cultivated together with teak trees (planted at the border of the farm) are more profitable than lesser yam monoculture. This supports the idea that indigenous crops, which are known to be more resilient to local conditions, are suitable to be integrated in agroforestry systems (with the benefit of having further profits from other crops and/or trees).

Summary

- Lesser yam, *Dioscorea esculenta* (Lour.) Burkill, is a staple crop massively cultivated in monoculture (yam monoculture: YM) and more rarely cultivated in agroforestry systems, where the shading effect of the trees it thought to reduce crop yield. This study aims to compare agroforestry and monoculture lesser yam systems in terms of tuber productivity, standing stock volume, harvest index (HI), efficiency of storage root production (ESRP), and financial analysis.
- We compared plots in YM with two agroforestry systems, trees along border (TAB) and teak–yam intercropping (TYI), in a yam production village in Central Java. Profitability analysis was done to predict the economic value of the plantations and to determine the most beneficial farming system to farmers.
- The YM produced the highest tuber biomass of yam, but the TAB produced the highest tuber yield ($F = 38.977$, $P < 0.001$). YM had the lowest Benefit–Cost Ratio (1.60), compared to TAB (2.01), TYI (1.84), and teak monoculture (TM, 1.90). TM was less profitable than TYI and TAB based on Net Present Value and Equivalent Annual Income.
- We found that lesser yam is suitable to grow under the canopy cover, and teak trees serve as living stakes for yam vines. Furthermore, upon financial analysis,

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TAB was the most profitable plantation type. This result suggests that the TAB can reasonably increase economic benefits, including the short-term (yam tuber) and long-term (teak timber) incomes for the farmers.

KEYWORDS
biomass, *Dioscorea*, food security, harvest, productivity, teak, yield

1 | INTRODUCTION

The potential of agroforestry systems to contribute to sustainable food systems and enhance food security is well supported by literature (Duffy et al., 2021; Leakey, 2020; Waldron et al., 2017). The integration of indigenous crops, which are often underutilized, into agroforestry systems remains underexplored (Leakey et al., 2022). Indigenous crops are more resistant to abiotic and biotic stresses and require fewer inputs than many introduced crops (Mabhaudhi et al., 2019; Leakey et al., 2022; Chase et al., 2023; Rampersad et al., 2023). Several authors (e.g., Hunter et al., 2019; Tadele & Bartels, 2019; Jamnadass et al., 2020; Leakey et al., 2022; Benitez-Alfonso et al., 2023; Chase et al., 2023; Rampersad et al., 2023) postulated that indigenous crops have the potential to increase food security, especially in emerging economies, given their adaptability and suitability to grow in highly diverse cropping systems and their resistance to climate change and pathogens. That said, the production of indigenous crops is often perceived as being of lower economic value compared to other, more commercial crops (Leakey et al., 2022). Further research is needed to demonstrate and support the viability of indigenous crops in agroforestry systems.

Agroforestry has beneficial impacts on landowners, both economic (e.g., food, timber, fuelwood production) and in terms of ecosystem services (e.g., increased biodiversity and soil fertility) (Atangana et al., 2014; Brown et al., 2018; Hanif et al., 2018; Kassa et al., 2023; Khan et al., 2017; Leakey, 2020; Liu et al., 2018; Manson et al., 2024; Mathukia et al., 2016; Prabawani et al., 2024; Wenda-Piesik & Synowiec, 2021). However, the tree domination in agroforestry systems may cause competitive interactions for water, nutrients, and light (Luedeling et al., 2016; Scordia et al., 2023), and excessive shading of woody plants can reduce crop yield (Blaser-Hart et al., 2021; Gao et al., 2013; Sabarnurdin et al., 2011; Zhang et al., 2013). Selecting shade-tolerant and adaptable crop species is essential for successful integration into agroforestry (Campera et al., 2024; Leakey et al., 2022). Several species of tropical tuber (e.g., greater yam, lesser yam, and elephant foot yam) have been cultivated under shade conditions and are thus suitable to be intercropped with trees (Suja & Nedunchezhiyan, 2018; Swadija et al., 2016; Swestiani & Maharani, 2023). In addition, cultivating wild edible plants such as *Dioscorea* spp. could ensure food security (Priyadarshini et al., 2024).

Lesser yam (*Dioscorea esculenta* (Lour.) Burkill, Dioscoreaceae) is a tuber crop indigenous to Southeast Asian countries; it is locally known in Indonesia as "gembili" (Purnomo et al., 2017). Yams were renowned and utilized by Indonesians as an alternative food, substituting rice or sago during dry periods in Maluku, Lesser Sunda, Sulawesi, and Java (Sulistiyoon & Marpaung, 2004). This crop is an herbaceous, spiny vine climbing tree poles, and it may produce 5–20 tubers underground with an average tuber weight of 0.25–1 kg (Prabowo et al., 2014; Wijaya et al., 2020). *D. esculenta* has a high nutritional value (Indriyatno et al., 2024). The tuber of lesser yam is a carbohydrate source used to substitute rice or sago (Obidiegwu et al., 2020; Prabowo et al., 2014). It contains high protein content and 14.77% inulin (Winarti et al., 2012). Inulin is a valuable probiotic dietary fiber with a relatively low carbohydrate content; it is widely used in the food industry, such as in Europe, the USA, Canada, and Indonesia (Muhammad et al., 2019; Pusporini & Anggraini, 2016; Winarti et al., 2013). The inulin market, currently at USD 0.96 billion, is expected to grow in the near future (Mordor Intelligence, 2025).

Although lesser yam cultivation has been practiced for a long time, the productivity and profitability of the farming systems remain unknown. The same is true for teak due to the long-life cycle and traditional management systems (Datta et al., 2024). The aim of this research was to determine if lesser yams can be integrated into agroforestry systems with teak trees without a decrease in productivity. In particular, we assessed the following parameters: (i) crop biomass production; (ii) Harvest Index (HI) and Efficiency of Storage Root Production (ESRP); (iii) profitability analysis (including both lesser yam and timber returns).

2 | MATERIALS AND METHODS

2.1 | Study site

The research was conducted in a privately owned area in Watubonang Village, Sukoharjo District, Central Java (S 7°44′52″ and E 110°44′48″) (Figure 1). Smallholder farmers in Sukoharjo, Central Java, adopted lesser yam cultivation 30 years ago in agroforestry and monoculture systems (Estiasih et al., 2022). The lesser yam is cultivated under mature stands (Suja & Nedunchezhiyan, 2018; Swadija et al., 2016) in agroforests because the trees serve as a living stake or pole for climbing vines. Teak reaches maturity at 10 years old, with a stem diameter of more than 10 cm (Maharani et al., 2022).

In monoculture systems, farmers use bamboo poles for cultivating lesser yams during a period of 6–8 months (Figure 2). The height of bamboo poles is usually around 2.0 m, and the yams grow evenly on the top of the construction. This height limits the height and length

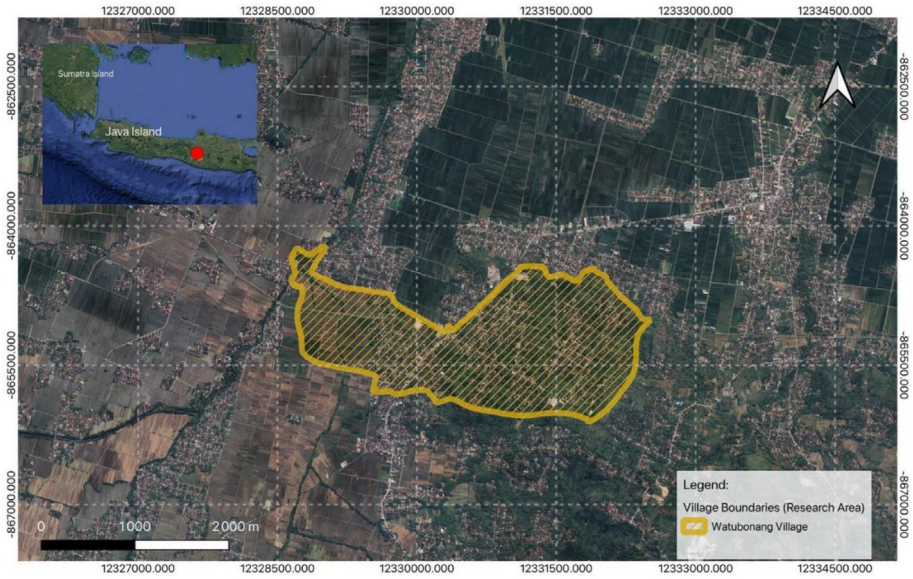

FIGURE 1 Location where the research has been conducted: Watubonang Village, Sukoharjo District, Central Java.



FIGURE 2 Lesser yam (*Dioscorea esculenta* [Lour] Burkill.) vine, (A) climbing a c.a. 10-year-old teak tree in an agroforestry system, and (B) growing on a bamboo staking in a monoculture system in a yam production village in Sukoharjo District, Central Java. Photos taken by the authors.

growth of the yam's vine and, consequently, leaf area. Most farmers in the village cultivate lesser yam, covering almost 200 ha of unirrigated areas, representing approximately 43% of the total village land area. The farmers usually apply cattle dung as fertilizer for yams, about 2 kg each plant. The village has a typical tropical dry climate with an average annual rainfall of 2000 mm year^{-1} and at an elevation of 118 m a.s.l. (Badan Pusat Statistik, 2020). The air temperature ranged between 24 and 29°C, with relative humidity ranging from 75% to 92% and a relative light intensity of 56.9%. The site is located at an altitude of 118 m a.s.l., with slopes ranging from 2% to 15%. The soil type in the research site is grumosol or vertisol with black color (Anggita et al., 2022). The high clay content may influence the unavailability of nitrogen and phosphorus, and is classified as poor-to-moderate soil to support crop production (Utomo, 2016).

2.2 | Data collection

The research was initiated by field observation and plot settlement (Sawitri, 2015), followed by biomass harvesting in the dry season of 2016, data collection, and data analysis in the subsequent years (we used the 2019 base price for financial analysis; Ariani &

Geo, 2020), while literature study and financial analysis were done in 2021–2022. A randomized complete block design (RCBD) was employed in this research to minimize the influence of environmental variability across the study site (Dutilleul, 1993). Variation in light intensity was identified as one of the major sources of heterogeneity, as certain plots received higher light exposure due to surrounding vegetation. To control this variability, experimental plots were grouped into blocks with relatively uniform light intensity, ensuring that differences in plant performance could be more reliably attributed to the treatments rather than environmental factors. Four plantation types were established: YM = yam monoculture, TAB = teak and yam in trees along the border, TYI = teak–yam intercropping, and TM = teak monoculture. YM was practiced in rows, with row spacing ranging from 30 cm to 100 cm, whereas the lesser yam vines climb on bamboo construction or staking during a growing period of 6–8 months. The row spacing of 30–100 cm reflects the actual practices of local farmers rather than a predetermined experimental design. To account for this variability, the research was established within blocks where row spacing was kept consistent, and the effect of spacing variation was minimized through replication and randomization within the RCBD framework. TM was practiced by planting teak trees in a regular pattern with a spacing of 3 × 3 m, with less intensive management until the final harvest of the timber. Fertilization for the TM is only provided in the first three years, and no additional treatments apart from thinning and pruning. In TAB, farmers planted teak trees as a boundary of farmlands and cultivated about four individuals of yams surrounding the teak stems. Given the squared shape of the farmland, the teak trees were planted on four sides with five to seven trees on each side (20 to 28 trees per plot) in an irregular spacing of 2.5 m to 5.5 m. The TAB plantation type has traditionally been practised by the local community as a means of demarcating land ownership; consequently, the trees were not arranged in a regular planting pattern as observed in the TM plantation type. The crown depth of the trees, measured using a hagameter, was approximately 3.3 m with the crown radius up to 3.0 m. Therefore, the space inside the TAB for crop cultivation was approximately 64 m^2. In TYI, teak trees were planted with a common spacing of 3 m × 3 m, each along with four individual yams. These four yams were systematically arranged equidistantly around each teak tree, positioned at the cardinal directions (north, south, east, and west) at a distance of approximately 30 cm from the teak stem base (Figure 3).

Observation plots of 20 m × 20 m were established in each of the planting types and replicated three times (independent plots located on separate farms within the village). The teak trees in the TAB, TYI, and TM plots were approximately 10 years old at the time of data collection. The plots were distributed randomly at a distance of 50 m. For measuring the yam in agroforestry (TAB and TYI), five

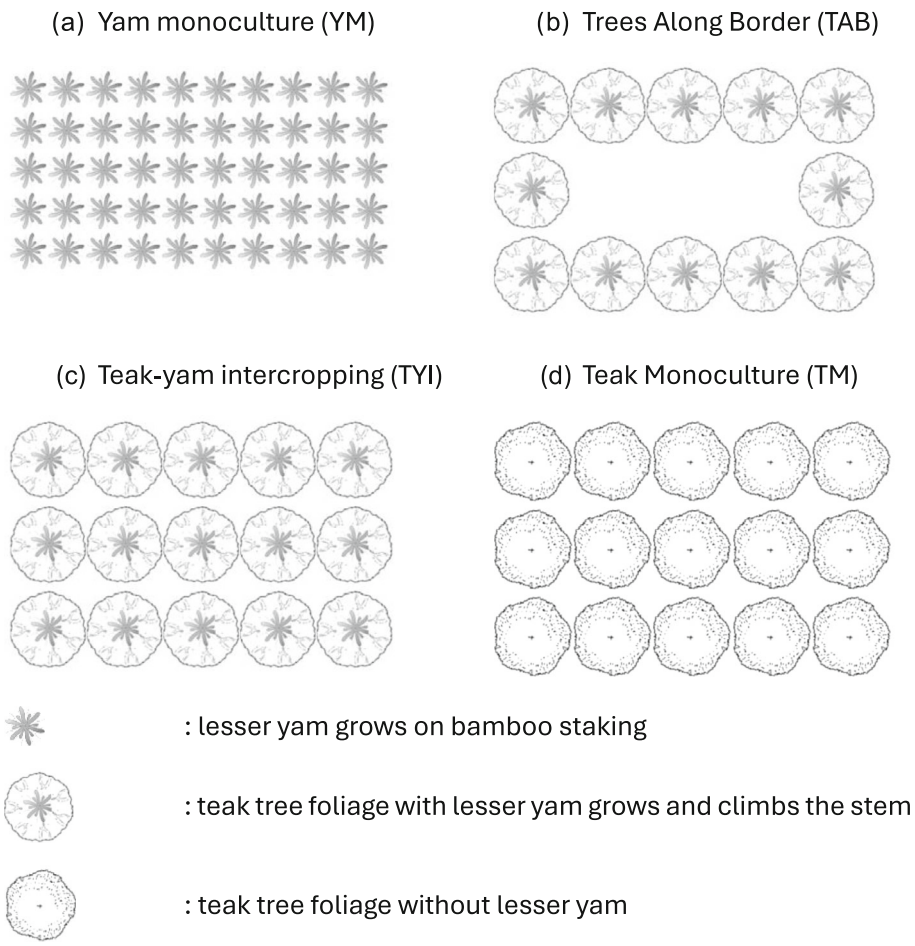

FIGURE 3 Vertical view of three plantation types of lesser yam (*Dioscorea esculenta* (Lour.) Burkill) and a monoculture of teak forest in a yam production village in Sukoharjo District, Central Java.

2 m × 2 m subplots were nested within each larger experimental plot (20 m × 20 m). Subplots were randomly established within the plot boundaries to avoid bias and to ensure representative sampling of yam growth.

2.3 | Data analysis

From the measurements, production of the whole plantation (t ha^{-1}) was calculated by multiplying the number of individuals per plot, considering 35 plots per yam planting pattern (105 plots in total). Yam tuber production was calculated from the average tuber weight (g) in plots and then multiplied by the number of individuals per plot and extrapolated to a production per-hectare basis (kg ha^{-1}). Since tuber productivity was not normally distributed, a Kruskal-Wallis test was employed to compare the tuber productivity, and a Dunn post-hoc test was done upon the significant differences ($\alpha < 0.05$) among the plantation types. Other parameters, such as harvest index (HI; HI = [Economic yield/Biological yield] × 100), efficiency of storage root production (ESRP), and economic yield (i.e., total harvested mass in tons/ha), were also estimated in this research. For these analyses, 24 plots per yam planting pattern were considered (72 plots in total). The biological yield is the total harvested biomass, including tubers, tendrils, and leaves (kg ha^{-1}). The HI, which is a measure of biological success in partitioning assimilated photosynthate to the harvestable product, is calculated by the ratio of harvested tuber dry weight to the total biomass (Chaimala et al., 2020; Ebrahim et al., 2018). Kruskal-Wallis test was employed to compare the HI, and Dunn post-hoc test was done upon the significant differences ($\alpha < 0.05$) among the plantation types. The ESRP was calculated from the linear regression of dry weight of the storage root and the total plant dry weight (Boerboom, 1978). The biomass production rate for ESRP measurement was Y = ax+b, where x: tuber dry weight (g); Y: total dry weight biomass (g); a: regression coefficient, i.e., = efficiency of storage root production (ESRP); b: regression constant. Each ESRP regression included 24 samples. We tested the assumption of linearity using the Durbin-Watson test, and we included an autocorrelation term using the Cochran-Orcutt test. Furthermore, financial analysis was conducted to evaluate profitability of managing the different plantations, including Net Present Value (NPV) (Nair, 1993), Benefit–Cost Ratios (BCR) (Friday et al., 2000), and Equivalent Annual Income (EAI) (Shukla & Viswanath, 2014). The benefits and costs of the tree-based agroforestry were measured for a specified period of 20 years, which refers to the life cycle of teak trees for producing timber (Budiadi et al., 2012; Na'iem 2014). The formulas for NPV (USD/ha/20 years), BCR, and EAI (USD/ha/year) are as follows:

$$NPV = \sum_{t=0}^{n} \frac{Bt - Ct}{(1+r)^t} \quad (1)$$

$$BCR = \frac{\text{Total discounted benefits}}{\text{Total discounted costs}} \quad (2)$$

$$EAI = NPV\, x \frac{i\,(1+r)^t}{\left[(1+r)^t - 1\right]} \quad (3)$$

where B is the benefits in year t, C the costs in year t, n is selected time period, and r is the selected discount rate. The net benefits were discounted at rates of 6% per year. Since yam is treated as an annual

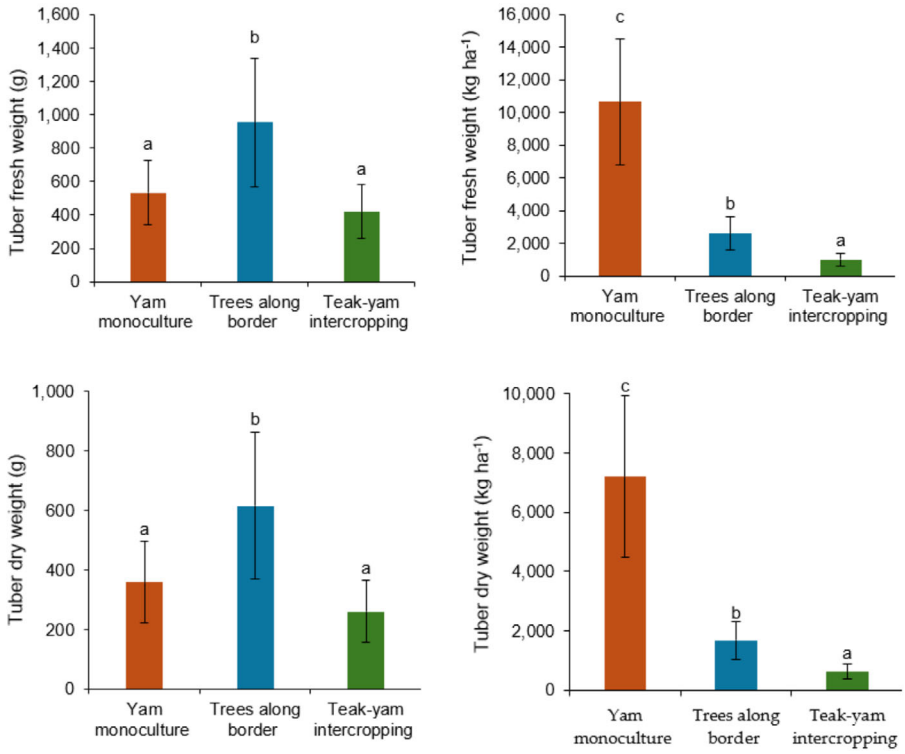

FIGURE 4 Lesser yam (*Dioscorea esculenta* (Lour.) Burkill) tuber production measured in fresh and dry weight (g $plant^{-1}$ and kg ha^{-1}) from the three plantation types on farmer land in a yam production village in Central Java. Values are means and SD. Letters above bars indicate statistically different groups based on Dunn post-hoc tests following Kruskal-Wallis tests.

crop, NPV and EAI were not possible since they need multiple years of data input and be multiplied with a discount rate. The teak-timber prices are based on the price guidelines of Perhutani (No. 183/KPTS/DIR/12/2020; Perhutani, 2021), while the yam prices were estimated using the method form Ariani and Geo (2020).

3 | RESULTS

3.1 | Yams production and productivity

The fresh and dry-biomass production of lesser yam tuber in the different plantation types was obtained through individual and area measurements (Figure 4). On an individual basis, the TAB produced higher tuber yield than the YM in fresh and dry weight estimation ($H(2, 105) = 47.831$, $P < 0.001$, and $H(2, 105) = 46.987$, $P < 0.001$, for fresh and dry weights of tuber, respectively). The average production from the TAB was 952.96 (±382.17) g and 614.70 (±246.54) g per plant, whereas the lowest was from the TYI, with 419.03 (±161.89) g and 261.24 (±105.80) g of fresh and dry tubers, respectively. On plantation bases, the YM produced higher tuber biomass than the TAB and TYI for fresh and dry weights of tuber ($H(2, 105) = 86.847$and $H(2, 105) = 87.014$, $P < 0.001$, for fresh and dry tubers, respectively). The YM produced the highest tuber biomass, with 10,650.53 (±3841.10) kg ha^{-1} and 7,190.14 (±2,724.49) kg ha^{-1} of fresh and dry tubers, respectively. By contrast, the TYI produced the lowest tuber biomass, with 1,005.68 (±388.68) kg ha^{-1} and 626.98 (±253.92) kg ha^{-1} of fresh and dry tubers, respectively. The average population of yams in the different systems is: YM = 20,000 ind/ha; TAB = 3,000 ind/ha; TYI = 2,400 ind/ha.

3.2 | Harvest index (HI) and efficiency of storage root production (ESRP) of yam

The HI varied among the plantation types (Table 1; $H[2,74] = 10.256$, $p = 0.006$). YM (Dunn post-hoc test: $p = 0.003$) and TAB (Dunn post-hoc test: $p = 0.011$) had a higher HI than TYI. No significant difference in HI was found between YM and TAB (Dunn post-hoc test: $p = 0.689$).

High total dry weight of the plant was related to high tuber biomass, although slight differences can be found between plantations (Figure 5). We found a strong linear relationship between the tuber and the total dry weight of biomass, with the highest R^2 in YM and TAB (0.990), followed by TYI (0.967). TYI showed a slightly higher ESRP (1.068) than TAB (1.055) and YM (1.016). [Correction added on 14 January 2026, after first online publication: In the preceding sentences, Table has been corrected to TAB in this version.]

3.3 | Economic value of teak and lesser yam in different plantation types

The financial analysis of teak and yam under the different plantation types was carried out at 6% discount rate. All parameters greater than zero were assumed to be financially feasible. TAB had the highest NPV (9109.86 USD/ha/20 years), BCR (2.01), and EAI (794.3 USD/ha/year) (Table 2). In the short term, yam monoculture provided higher income (Figure 4) because the seasonal crops generate quicker returns than teak timber, although the BCR was lower than that of the tree-based plantations. Among the tree-based plantations, the farmers were able to harvest a reliable value of the combined products of the cash crop and timber from the TAB, which was higher than that from the TYI and TM. The TM plantation type produced the lowest NPV and EAI, at 5186.85 USD/ha/20 years and 452.25 USD/ha/year, respectively. The productivity data of the teak timber were: TYI = 148.91 m^3/ha; TAB = 126.62 m^3/ha; TM = 148.24 m^3/ha.

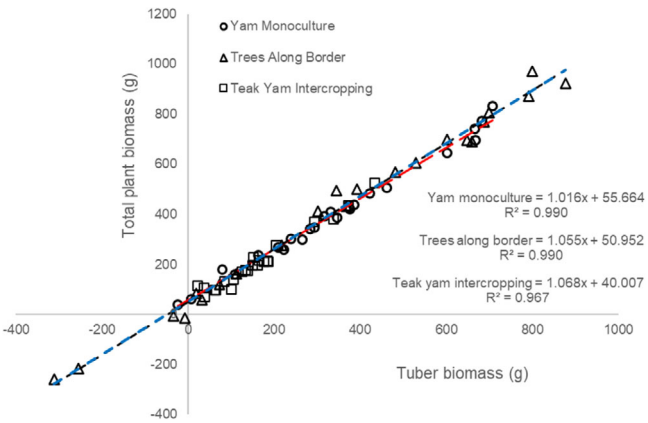

FIGURE 5 Relationship between tuber and total biomass of lesser yam (*Dioscorea esculenta* (Lour.) Burkill) in different plantation types in a yam production village in Central Java. Regression analysis was done following linearity tests using Durbin-Watson, and autocorrelation test using Cochran-Orcutt. The regression coefficient of each trendline (yam monoculture: red; trees along border: blue; teak yam intercropping: black) for the plantation types reflects the efficiency of storage root production (ESRP) (Table 1).

TABLE 1 Harvest index (HI) and biomass production rate of lesser yam (*Dioscorea esculenta* (Lour.) Burkill) in different plantation types in a yam production village in Central Java.

		Biomass production Rate[i]		
Plantation type	HI (±SD)	Equation	R^2	ESRP[ii]
Yam monoculture (YM)	0.8095 (±0.0981)	$y = 1.016x + 55.666$	0.990	1.016
Trees along border (TAB)	0.7964 (±0.1039)	$y = 1.055x + 50.951$	0.990	1.055
Teak-yam intercropping (TYI)	0.7317 (± 0.1078)	$y = 1.068x + 40.007$	0.967	1.068

[i]Biomass production rate is a ratio of dry weight of storage root biomass to total biomass.
[ii]ESRP: efficiency of storage root production.

Plantation type	NPV (USD/ha/20 years)	BCR	EAI (USD/ha/year)
Trees along border (TAB)	9109.86	2.01	794.3
Teak-yam intercropping (TYI)	6213.76	1.84	541.79
Teak monoculture (TM)	5186.85	1.90	452.25
Yam monoculture (YM)	Not applicable	1.60	Not applicable

Note: Value of yield per season per year. NPV and EAI analyses were not performed on YM because these analyses need multiple years of data input and must be multiplied with a discount rate.

TABLE 2 Financial analysis (at 6% discount rates) of agroforestry and monoculture plantations for 20 years rotation of teak timber (USD ha^{-1}) in a yam production village in Central Java. NPV: net present value; BCR: benefit–cost ratios; EAI: equivalent annual income.

4 | DISCUSSION

We showed that lesser yam in agroforestry systems is more profitable than in monoculture crops. This finding supports the idea that agroforestry systems integrating indigenous crops can be profitable and thus sustainable in the long term. Given the decrease in yields of yams worldwide, also due to non-sustainable farming practices, despite an increase in total production due to an augmented cultivated area (Kouakou et al., 2023), our findings indicate that more yam production should be done in agroforestry systems. This would also grant longer-term benefits, such as harvesting teak wood. Although not directly measured in our study, agroforestry systems may also enhance soil fertility and ecosystem services, as reported in previous research e.g., improvement of soil fertility and ecosystem services associated with biodiversity (Campera et al., 2024; Chavez et al., 2024; Manson et al., 2024), due to intercropping operations in yams. Our study supports the use of lesser yams as alternative staple crops to be integrated in agroforestry systems without a decrease in profits (and potentially, such as the case studied, with an increase in profits). Shading is indeed a limiting factor to plant growth (Chen et al., 2019; Miao et al., 2023; Ong & Kho, 2015; Wagner et al., 2011), but shading also reduces the negative effect of direct sunlight radiation on understory vegetation. It is likely that trees such as teak support the productivity of annual crops by reducing solar radiation to a more moderate temperature regime and higher humidity compared with an open environment (Ong & Kho, 2015; Singh et al., 2012). Teak is a suitable shade tree due to its slow growth and shedding its leaves during the dry season, while yam is a tuber and vine crop that appears just before the rainy season.

Soil fertility, particularly high organic matter and nutrient content, is a key factor affecting yam growth (Agbede et al., 2013; Maliki et al., 2017; Reazei et al., 2016). The most important nutrients—nitrogen (N), phosphorus (P), and potassium (K)—promote vegetative growth, photosynthesis, energy transfer, cell division, metabolism, and protein synthesis, thereby influencing dry matter accumulation and tuber yield (Diby et al., 2011; Hgaza et al., 2012; Johnson et al., 2022; Reazei et al., 2016; Yagoub et al., 2012). Nutrient availability is strongly affected by cultivation practices, particularly fertilization. Intensive management, including frequent or targeted fertilizer applications, can elevate soil N, P, and K levels, enhancing plant growth and productivity. Differences in soil nutrient status among planting patterns often reflect farmers' practices: the yam monoculture pattern, managed more intensively, shows higher N (201 ppm) and P levels (54.7 ppm), whereas TAB and TYI patterns have lower concentrations of N (153; 178.3 ppm) and P (50.3; 25 ppm), likely due to reduced fertilizer input (Sawitri, 2015). In agroforestry, teak trees are expected to improve soil fertility by increasing nutrient inputs from organic matter via litterfall (Kuyah et al., 2016). The combined effect of fertilizer and plantation management (Frossard et al., 2017), i.e., plantation patterns (TAB and TYI), may explain long-term production sustainability. However, it is essential to maintain soil sustainability and long-term fertility via the integration of agroforestry systems and the diversification of crops and trees in cropland (Chavez et al., 2024; Manson et al., 2022).

4.1 | Yam production and harvest

The production of the lesser yam on an individual basis was lower in the YM than in the TAB. The low tuber production in the YM was probably affected by the limited height (usually less than 2 m) or length growth of the yam vine and, consequently, less leaf area. By contrast, the stem of the trees in the TAB supported the growth of the yam vine to climb higher and placed the leaf in a relatively open space to optimally catch sunlight for efficient photosynthesis and generate energy for tuber growth and production. The TAB highlighted the critical role of vertical growth for yams as a strategy to avoid low-light conditions, where it compensates by producing high levels of chlorophyll (Lestari et al., 2019), although the lesser yam could adapt to a moderate level. Furthermore, there were differences in growth performances under different shade levels of yams, which affected the tuber size and total number of tubers (Lestari et al., 2019). The result, in line with Hamaoka et al. (2022), stated that yams without staking had lower yields and weight than those with staking, accounting for 19% and 29%, respectively. In addition, the vertical growth could be beneficial for yams in avoiding disease. The comparison between staking and non-staking mentioned that staking could contribute to more fresh tubers and had a good implication for disease resistance (Norman et al., 2015). Adaptation of lesser yam (*D. esculenta*) to agroforestry type (especially in the TAB) suggests its growth plasticity to a stressful environment (Sawitri & Budiadi, 2020). This finding also indicates that teak could be a good alternative to coconut, areca nut, rubber, and mango for yam intercropping (Suja & Nedunchezhiyan, 2018). Furthermore, teak–yam planting patterns can

maintain a sustained yield, economic return, social benefits, and fertilizer use efficiency and thus increase the overall profit (Dodiya et al., 2018).

On the plantation basis, given the impact of plant density per unit area, the yam monoculture produced the highest total weight of tuber. This result agrees with the finding of Ijoyah (2011) that intercropping significantly decreases the tuber yield of yam by 16% compared with sole cropping. Begum et al. (2016) also reported that the tuber yield of potato is higher with sole cropping than with intercropping. Some researchers reported that planting system (monoculture/intercropping) and population density significantly affected the crop yield of various yams in Nigeria (Enesi et al., 2018; Law-Ogbomo & Osaigbovo, 2014). Scordia et al. (2023) also reported that agroforestry could reduce the crop yield in Mediterranean countries, yet may lead to a diversification and increase overall productivity. The high yield of lesser yam in monoculture could also be affected by less competition effects from tree species in capturing water, light, and nutrients (Bertomeu, 2012). The reduced number of lesser yam per unit area and the effect of competition by the trees may significantly affect tuber productivity (but not system productivity).

TAB was the most efficient plantation type for yam tuber production when the BCR values were compared. The trees in the TAB support the vertical growth of the vine of lesser yam to absorb light radiation in a relatively greater space. The vertical growth and length of the vine are predicted to have a positive relation to tuber production. Sawitri & Budiadi (2020) stated that cropping patterns and Relative Light Intensity (RLI) significantly affect the morphological and anatomical characteristics, such as leaf size, tendril length, and internodes, of lesser yam. The similar HI of the TAB and YM indicated the suitability of yam to a relatively open space, but with the possibility to grow under shade. This result is slightly different from the findings of Liu et al. (2018) that the HI of maize is consistently lower in agroforestry than in monoculture and of Jalilian et al. (2017) that bitter vetch achieves higher HI and more pod number when intercropped with safflower. Lesser yam vines adapt to grow higher and climb the teak trees to reach available sunlight for photosynthesis (Bijalwan et al., 2016) and produce a high tuber-to-total biomass ratio. Therefore, a good management practice is needed to optimize resource utilization; increase the yield, production, and HI; and thus enhance profitability from tree intercropping systems (Bertomeu, 2012).

Despite not being implemented in the study area, pruning of the tree branches has been suggested as an effective strategy to minimize the competition of upper-story trees on crops and thus increase RLI. Patel et al. (2017) showed that different pruning intensities of *Dalbergia sissoo* Roxb. significantly affect the biological yield of staple crops. The combination of pruning and fertilization on teak–ginger agroforestry significantly affects ginger biomass, leading to increased rhizome productivity (Sudomo et al., 2019). Crown pruning increases the availability of photosynthetically active radiation (PAR) and reduces the competition for light, resulting in the accumulation of photosynthates in crops and their translocation from source to sink (Laužikė et al., 2020). A well-planned pruning treatment should be considered to promote a favourable light environment, especially in the TYI plantation type.

4.2 | Economic implications

Combining cash crops with teak trees (mostly TAB) was able to increase economic value compared to the monocultures (i.e., the TM and YM). When adopting the teak tree, farmers must accept reduced yields of yam before receiving an increase in income from harvesting teak timber. Agroforestry increases the income of smallholder farmers by reducing crop failures, market demand, and price fluctuation, which may be affected by managing only a single cash crop (Dodiya et al., 2018; Rahman et al., 2016). However, the tree domination, canopy closure, and intensive shading of tree foliage in the TYI caused the low tuber production of yams. This problem can be addressed by optimizing the growing space, so that less cash crop production might be compensated by the timber stock value. It is advised to arrange the planting pattern and row orientation, e.g., east-to-west orientation. A study (Sawitri & Budiadi, 2020) recommended that more uniform planting patterns with relative light intensity (RLI) of 50–60% are better for morpho-anatomical adaptation of yam and will impact plant production.

In the TAB and TYI plantation types, the teak trees acted as the living stake or pole for the yam instead of bamboo stakes. Danquah et al. (2014) previously reported that farmers in Ghana select trees and shrubs and leave them during land preparation as stakes. The use of the living stake of *Gliricidia sepium* has also been reported by Ernest and O'Sullivan (2004) to support yam crops. By climbing the tree stems, the yam exposes the leaves to sunlight, thereby promoting photosynthesis (Saravaiya et al., 2013). In short, the living stakes can reduce the cost of cultivation and increase tuber production and stand value. Comparatively, the farmers were predicted to obtain an extremely low yield from the timber as a single long-term product (Roshetko et al., 2013), such as in the TM in the study.

Smallholder farmers practicing the traditional cultivation system face the problems of small land area, less investment, and high labour cost, and therefore experience difficulty enhancing productivity and obtain low-profitable outputs (Ayanwuyi et al., 2011; Merten et al., 2021; Migap & Audu, 2012). A relatively high cost for yam monoculture cultivation was due to the material needed for artificial support or staking (of bamboo) and a higher number of lesser yam tubers per area than the other plantation types. Staking is important for developing a lesser yam monoculture because it is a climbing plant (Saravaiya et al., 2013) constructed to support yam vines. Specific interventions such as microfinancing and training are advised to support the adoption of yam-based agroforestry systems.

The highest cost required in all of the lesser yam plantations is for planting materials and cultivation. Hence, the largest tubers of harvested yams are mostly used as seed or planting material to accelerate the growth in the next rotation. This method reduces the number of harvested tubers and decreases the yearly economic value. Iseki and Matsumoto (2020) reported that the use of yam seeds constitutes approximately 30% of the total harvested yams. Recently, the modern technology of minitube seed production through vine cutting propagation and the minisett technique using tissue culture has been applied to increase benefits for farmers (Aighewi et al., 2015, 2021).

Relevant training is needed in the study area to adopt these improved propagation techniques.

Combining the cultivation method with intensive silviculture, such as tree thinning, pruning, and lopping (Asaro et al., 2017; Krajnc et al., 2019; Pinno et al., 2021; Skovsgaard et al., 2021), and in addition to protecting the yams from some pests and diseases (Akinbo & Opara, 2019; Kolombia et al., 2017), lesser yam-based agroforestry systems will obtain high profits in short- and long-term periods. Based on financial or feasibility analysis, the potential to further enlarge income from yam cultivation is still high. Yam cultivation will contribute to the source of staple food for the people and support food security for the community. Processing yam tubers into various preparations certainly increases the economic value of yam commodities (Ariani & Geo, 2020).

Integrating trees in cropland and promoting sustainable agricultural practices are consistent with Indonesia's national strategies, as articulated in Law of the Republic of Indonesia Number 59 of 2024 on the National Long-Term Development Plan 2025–2045. These efforts are further reinforced by the country's social forestry policies, particularly Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 9 of 2021 on Social Forestry Management, which explicitly encourages the development of agroforestry systems. Reforestation programs have been campaigned by the Indonesian government since the 1950s to rehabilitate degraded lands and increase land cover (Austin et al., 2019; Casson et al., 2014; Darmawan et al., 2016; Nugroho et al., 2022). In Java Island, afforestation and land rehabilitation are implemented on community lands outside forests because of high population density and land scarcity (De Royer et al., 2018; Santika et al., 2017). The acceptability rate of rehabilitation programs using perennial species (such as teak, albizia, and mahogany) on community lands is relatively high in Java due to the high economic value of the timber (Liu et al., 2018; Roshetko et al., 2013).

Unsustainable production of yam can bring about a decrease in production with consequences for food security (Kouakou et al., 2023). Also, a shift toward the greater use of agrochemicals in yam production that, in the long term (Condé et al., 2025), can decrease soil fertility. Thus, agroforestry can represent an avenue considering the productivity is not decreasing. More empirical evidence is needed to demonstrate that yam-based agroforestry systems consistently offer agronomic and economic benefits compared to monoculture approaches, particularly under smallholder conditions. This study attempts to contribute toward developing a proper farming system on small farmlands to achieve food security, household income, and environmental quality in the highly populated island of Java.

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, formal analysis, writing original draft, writing—review & editing, visualization: Budiadi; data curation, formal analysis, writing—original draft: Sawitri; data curation, formal analysis, writing—original draft: Enggal Primananda; data curation, financial analysis, writing—original draft: Rika Bela Rahmawati; writing—original draft, writing – review & editing: Marco Campera; formal analysis, writing—original draft, writing—review & editing: Aqmal Nur Jihad. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable.

INFORMED CONSENT STATEMENT

Not applicable.

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