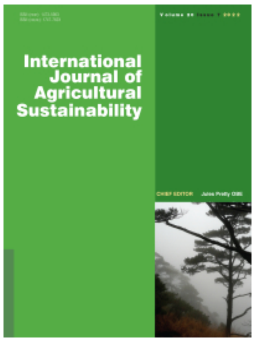

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Farm gate profitability of organic and conventional farming systems in the tropics

Amritbir Riar, Eva Goldmann, David Bautze, Johanna Rüegg, Gurbir S. Bhullar*, Noah Adamtey**, Monika Schneider, Beate Huber and Laura Armengot***

Department of International Cooperation, Research Institute of Organic Agriculture (FiBL), Frick, Switzerland

ABSTRACT

Systematic studies on the economic competitiveness of organic farming systems compared to conventional farming systems are particularly lacking in tropical environments. In tropical regions, the evaluation of organic production systems typically concentrates on main cash crops earmarked for export markets. Consequently, crops grown in rotation or in association with these main crops have been largely overlooked, with their contribution to farm profitability is often considered negligible due to perceived challenges in securing premium organic prices. To address this knowledge gap, we conducted an analysis of twelve years of economic data from four long-term farming system comparison trials in tropical regions. Our objective was to delve into the economic competitiveness of both organic and conventional production systems at the system level, considering not only the main cash crops but also the associated and rotational crops. The outcomes of our analysis revealed that in three out of four systems, the gross margins of organic and conventional systems were comparable. In the fourth system, the gross margins of the organic system were 13.13% lower, equivalent to $169.8 per hectare per year compared to the conventional system. Furthermore, the contribution of crops grown in rotation with these main crops remains similar even when premium prices are not obtained. In instances where premium prices for non-cash crops are secured, their profitability can even surpass that of cash crops. Additionally, in the case of agroforestry, companion plantings serve as valuable additions for both dietary and income diversity. These findings suggest that the profitability of an agricultural system is not solely dependent on whether it is organic or conventional but is instead influenced by various system components. The emphasis should shift from a singular focus on main cash crops to a more comprehensive understanding that considers the entire spectrum of crops within a farming system.

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KEYWORDS
Long-term experiments; conventional vs. organic farming; farming systems; profitability

1. Introduction

(Babajani et al., 2023; Ha et al., 2023; Michalscheck et al., 2023; Peltonen-Sainio et al., 2024; Thiombiano et al., 2023)

Climate change, land degradation, and the burgeoning global population present imminent threats to food security, as highlighted by various (Azadi et al., 2011; Tubiello et al., 2008). The gravity of these challenges is particularly pronounced in tropical regions, which are anticipated to accommodate half of the global human population by 2050 (Wilkinson, 2014). Despite substantial economic growth in these

CONTACT Amritbir Riar amritbir.riar@fibl.org Research Institute of Organic Agriculture, Frick 5070, Switzerland
*Present Address: School of Agricultural, Forest and Food Sciences (HAFL), Berner Fachhochschule, Zollikofen, Switzerland
**International Water Management Institute – Ghana, Accra, Ghana
***Department of Evolutionary biology, Ecology and Environment Sciences, Faculty of Biology, University of Barcelona, Barcelona, Spain
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areas over the last three decades, contributing, only a fifth to the global economic output (Wilkinson, 2014)this progress has often come at the expense of biodiversity losses, compromised water quality, and unsustainable utilization of natural resources (Edelman et al., 2014).

While global initiatives strive to enhance resource use efficiency and reduce dependence on non-renewable resources (Schoonbeek et al., 2013), aligning with calls to safeguard planetary boundaries (Lee et al., 2023), sustainable development discussions have prompted exploration of alternative farming practices such as agroecological and organic farming (Seufert & Ramankutty, 2017; Trewavas, 2001).

Of particular interest is organic farming, which has gained attention for its potential to enhance soil and water quality and support biodiversity conservation (Gomiero et al., 2011; Lichtenberg et al., 2017; Marconi et al., 2022; Mäder et al., 2002). Furthermore, organic food production has shown promise in mitigating climate change (Armengot et al., 2021; Borron, 2006; Hansen et al., 2001; Niggli et al., 2007; Scialabba & Müller-Lindenlauf, 2010). Consequently, organic farming is often considered a viable alternative to conventional practices that can help alleviate the negative impacts on planetary boundaries.

However, the feasibility of organic farming remains a topic of debate, as numerous studies report lower yields and higher labour requirements compared to conventional counterparts (Connor, 2008; De Ponti et al., 2012; Kniss et al., 2016; Ponisio et al., 2015; Seufert et al., 2012; Trewavas, 2001; Wilbois & Schmidt, 2019). On average, organic farming has been associated with yield gaps ranging from 19 to 25%, depending on the specific crop and management practices(Ponisio et al., 2015; Seufert et al., 2012). Some studies suggest that these yield gaps may diminish over time as improvements in soil biotic and abiotic properties occur (Schrama et al., 2018). Nevertheless, these yield disparities can translate into economic losses, posing challenges to the long-term viability of organic farming, especially among smallholders.

To address these challenges, strategies such as low external inputs and higher compensation through premium prices for quality products can help offset the economic disadvantages (Crowder & Reganold, 2015). While numerous studies have investigated the performance potential of organic and conventional farming systems under temperate conditions (Alvarez, 2022; Seufert & Ramankutty, 2017), the applicability of this knowledge to tropical environments is limited, as considerably fewer studies have been conducted in such regions (Alvarez, 2022; Djokoto & Pomeyie, 2018; Seufert & Ramankutty, 2017).

The question of economic sustainability is further complicated in the developing economies of the tropics (DESA et al., 2022), where a substantial proportion of organic producers are based (Willer et al., 2023). In these countries, organic production often focuses on exporting 'main/cash crops' that can command premium prices (Valkila, 2009). Conversely, other crops grown in rotation or mixed cropping systems typically lack premium prices due to underdeveloped domestic markets for organic products (Giovannucci, 2006; Pretty et al., 2003). This situation, coupled with infrastructure and policy incentives geared towards main crops, often encourages specialized crop production and mono-cropping systems.

Thus, evaluating the economic viability of organic production in developing economies solely based on main crops does not provide a comprehensive view of organic agriculture's overall performance. To gain a more holistic understanding, it is crucial to assess the economic competitiveness of organic farming compared to conventional methods at the level of complete farming systems rather than focusing solely on main cash crops. Unfortunately, such comparative studies conducted under field conditions are scarce, particularly in tropical regions (Alvarez, 2022; Djokoto & Pomeyie, 2018; Seufert & Ramankutty, 2017).

'On-farm' studies comparing organic and conventional farming are hindered by variations in preconditions inherent to each farming system, such as soil fertility and cropping patterns chosen by organic and conventional farmers (Kirchmann et al., 2016). These challenges can be addressed through standardized 'on-station' experimental conditions. Additionally, differences in the performance of the different farming systems may only become evident in the long term (Fließbach et al., 2007; Rasmussen et al., 1998). Consequently, long-term on-station field trials offer valuable insights into the performance of different farming systems under comparable conditions as well as compensating for annual variations in productivity, input costs, etc (Adamtey et al., 2016; Armengot et al., 2016; Forster et al., 2013; Pérez-Neira et al., 2020). On the other hand, the cumulative values allow comparing the overall performance over a time series, including the fluctuations encountered over the year. In this study, our focus on the overall results at the long term, rather than seasonal dynamics, aims to compare the economic performance of organic and conventional farming systems. Our primary objective is to identify commonalities and differences among various farming systems, considering complete crop rotations or associated systems centred around different main crops. Our hypothesis is that the economic performance of organic and conventional farming systems in the long term is influenced by both main and associated crops, rather than being solely determined by the performance of main crops.

2. Materials and methods

2.1. Experimental sites and setup

In the present study, we worked with twelve years of economic data from four long-term experiments set up in Bolivia, India, and Kenya. The three countries were chosen as divers farming and socio-economic conditions in the respective countries and the sites were selected as representatives of different agro-ecological zones and characteristic crops of the respective countries. In the case of Bolivia and India, the crops of cocoa and cotton serve as model crops, as they have a long history of organic production in these countries. For instance, the El Ceibo cooperative, a second-order cooperative in Bolivia, and partner to the project, has been producing organic cacao since 1977. Kenya was chosen as the entry point for eastern African context. Though all four experimental sites are located in the tropics, there are significant environmental differences. In Alto Beni, Bolivia, the average annual precipitation is 1540 mm and the mean temperature is 26.6°C. The site is at an altitude of 380 m.a.s.l., and Luvisols and Lixisols are the prevalent soil types. In Kasrawad, India, the average annual temperature is 21.7 °C and the average annual precipitation is 800 mm, concentrated in a single monsoon peak. The altitude is 250 m.a.s.l. and Vertisol is the dominant soil type. In Chuka and Thika, Kenya, rainfall is bimodally distributed, showing annual precipitation and temperature average of 1373 mm and 19.2°C in Chuka, and respectively 840 mm and 19.5°C in Thika. Chuka is located at 1458 m.a.s.l. and Thika at 1500 m.a.s.l. In both locations, the soil type is Nitisol.

In each experimental site, four different conventional and organic farming systems (from here on, organic and conventional) were implemented and managed according to prevalent local practices or local expert panel suggestions. Organic and conventional systems differed in terms of fertilizer (compost vs. mineral) and weeding (mechanical vs. herbicides), and plant protection products (botanicals vs. synthetic) were applied. Detailed descriptions of the respective experimental setups and management practices can be found in Table 1 and previous publications (Adamtey et al., 2016; Armengot et al., 2016; Forster et al., 2013; Pérez-Neira et al., 2020).

In Bolivia, cacao plantations were fully implemented in 2009. Cacao was planted in four farming systems where monoculture (full-sun systems) and agroforestry systems (shaded systems) were managed according to organic or conventional farming practices. In a Complete Randomised Block Design, each system is replicated four times on a gross plot dimension of 48 m x 48 m with a net plot size of 24×24 m. Plantains were planted in all systems as temporary shade for young cacao trees. They were removed from all systems in 2011. The agroforestry systems, include timber, fruit, leguminous and palm trees from the installation of the plantation. In addition, bananas were planted in the agroforestry systems after the removal of the plantain.

In Kenya, the started in 2007. Maize- vegetable-legumes -potato are grown in a six-season, three-year crop rotation. At both sites, conventional and organic farming systems were compared at two levels of input management. the high input mimics commercial production and recommended rates of fertilizer, pesticides and supplementary irrigation are used. The low input management mimics smallholder production, largely for subsistence use, where limited amount of fertilizer and pesticides. Low input management The farming systems were arranged in a Complete Randomised Block Design four and five repetitions at Chuka and Thika, respectively. The plot size was 8×8 m, with a net plot of 6×6 m.

In India, a cotton-based two-year crop rotation has been implemented since 2007, i.e. cotton in rotation with soybean and- wheat. Two conventionally managed systems were tested, one with genetically modified Bt-cotton seeds and the other without. The two organically managed systems were distinguished by the application of bio-dynamic preparations. Each of the four systems was replicated four times in two strips using a Randomized Block Design with a gross plot extension of 16×16 m and a net plot of 12×12 m. Crop rotations were alternated in two strips to have all crops grown on either of the two strips each year.

Table 1. Data points of harvested crops over the study period per site, system and crop type as well as the average premium prices paid during the study period* where n represents the number of crops grown and included in this analysis for the study period(2007/10- 2018).

Site	System	Crop type	Data points	Average % premium over conventional#	Crops (n)
Bolivia	conventional	Main crop	8	–	Cacao (8)
Bolivia	conventional	Associated crops	14	–	Plantain (2), Banana (7), Avocado (3), Copoazu (2)
Bolivia	organic	Main crop	8	11.7	Cacao (8)
Bolivia	organic	Associated crops	14	–	Plantain (2), Banana (7), Avocado (3), Copoazu (2)
India	conventional	Main crop	24	–	Cotton (24)
India	conventional	Associated crops	60*	–	Soybean (24), Wheat (36)
India	organic	Main crop	24	13.5	Cotton (24)
India	organic	Associated crops	56*	–	Soybean (24), Wheat (32)
Chuka	conventional	Main crop	16	–	Maize (8), Maize + Common bean (8),
Chuka	conventional	Associated crops	32	–	Babycorn (8), Cabbage (4), Common bean (2), French bean (4), Kale - Swiss chard (4), Potato (8), Soybean (2)
Chuka	organic	Main crop	16	33.6	Maize (8), Maize + Common bean (8)
Chuka	organic	Associated crops	32	85.7	Babycorn (8), Cabbage (3), Common bean (2), Cowpea (1), French bean (4), Kale – Swiss chard (3), Potato (8), Soybean (2), Swiss chard (1)
Thika	conventional	Main crop	16	–	Maize (8), Maize + Common bean (8)
Thika	conventional	Associated crops	32	–	Babycorn (8), Cabbage (4), Common bean (4), French bean (4), Kale – Swiss chard (4), Potato (8)
Thika	organic	Main crop	16	64	Maize (8), Maize – Common bean (8)
Thika	organic	Associated crops	32	92.4	Babycorn (8), Cabbage (3), Common bean (4), Cowpe (1), French bean (4), Kale – Swiss chard (3), Potato (8), Swiss chard (1)

#Premiums were paid for organically grown cacao and cotton from 2011-2018, maize and associated crops in Kenya for 2011-2018.
*Due to adaptations in the crop rotation, the number of associated crops grown over the study period differs between organic and conventional in India.

2.2. Data consolidation

The evaluation of the economic performance of the different farming systems was differentiated between main crops and associated/rotational crops and the entire production system to offer a holistic picture of the economic viability of organic compared to conventional farming systems. Data from each site were aggregated at conventional and organic farming systems levels, disregarding input intensity and crop management practices. i.e. for the trial in Bolivia monoculture and agroforestry practices under organic management were merged as one organic farming system, and the same applies to conventional systems for the trial in Bolivia. Kenya's high and low input intensities were also merged for organic and conventional systems. Similarly, in India, biodynamic and organic treatments were considered organic and conventional systems with and without genetically modified seeds were merged as conventional.

From Bolivia, nine-year data from 2010 to 2018 were considered, the land clearing and installation phase in the years 2008 and 2009 was excluded from the analyses, as it did not differ substantially for the 4 analysed systems. From Kenya and India, twelve-year data from 2007 to 2018 were included. We calculated cumulative revenues (hereafter, revenues), cumulative variable production costs (production costs), cumulative partial gross margin (gross margin), cumulative input costs (input costs), and cumulative labour costs (labour costs). Cumulative variables were calculated by accumulating per plot the yearly data to overcome the seasonal variation with different crops in a given rotation Revenues were calculated based on farm gate prices multiplied by the yield of all marketable crops for the respective year or season, following:

$$\text{Revenues (R)(USD ha}^{-1}) = \sum (\text{yield xi} \times \text{price xi}),$$

$$\text{where yield (kg ha}^{-1}) \text{ of crop x in the year I,}$$

$$\text{price (USD kg}^{-1})$$

A premium for organic production was included according to the available market premium for specific crops in the respective sites. Premium prices at the trial site in Bolivia were only paid for cocoa. In Bolivia, cacao is sold to the farmers cooperative El Ceibo, and bananas and other products to the local market. In Kenya and India, premium prices have been given since 2010, three years after implementing organic management practices (after the conversion period according to IFOAM guidelines). In Kenya, premium prices were received for all

Table 2. Summary of the items included in the calculations of the variables: Income, Labour cost, and Input cost.

Country	Revenues	Labour cost	Variable input cost
Bolivia	Harvested yield * average annual farm gate price	Compost/fertilizer preparation/purchasing and application time	Cost of material for compost preparation/cost for mineral fertilizer (Blaukorn)
	Premium prices are given only for cacao	Harvest, management, and replanting trees	Planting material for first planting, replanting and tools for harvesting, pruning, grafting, spraying, weeding and post-harvest processes, considering the useful life of tools and equipment
		Weeding /herbicide purchasing and application	Herbicide cost
		Post-harvest labour for cacao and banana	
India	Harvested yield * average seasonal farm gate price	Sowing, Cotton Nursery, Transplanting, and gap filling	Seeds
	Premium prices are given for cotton including certification cost	Compost/fertilizer preparation/purchasing and application time	Cost of material for organic fertilization (FYM, Compost, Rockphosphate)/cost for mineral fertilizer (Urea, DAP, MOP, SSP)
		Pesticide and herbicide purchasing and application time, preparation and application time for botanical and biodynamic preparations	Pesticide and herbicide cost, the cost for ingredients for botanical and biodynamic preparations
		Land preparation and blade harrowing for weed control	
		Irrigation (maintenance and monitoring)	
		Harvest	
Chuka and Thika Kenya	Harvested yield * actual farm gate price	Land preparation, planting, gapping, mulching	Seeds/seedlings
	Premium prices given for all crops	Fertilizer application and compost preparation and application time	Cost of material for organic fertilization (FYM, rock phosphate)/cost for mineral fertilizer (CAN, DAP, TSP)
		Pesticide application	Pesticide and herbicide cost
		Weeding/herbicide application	Irrigation water
		Harvest and post-harvest	Certification cost (group certification)

marketable crops but with a considerable difference associated with site location. Premium prices for organic were higher at Thika than at Chuka due to its proximity to Kenya's capital city, Nairobi. In India, premium prices were only given for cotton and was sold at farm gate to BioRe.

The production costs consisted of input and labour costs, following (Table 2):

$$\text{Total production costs (USD ha}^{-1}) = \sum \text{I xi} \times \text{P} + \left(\sum \text{L} \times \text{W}\right), \text{ where I are the}$$

input x (seeds, fertilisers, etc.) in year i, P price (USD), L is the labour time registered (days) and W is the daily wages (USD day^{-1})

Labour for each farming activity in each plot was recorded, as well as, outside the plots when relevant (postharvest, compost preparation, etc.). We register the time either using stopwatchers or registering the initial and the final time and the number of people performing the activity. Therefore, the labour costs included costs for crop and field management, input purchasing or preparation, and post-harvest management but not for selling the produced goods. For this study, we assumed that all work performed is paid. This might not accurately reflect the reality in the case of family farming, i.e. when work is performed by family members and labour is no remunerated. In this case, to be able to compare the 3 countries, we monetarized all associated labour of the systems analysed. To calculate the labour costs, country-specific wages were used: in Bolivia, daily wages were calculated based on the monthly minimum wages set yearly by the Bolivian government . In Chuka and Thika, wages were calculated based on data provided by the government and the real paid wages were used for India. Input costs include the cost of fertilizers, tools, equipment, pest and disease control, and weed management inputs. The irrigation material and land tenure cost were similar for all systems and treated as fixed costs, so they were not included in variable production costs. Similarly, external financial costs associated with interest rates and loans are not considered as this study assumes uniform applicability of such factors to both organic as well as conventional systems. The cost for organic certification was only included as a separate asset in Chuka and Thika. In Bolivia and India, certification costs were covered by procurers and recovered by adjusting farm gate premium prices. For Bolivia, the cost of tools and equipment, for instance, pruning scissors, chainsaws, spraying equipment, etc. was amortized according to the expected respective lifespan. To bring data on a comparable scale among countries, data was converted from plot levels to per hectare, and local currency was converted to USD, according to the average annual exchange rates. We calculated the partial gross margin by subtracting the production costs from the revenues. Some authors suggest that discounted utility as a more reliable indicator because it includes the before-mentioned aspects (Knoke et al., 2020). However, for this study we focused on organic and conventional comparison in past 10 years.

In addition to systems comparison, the same data set was used to differentiate the role of different crops in revenue generation. For each site, crops were differentiated into main crops and associated/rotational crops based on the assumption that the main crop of each farming system is also the crop intended as the primary interest or revenue source for the farmer.

In Bolivia and India, cocoa and cotton are the main crops, which in most contexts are mainly destined for export markets and are thus essential revenue sources. In Kenya, maize is the main crop for consumption but is also majorly grown for revenue generation. The associated crops within each farming system (be it in mixed cropping systems or crop rotation) were categorized as associated crops (Table 1).

2.3. Statistical analysis

We used linear mixed models for statistical analysis. A global analysis was performed including site (Bolivia, India, Chuka and Thika), system (organic or conventinal), crop type (main crop, associated crop) and their interactions as fixed factors, whereas plots nested into replication per site were included as a random factor. A significant effect of site was shown for all variables analysed (Table S1). Therefore, site-wise models were also conducted. For site-wise analysis, systems, crop type and their interactions were included as fixed factors and plots nested into replications as random factors (Table S2). Datasets violating the principle of homoscedasticity and normality of the residuals were transformed using the ordered quantile transformation from the ordernorm package within the statistical software R (Peterson & Cavanaugh, 2019). All analyses were performed in R 4.0.0 (2020), using the 'lme4' package for mixed models (Bates et al., 2014), 'lmerTest' to evaluate the significance of effects (Kuznetsova et al., 2017),as well as 'emmeans' for posthoc comparisons (Lenth et al., 2022).

3. Results

In Bolivia, both conventional and organic farming systems generated similar levels of revenues (Figure 1a, Table S2, Table S3). The analysis also showed that production costs and gross margins were comparable between conventional and organic systems. The breakdown of production costs into input and labour costs revealed interesting differences. The labour costs were nearly identical between the systems, attributed to their comparable levels of mechanization and operations, suggesting that the type of production system did not significantly affect labour expenses. In contrast, input costs were significantly lower in organic systems compared to conventional systems. Importantly, input costs were similar between organic and conventional systems for associated crops. Within the crop types analyzed, cash crop cacao stood out with higher revenues compared to the associated crops (i.e. banana, avocado, and copoazú). Although cacao had higher revenues, it also incurred higher production costs compared to associated crops.

In Kenya, at both Thika and Chuka sites, it was observed that organic farming systems exhibited higher production costs and rvenues in comparison to conventional systems. Consequently, gross margins, representing the profitability of these systems, were found to be comparable between organic and conventional production systems (Figure 1c and d, Table S2, Table S4). A deeper dive into the composition of Production Costs revealed nuanced differences between the two sites. At the Thika site, organic systems incurred in higher input and labour costs when compared to their conventional counterparts. In contrast, at the Chuka site, organic systems displayed higher input costs but, with labour costs remained comparable to those of conventional systems. This suggests that while organic farming at Chuka incurred elevated input

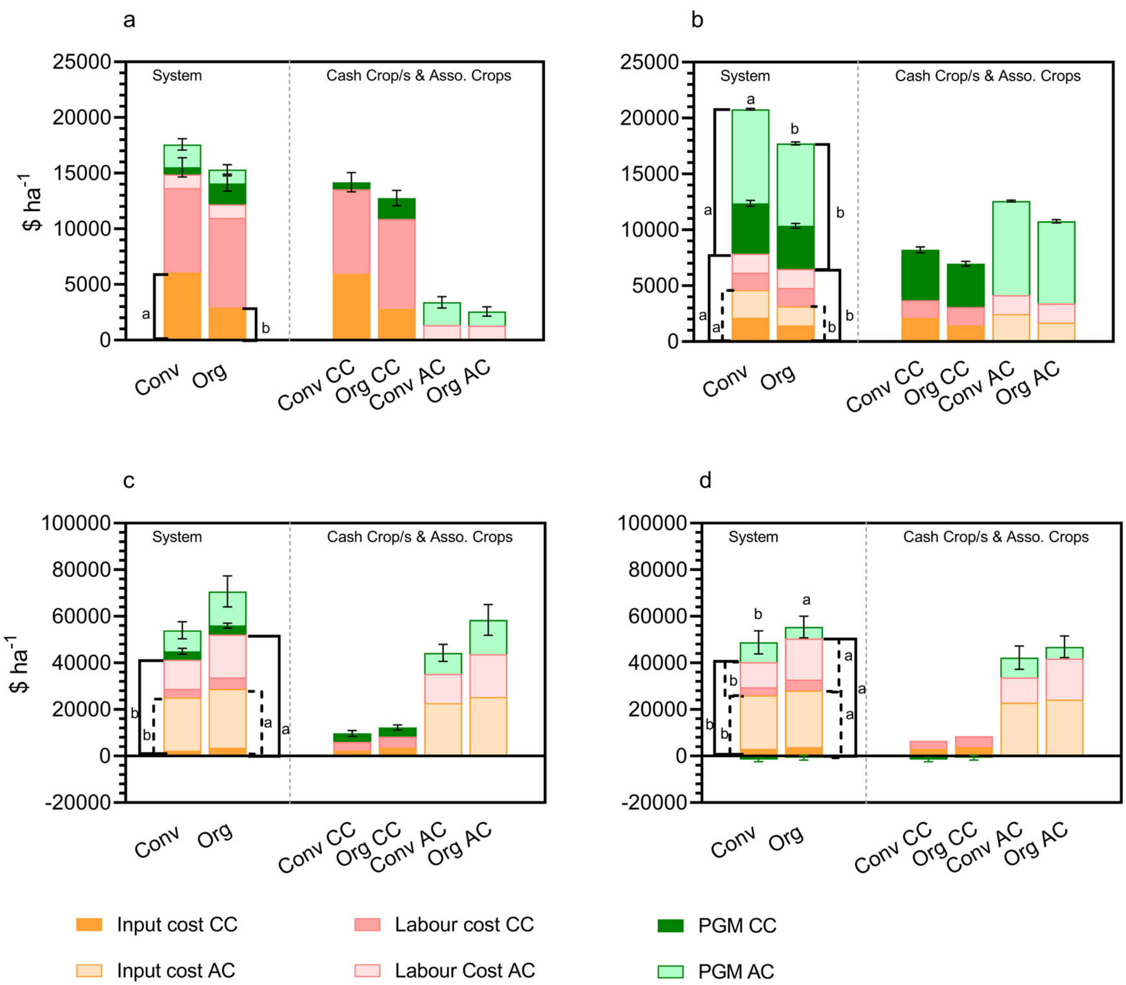

Figure 1. Cumulative variable production costs and partial gross margin at farm gate for cash (CC) and associated crops (AC) of conventional and organic farming systems in the long-term system comparison trials at a) Bolivia, b) India, c) Chuka and d) Thika site of Kenya.

expenses, labour costs did not exhibit significant variation between systems as the mechanization level in both systems are similar. At both sites, cash crops, specifically maize grain and baby corn intercropped with common bean, were found to yield lower revenues compared to all the sequential crops together included in the rotation. Similar results were found for the production costs at both the Thika and Chuka sites. Not to overlook that the total cash crop in the rotation were 16 vs. 32 of rotational crops (Table 1). Consequently, the gross margins for cash crop did not demonstrate significant differences when compared to those of rotational crop, such as potato and vegetables at Chuka (Table S4). Howerer it did different when premium prices were gain for these crops from Tikka site (Table S4). When evaluating the cost components adjusted to the equal number of crops, it was observed that both inputs and labour costs were higher for rotational crops in comparison to cash crops at both sites (e.g at Tikka, Input costs of $3475 for cash crops vs. $11804 for rotational crop; Labour cost of $4093 for cash crop vs $7108 for rotational crop) (Table S4). Importantly, the interaction between Production Systems and Crop Types did not yield statistically significant differences in the financial metrics at either the Thika or Chuka sites. This implies that the choice of Production System (organic or conventional) did not substantially influence the financial performance of different Crop Types.

In India, revenues in the organic systems were found to be lower than those in conventional systems (Figure 1b, Table S2, Table S5). It is noteworthy that production costs were also lower in the organic systems when compared to their conventional counterparts. Despite the cost advantages in organic farming, the lower revenues in the organic systems could not fully compensate for the revenue gap. Consequently, organic systems in the trial in India were associated with lower gross margins compared to conventional systems. This underscores the significance of revenue generation in determining the overall profitability of farming systems. A more detailed examination of the cost components revealed that input costs were lower in the organic systems in comparison to their conventional counterparts. However, both systems displayed similar labour costs. Labour expenses showed little variance between the systems due to their comparable levels of mechanization. Cash crops, represented here by cotton, were observed to yield lower revenues, incur reduced production costs, and consequently display lower gross margins when compared to sequential and rotational crops, which included wheat and soybean. However, similar to Kenya, total cash crop in the rotation were 24 vs. 60/56 of rotational crops (Table 1). Still adjusting to equivalent number comparison it was observed that both inputs and labour costs were lower for rotational crops than cash crop (Input costs of USD 1791 for cash crops vs 863 for rotational crop; Labour cost of USD 1608 for cash crop vs 698 for rotational crop). It is also important to know that in two-year crop rotation of Cotton-Soybean-Wheat, cotton crop duration is 5–7 months whereas Soybean and Wheat crops only takes 3–4 month for maturing thus less number of crop operations required. One another noteworthy finding is the absence of interactions between Production Systems and Crop Types, suggesting that cash and associated crops have similar financial performance in either the organic or conventional systems.

4. Discussion

4.1. The economic performance of organic and conventional farming systems

The economic performance of organic farming systems was found to be comparable to conventional systems, with gross margin showing no significant differences in Bolivia and Kenya but only at the system level in India. In Bolivia, similar revenues combined with comparable production costs led to comparable gross margins for organic and conventional systems. It is noteworthy that the lower input costs for organic systems in Bolivia did not significantly impact the total production cost of the system. However, this cost advantage could be a crucial factor encouraging the adoption of organic systems, particularly among smallholder farmers with limited financial resources and risk-bearing capacity (Riar et al., 2017; Riar et al., 2020b).

In contrast to Bolivia, organic systems in Kenya exhibited higher input and production costs compared to conventional systems. Despite the increased costs, the higher revenues of organic systems at the Chuka site in Kenya offset these input costs, resulting in comparable gross margins. Notably, even with higher labour costs, organic systems in Kenya were able to maintain similar gross margins, underscoring the significance of revenue in determining overall profitability. The higher revenues of organic systems in Kenya offset these input costs, resulting in comparable gross margins. Interestingly, at the Thika site of Kenya, even with higher labour costs, organic systems in Kenya were able to maintain comparable gross margins, emphasizing the importance of revenue in determining overall profitability. The higher revenues of organic systems in Kenya are due to the premium prices received for organic products. However, this pattern was not universally observed. In India, the lower production cost in organic farming did not compensate for reduced revenue, resulting in lower gross margins compared to conventional systems. These findings align partially with previous research on production costs associated with organic farming (Durham & Mizik, 2021; McCluskey, 2000; Stockdale et al., 2001), specifically noting lower input costs and higher labour requirements in organic farming. Input costs are often lower in organic farming than in conventional farming, as many inputs can be sourced on-farm, leading to lower production costs, as observed in India and Bolivia (Armengot et al., 2016; Forster et al., 2013).

Labour requirements in organic farming are often higher (Crowder & Reganold, 2015), translating directly into labour costs. This was evident at the Chuka site in Kenya, where the preparation and application of organic inputs were labour-intensive, including the use of external organic inputs (Adamtey et al., 2016). However, in the present study, three out of four sites showed similar labour costs for organic and conventional systems. The labour requirements in any system are highly related to the level of mechanization, and in low-medium income countries, especially on farms managed by smallholder farmers, the level of mechanization and inputs are often quite low and similar for organic and conventional systems.

Although three out of four analyzed long-term experiments revealed comparable gross margins for organic and conventional counterparts in their respective regions, the different pathways leading to comparable gross margins highlight the context-specific performance of organic systems, influenced by factors such as the level and availability of inputs, market dynamics, and the choice of associated and sequential crops (Babajani et al., 2023; Michalscheck et al., 2023; Peltonen-Sainio et al., 2024; Thiombiano et al., 2023).

4.2. Role of associated, sequential and rotational crops in organic and conventional systems

The selection of associated and sequential crops in any farming system depends on their compatibility with the main/cash crop and the local context. Historically, early organic value chains in the global south targeted developed countries with high affordability for the export of organic products, shaping a narrative around organic systems focusing on cash crops for export. However, in the past three decades, global progress in organic agricultural systems has challenged this narrative (Arbenz et al., 2017; Willer et al., 2023). Increased awareness, behavioural change(Ha et al., 2023), and greater consumer affordability have led to local market development in developing countries, challenging previous perspectives on organic agriculture.

The study indicates that the contribution of cash crops and associated, sequential, or rotational crops to farm economic performance was similar in both organic and conventional systems. Revenue from sequential and rotational crops was comparable to that from cash crops (Valkila, 2009). When considering all crops in the rotation, the gross margin from associated crops compared to cash crops was statistically equal in Bolivia, with sequential and rotational crops performing two times higher in India and around threefold more at the Chuka site in Kenya. However, the high contribution from associated crops or sequential and rotational crops is also linked to the number of crops grown in a given system. For instance, the twofold contribution from associated crops in India and Kenya is directly linked with a greater number of sequential and rotational crops in the crop cycle.

The revenue from associated crop production was comparable for organic and conventional systems when adjusted for the number of crops in a rotation, irrespective of whether premium prices were paid or not. Premium prices for associated crops were only paid at the Thika site in Kenya in this study, where the high premium prices received for associated crops led to comparable gross margins across different farming systems. The availability of premium prices for associated crops in Kenya is attributed to the initial market stage of the organic domestic market in the country(D'Alessandro, 2018), showcasing the potential observed in emerging markets where high prices are evident before mainstreaming (Hamm & Michelsen, 1996).

When premium prices were not available, as observed in Bolivia and India, the revenue from associated crops was lower for organic in India, resulting in lower revenue when compared at the system level. This underscores the importance of domestic markets, the relative significance of associated crops, and the role of premium prices in generating comparable revenue in organic as compared to conventional systems. Developing the organic sector in resource-poor countries is crucial to sell crops on domestic markets and achieve higher prices for organic produce, especially as the urban middle classes in developing economies become a growing consumer base for organic produce (Niggli et al., 2011).

In Bolivia, where the organic cacao value chain is well-organized, resulting in cacao prices about 30-50% higher than the stock market price, both organic and conventional cacao prices benefit (Jacobi et al., 2015; Roth et al., 2020). Being closely connected to growing urban markets, as observed in Thika, Kenya (46 km from Nairobi), is an asset that contributes to the possibility of higher premium prices. Additionally, the productivity and profitability of organic production systems depend on well-designed crop rotations and mixed cropping systems (Stockdale et al., 2001).

The cost of organic certification for cash or export crops can be seen as a means to indirectly subsidize the production of pesticide-free ecological goods available at a standard price, contributing to improved food security. For main crop production, organic revenue with premium prices was comparable to conventional at all sites. Premium prices for main crops ranged from 11-92%, substantially higher than the 5-7% reported the economic breakeven point for organic with conventional produce by Crowder and Reganold (2015). However, this study compares different main crops across countries with diverse organic product markets, explaining the observed variation in premium prices. Factors such as market development, crop diversity, and market channels significantly influence the attainable premium prices for organic products(Dimitri & Gardner, 2019; Michelsen et al., 1999).

Export-oriented main crops like cotton and cacao, marketed through well-established global value chains influenced by global market trends, achieved comparatively low price premiums (cotton 13.5%; cacao 11.7%). The premium prices paid at this level for cash crops such as cacao and cotton can lead to comparable (Bolivia) profitability for organic produce, as shown in gross margin, though this was not the case for cotton in India. It is important to notice that cooperative El Ceibo pays one of the highest cocoa prices worldwide while selling around 70% of their production nationally, demonstrating the added value for farmers when included in the value chain (personal communication, El Ceibo 2020).

In Kenya, premium prices for main crops obtained on the local market were higher than in Bolivia and India, leading to comparable (Chuka site) or higher revenue (Thika site). The profitability of sequential and rotational crops in annual cropping systems in Kenya and India makes them promising options compared to the profitability of the main crop in rotation. However, farmers' decisions to keep maize as the main crop in rotation in Kenya, for example, go beyond productivity or profitability considerations (Adamtey et al., 2016). Similarly, the choice to grow cotton in India, sometimes less economically rewarding than other rotational combinations (e.g. Soybean-wheat)(Riar et al., 2020a), is influenced by social and biophysical factors (Riar et al., 2017).

5. Conclusions and policy implications

The study furnishes empirical evidence affirming the economic competitiveness of organic farming in tropical regions. It establishes that organic farming constitutes a viable and economically sustainable alternative for farmers, showcasing comparable economic performance to conventional farming systems in three out of four study cases spanning different continents. The economic viability of organic systems is not solely dependent on main crops, as the substantial contribution of associated, sequential, and rotational crops significantly influences farm economic performance. In light of these findings, policymakers are urged to adopt a comprehensive approach that incorporates various system components, individual crop performance, and diverse decision-making factors when formulating policies related to agricultural systems and food sustainability.

In consideration of the above conclusions, the following recommendations are made:

a. Farmers should be encouraged to diversify their crop rotations and embrace associated, sequential, and rotational crops to bolster economic resilience and profitability. Policies should actively promote training and knowledge-sharing initiatives to underscore the benefits of crop diversification.
b. Policymakers should devise strategies to incentivize organic and agroecological low-input farming, especially in regions where it can offer cost advantages, such as lower input costs.
c. Support measures, including subsidies and technical assistance, should be targeted at smallholder farmers to stimulate the adoption of organic systems, fostering sustainability and economic viability.
d. Policies should be formulated to support the development of sustainable and inclusive value chains, ensuring fair prices for farmers, particularly for export-oriented crops. Collaboration with cooperatives and organizations can play a pivotal role in creating fair market conditions.
e. Encouraging the development of local organic markets and promoting consumer awareness can boost demand for diversified and nutritious products. Policies should prioritize market development to ensure fair and competitive premium prices for organic produce.

By implementing policies grounded in these recommendations, governments and stakeholders can actively contribute to promoting sustainable farming practices, augmenting farmer incomes, and ensuring food security. This approach emphasizes a balanced consideration of the economic viability of different farming systems, aligning with broader goals of agricultural sustainability.

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Authors' contributions

Amritbir Riar: Conceptualization, Data Analysis, Visualization, Writing & results discussion. Eva Goldmann: Data consolidation and Writing Methodology and contribution to introduction. David Bautze and Johanna Rüegg: Data consolidation, Gurbir S. Bhullar, Noah Adamtey, Monika Schneider1, Beate Huber: Coordination of trials and resources, Laura Armengot: Conceptualization, contribution to data analysis and writing. All authors prodived feedback to drafts, proofread and revised the final manuscript.

Consent for publication

All authors consent to publish.

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Availability of data and material

Data used for the manuscript can be provided on request.

ORCID

Amritbir Riar http://orcid.org/0000-0002-7809-1681
Gurbir S. Bhullar http://orcid.org/0000-0001-7311-2562
Laura Armengot http://orcid.org/0000-0002-9820-9667

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