Exploring Organic and Conventional Tea Cultivation Systems in Thai Nguyen Province: Soil, Leaf Quality and Farmer Perceptions

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Abstract

Tea (*Camellia sinensis*) cultivation has long been a major livelihood in Thai Nguyen, Vietnam. The region's growing interest in certified organic production offers new opportunities for farmers, yet limited data exist on its environmental and physiological impacts, particularly regarding heavy metal accumulation. This study aimed to compare the social dimensions and crop management of organic and conventional tea systems and assess their implications for soil quality and tea safety. A mixed methods approach combined farmer interviews with analyses of soil and leaf chemical properties.

Farmers generally viewed organic practices positively, citing benefits for health and the environment, although many later emphasized that integrating mineral fertilizers with organic ones resulted in better yields and higher quality. Chemically, all farm plots exhibited severe soil acidification and Zn levels exceeding the Vietnamese permissible limits. Organic systems, however, tended to have soils with lower Zn and Cu concentrations and higher organic carbon content than the conventional farms. Tea metabolites on the otherhand (caffeine, catechins,and polyphenols) did not differ significantly between systems and the estimated heavy metal intakes from all teas indicated no potential health risk to consumers. Heavy metal stress affected tea quality, with Cu accumulation in leaves reducing caffeine content. Overall, organic farming demonstrated potential to improve soil quality and reduce heavy metal risk to the environment, though its effectiveness remains highly dependent on local soil conditions.

Keywords: Organic tea, Conventional tea, Secondary metabolites, Caffeine, Catechins, Polyphenols, Trace elements, Aluminum, Copper, Zinc, Tea agroforestry, Gendered farming, Vietnam

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Abbreviations

Abbreviation	Description
ANOVA	Analysis of variance
BCF	Bioaccumulation factor
BW	Body weight
CEC	Cation exchange capacity
EC	Electric conductivity
EDI	Estimated daily intake
HPLC	High-performance liquid chromatography
HQ	Hazard quotient
IR	Ingestion rate
LM	Linear model
LS-means	Least squares means
OC	Organic Carbon
PCA	Principal component analysis
QCVN	Quy chuẩn Việt Nam (translation: Vietnamese National Technical Regulation)
SOM	Soil organic matter
SFRI	Soil and Fertilizers Research Institute
TCVN	Tiêu chuẩn Việt Nam (translation: Vietnamese Standards)
TDI	Tolerable daily intake
TN	Total nitrogen
VietGAP	Vietnamese Good Agricultural Practices

1. Introduction

Tea (*Camellia sinensis*) is a perennial shrub that has a long history in Vietnam, playing an essential role in the traditions and culture (Nghia 2009). Owing to the favorable climate and terrain, tea is the most strategic crop of Thai Nguyen province and many of farmers' primary source of income. The collective trademark “Thai Nguyen Tea” has protected the brand in many countries since 2006 (Ha et al. 2024). Dedicating over 22,500 hectares to tea production, Thai Nguyen is the largest tea growing area in the country and the province produces 260,000 t yr-1, generating approximately 486 million EUR yr-1 on the market (TTXVN 2024). While Vietnamese tea production and export volumes have risen over the past years, the majority of tea is sold on low-value markets such as Pakistan, Indonesia and Russia (Doanh et al. 2018).

Higher incomes are generally a big driving force for making changes in management and adoption of organic practices, as it allows farmers to demand a higher price on the market (Le et al. 2021a). Yet many conventional farmers are hesitant to make the switch to an organic system, as the certification programs demand requirements that do not match with their current management style like use of mineral fertilizers (Huang et al. 2022). Converting to an organic system is especially a high risk for smallholders in the short run, given the high certification costs and anticipated losses during the establishment period (Bui & Nguyen 2021). It is also important to consider that organic fertilizers are bulky and require large volumes and high transportation costs.

In Vietnam, the traditions of tea cultivation are dominated by conventional management practices featuring intensive sole-cropping systems and mineral inputs (Le et al. 2021). Farmers tend to apply high rates of inorganic fertilizer with an imbalanced emphasis on nitrogen (N) (Qiao et al. 2018). For green tea, the standard practice followed in the study region is the finest quality, meaning only the younger shoots are hand-plucked, also known as “two leaves and a bud”. Given that the immature shoots contain the highest concentration of nutrients in the plant, to produce an economically beneficial yield and ensure multiple flushes (an average of 8 times out of 12 months harvest), a high amount of nutrients via fertilizers are necessary to replenish the soil (Sitienei et al. 2019; Zhou et al. 2022) . The risk of only focusing on N may lead to deficiencies in other essential nutrients like calcium (Ca), magnesium (Mg) and sulfur (S) (Bonomelli et al. 2021; Grzebisz et al. 2023). Furthermore, the long term overuse of N fertilizers will contribute to stunted yields, and potential high nitrate levels in tea products, lowering their quality (Chowaniak et al. 2021). However, it is crucial to consider the local soil conditions when assessing the effect of a management choice, considering that interaction effects are decisive.

Figure 1. Tea plucking standard: two leaves and one bud. Photo by author (2024).

In Vietnam, tea is grown under 3 main concepts: Conventional, VietGAP (Vietnamese Good Agricultural Practices, a national certification to ensure safe, sustainable and traceability of products) and organic. While there has been increased encouragement and investment in Thai Nguyen towards a more controlled and safe tea production than in the past, only a small area has been converted from conventional, with just over 5000 ha to VietGAP and 80 ha to organic cultivation (Duong 2024). Organic agriculture emphasizes minimizing the use of off-farm inputs and taking into account regional and local conditions when managing the farm (National Standards TCVN 11041-6:2018 Organic Agriculture - Part 6: Organic Tea 2018). It aims to promote and enhance the health of agricultural ecosystems including biodiversity, biological cycles and biological productivity. For instance, organic agriculture does not permit mineral fertilizers or the usage of chemical inputs to combat weeds, pests and diseases, like that often used in conventional systems.

Organic fertilizers are favorable over mineral fertilizers due to their contribution to higher soil organic matter (SOM). It can increase crop resilience to climate changes and act as a protective buffer against excessive concentrations of toxic elements in its ability to form chelated compounds with heavy metal ions in the soil (Kwiatkowska-Malina 2018). Nevertheless, organic fertilizers can also be a source of pollution and are poorly regulated in Vietnam (Quynh & Kazuto 2018; Nguyen et al. 2020). Numerous fertilizers marketed as organic are available, but the standards and quality of their raw materials and production methods have not been strictly defined. In some cases it is even common practice to combine organic compost with mineral N, phosphorus (P) and potassium (K) to increase their nutrient contents (Thanh & Matsui 2011). Indeed, it has been reported that for tea orchards, organic fertilizers are generally not available in quantities enough to match the nutrient demands of the crop (Huang et al. 2022). Overall, the comparison of conventional tea farming and other systems is largely undocumented in Vietnam. The organic agriculture arena in Vietnam is meagre and elaborate policy that supports these implementations and integrations are also lacking (Quynh & Kazuto 2018).

Soil acidification is particularly a concern for where tea grows. Tea plant growth is stimulated by moderately acidic conditions and the plant acidifies the soil via proton pumps in a mechanism to maintain a charge balance during absorption of cations, particularly ammonium (NH_4^+) and aluminum (Al^{3+}) (Wan et al. 2012). This acidifying effect has been observed to intensify as the plantation ages (Wang et al. 2010a; Lin et al. 2023). Intense soil acidification can cause diminishing soil fertility via disruption of chemical processes, leaching and losses of beneficial nutrients, fixation of nutrients (such as P) in forms not available to the plants, aluminum toxicity, and decreasing biodiversity and overall population of microorganisms in the rhizosphere (Yang et al. 2024).

Given that tea is commonly grown on sloping lands in Vietnam, rainfall brings about an increased risk of soil erosion and nutrient leaching (Phong et al. 2015). This is especially a risk given that the IPCC predicts northern Vietnam to experience more frequent and intense precipitation, inducing more landslides (Nguyen et al. 2025). The region is also reported to be increasingly at higher risk of drought, having major implications for irrigated tea-based systems whom are already one of the major water users in the country, particularly during dry season in November-May (Hong & Yabe 2017). On another note, the land use changes from forested land to sole-cropping systems, generally prompts a loss in biodiversity, which may directly affect ecosystem functionality, playing a role in decreasing yields over time. These issues hinder the sustainability of tea cultivation.

While environmental factors and stresses are primary agents of tea quality, the physical and chemical elements of the soil are closely related to the essential elements in the tea plants and the shrub’s secondary metabolism (Liu et al. 2023).

There are examples of studies showing soil parameters such as pH, soil N, P, K (and more) affecting tea polyphenols, caffeine and amino acids (Tseng & Lai 2022; Liu et al. 2023). For example, in conventional tea plantations, with soils characterized by low pH, were deficienct in mineral base cations and showed increased levels of manganese (Mn^{2+}) and Al^{3+}, and had tea leaves that produced low levels of polyphenols and vitamins, and high levels of free radicals, suggesting plant stress (Jahan et al. 2022).

Heavy metals like copper (Cu) and zinc (Zn) are essential micronutrients for normal plant growth; however, its availability in the growing medium is a crucial factor, as excess can result in diverse toxic effects (Kumar et al. 2019). There are also harmful heavy metals with no known role or benefit like cadmium (Cd), that contaminate agricultural inputs. Due to the soil's acidic nature in tea plantations, tea plants have commonly been observed to accumulate aluminum in their leaves (Huu Chien et al. 2019; Jahan et al. 2022; Peng et al. 2018; Wang et al. 2010b; Yan et al. 2020). Other studies have seen Mn, arsenic (As) and Cu accumulation (Chien et al. 2024; Chu Ngoc et al. 2009; Ju et al. 2024). This is not only concerning for plant and environmental health, but also for human health (He et al. 2020). At toxic levels, Cu can pose serious health risks to humans and has been associated with disorders such as Wilsons's disease (Veríssimo et al. 2005). In fact, it is the high levels of potentially toxic elements that hinder a more international export of Vietnamese tea (Le et al. 2021). Aluminum exposure in humans primarily occurs through ingestion, either through naturally occurring sources or food additives (providing approx. 3.5 to 10 mg/day), or from utensils and packaging (Yokel 2012). Aluminum is considered a neurotoxicant, and has been associated with neurodegenerative diseases, like Alzheimer's disease (Rondeau et al. 2009; Tomljenovic 2011; Yokel 2012).

The price and quality of tea is usually established by the judgement of professional tea tasters, and there is a growing interest for developing an objective measurement quantifying certain compounds and the plant's ability to provide medicinal acclaimed properties (Le Gall et al. 2004). Tea quality is often characterized by content of secondary metabolites and concentrations of nutrients and trace elements, that are also involved in the plants' metabolic processes (Pękal et al. 2013). A plant's secondary metabolism produces compounds that determine its flavor, aroma, appearance, and health-promoting properties, including responses to micronutrient deficiencies (Ahmed et al. 2018). Tea leaf infusions are known for their salubrious and organoleptic qualities, which are largely derived from the abundance of these secondary metabolites like polyphenols, catechins, theanines and caffeine (Tseng & Lai 2022).

Polyphenols are a major group of bioactive compounds in tea that make up a large proportion of tea leaves: 15-35% of the dry weight (Luo et al. 2024). Polyphenols are known for their strong antioxidant activity as well as antibacterial, antifungal, and antiviral properties (Friedman 2007). Catechins are a type of polyphenol and are among the principal active compounds that directly affect the quality of tea and tea products. Catechins consist of four major subtypes: Epicatechin (EC), Epigallocatechin (EGC), Epicatechin gallate (ECG), and Epigallocatechin gallate (EGCG) (German et al. 2024). Catechins are widely used as antibacterial agents in food and are ingredients in many functional food products (Wu & Brown 2021). According to TCVN 9740:2013 it is mandatory for the dry matter of tea to meet the minimum standard of 7% total catechins. Caffeine is another important secondary metabolite found in green tea leaves, which contain about 2-5% caffeine (Trong Bien & Thi Lan Phuong 2020). Caffeine is a widely used psychoactive substance, influencing mood, memory, alertness, physical performance, and cognitive function (Guest et al. 2021).

Despite the said ecologically sound practices and high soil merits brought about by organic agriculture, the sensory qualities of tea in organic systems have scored quite low in comparison to a system that allows for mineral fertilizers (Phong et al. 2015). However, organic grown tea leaves have also been found to be richer in catechins than those coming from conventional systems (Piyasena & Hettiarachchi 2023). Other studies have not found any significant differences between the farming systems in terms of tea leaf quality as evaluated by content of catechins and caffeine (Chin et al. 2010; Das et al. 2016).

The soil and tea properties investigated in this study are chosen considering the aspects of crop and human health concerns, market significance, project budget and the capabilities of the laboratory. Quantifying soil quality is inherently complex because perceptions of what constitutes “good soil” vary depending on land use objectives and the specific functions the soil is expected to serve. As Doran & Parkin (2015) note, assessments should interpret biophysical measurements within their societal and land use context and its effects on air, water, soil and food quality. This paper draws theoretical inspiration from Larson & Pierce (1991), pioneers of sustainable land management, who shifted soil science from mere focus on crop productivity and towards soil quality and environmental health. Their work compares soil health to human health such that the quality of certain measurements are seen as indicators or symptoms of certain system functions, with emphasis on the time and space where samples are taken.

Organic tea cultivation is an emerging approach which can offer numerous benefits in the country, although limited data exists on its specific impacts in the

Vietnamese context. Organic systems' impact on tea quality compared to conventional systems remains unclear. This study addresses that knowledge gap by comparing soil properties and leaf quality for organic, and conventional systems, particularly Al, Cu, Zn concentrations in the soil and accumulation in tea leaves, and total polyphenols, catechins and caffeine content in the leaves. To influence transition, it is important to understand farmer's beliefs and perceptions of organic tea farming. By also investigating farmer perceptions and cultivation methods, the study provides a holistic understanding of tea production systems and its implications for sustainability. With emphasis on organic practices in the region, this study can offer valuable insights for policy makers, farmers and consumers interested in sustainable and high-quality tea production.

1.1 Project aim and Objective

The study's aim is to contribute to the sustainable development of tea cultivation in the province of Thai Nguyen by providing evidence-based insights on system differences and trade-offs. The study compared the impacts of organic and conventional systems on farmer realities, soil and tea leaf quality by investigating conventional and newly established organic tea farms. With respect to farmer experiences, soil physicochemical properties, potential heavy metal contamination of soils and leaves (e.g. Cd) and tea leaf secondary metabolites, this study has implications for improving sustainable tea production and policy development of tea industry in the region and country.

1.2 Research questions

Socioeconomical factors:

A. What are the attitudes of the farmers regarding their tea management practices?
   - i) What are the primary motivations for the farmers to become organically certified?
   - ii) How do the farmers describe gender roles in tea farming?
   - iii) How do the farmers' perceptions of climate change affect tea farming?
   - iv) What are the farmers´ stance on intercropping and tea agroforestry?

Chemical compositions:

B. How do different tea cultivation systems influence soil characteristics, tea quality and management sustainability in Dai Tu?

i) How do soil properties differ between the two tea cultivation systems?
ii) How do leaf properties differ between the two tea cultivation systems?
iii) Are heavy metals a risk in in any of the systems?
iv) Does the current management of the systems need to change?

2. Materials and methods

2.1 Site Information

The study features a mixed-methods design, incorporating qualitative and quantitative research tools in the form of interviews and soil and tea leaf sampling. The population from which samples were sourced consists of organic and conventional tea farms in Dai Tu district in Thai Nguyen province. The province aspires to have 100% of its tea areas to follow either the standards of VietGAP or organic by 2030 (Ha et al. 2024).

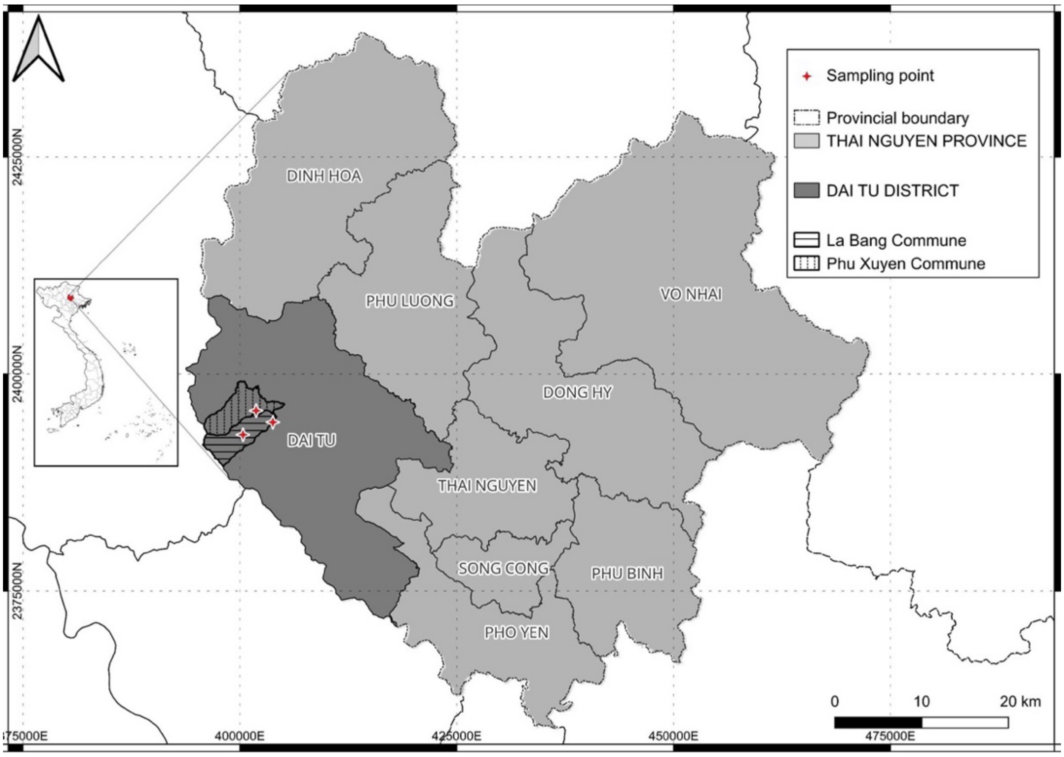

Figure 2. Map showing the sampling locations in Dai Tu district, Thai Nguyen Province, northern Vietnam. The red stars indicate the three farming areas where samples were collected. Courtesy of Tran Dinh Tung (2024), Thai Nguyen University. [GIS map]

In the last decade, the annual average temperature of the province was 23.6°C with the maximum of 29.0°C in July. The minimum temperatures were generally observed in January with an average of 15.8°C. Eighty-four percent of the annual rainfall occurs during April to September, with an average annual precipitation of 1767 mm (Huu Chien et al. 2019).

2.2 Data Collection

To answer the research questions (1.2), both primary and secondary data were collected. Secondary data consisted of a literature review, which was used to inform the theoretical framework, methodology and discussion while primary data consisted of a structured survey, interviews, soil and leaf analyses.

2.2.1 Literature Review

The literature review was mainly performed through the search engine platform Google Scholar. Articles were obtained through searching keywords in multiple combinations “Heavy metal” or “Trace element”, “Organic fertilizer or “Organic farming”, “Tea cultivation or “Tea farming”, “Thai Nguyen” or “Vietnam”, “Soil health”, “Tea component” or “Tea secondary metabolite”. Papers in English and Vietnamese languages were included in the study. Additional relevant references cited within these papers were also used to broaden the scope of the review. The literature review continued until the end of the study.

Furthermore, relevant national standards of Vietnam called TCVN and QCVN were reviewed extensively for relevant standards particularly for tea organic farming, heavy metals and for laboratory testing.

2.2.2 Interviews

The purpose of the interview study is to inform about the details of general tea farm management practices. It is also used to document the farmers’ perceptions about the landscape of organic farming, including the intersectionality of climate change and gender roles.

HTX Chè La Bang is a tea cooperative found in the district of Dai Tu. After establishing relationship with the head and local representatives of the tea cooperative, the sampling locations were identified. A trial interview with one farmer was then conducted together with the translator to determine approximately how much time the interview would take (45-60 minutes). After translation of the pilot study, it was determined that questions regarding fertilizers needed to be more specific due to a very generic response.

Location visits were then carried out together with the local head, where 18 farm plots were selected for analysis (for plot selection criteria see Figure 3) and the corresponding farmers were gathered for interviews. The rest of the sampling population (32 farmers, total of 50) was identified via snowball sampling through the help of two locals that worked close to this project. This method was chosen because the target demographic is known to be difficult to reach (Sadler et al. 2010).

The interview (see Appendix 1: Interview questions) comprised of both a Likert scale and structured, open-ended questions. The interview took place in written format where we met with the farmers either on a one-to-one basis or as a group depending on their availability. These were conducted in different locations depending on the size of the group, usually on the premises of the tea cooperative, the farmer's home or the town hall. The farmers usually preferred to conduct the interview after work hours, between 5-9 pm. After the interviews were collected, the data were transcribed onto the computer and translated by a translator. Participants' anonymity and confidentiality were prioritized when managing the data by introducing codes and enumerations of the data.

2.2.3 Field data collection

Considering the scarcity of organic farms, cultivation sites were chosen by first locating organically managed fields in the area. In Vietnam, tea cultivation lands are often divided amongst multiple households that form a "collective". Organic farms can co-exist on the same hillslope as conventional farms and grow in very close proximity to each other. Thus, sites were selected such that organically and conventionally managed plots can be found as "pairs" at different slope positions within the same site, ensuring that the pairs were facing the same direction towards the sun. Three pairs were chosen at different slope positions: top, middle and lower hill (Figure 3) which were replicated at 3 different farm locations: Phu Xuyen, Non Beo and Tan Son. The 18 chosen plots were comprised of 9 conventionally and 9 organically managed sites. Plots producing the LDP1 tea variety were chosen for analysis because it is the most common variety in the region. In addition, precise information on the timing of the most recent fertilizer application was not consistently available across farms. Hence, some unknown variation may have existed between plots with regard to the time elapsed between the latest fertilizer application and sample collection.

Collection of soil was conducted at the end of harvest season in November 2024 and leaf samples were taken in the first flush of growth in the following year. The collection of tea leaves occurred during the spring season of 2025, since the growing season of 2024 ended earlier than normal due to dry weather.

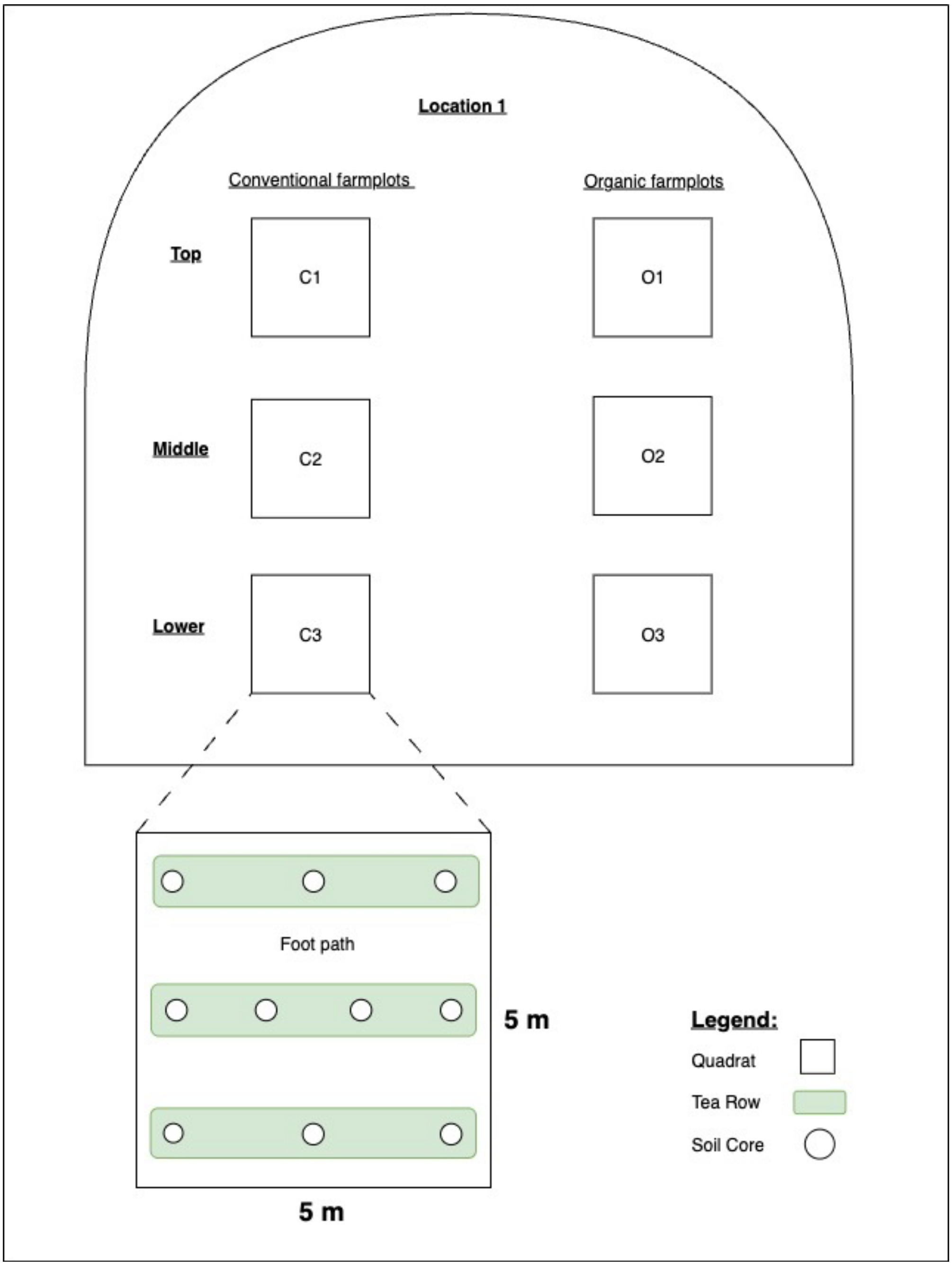

Figure 3. Sampling protocol. Illustration by author

At each sampling plot, a 5x5 m^2 quadrat was measured and marked using 4 red PVC pipes that were hammered into each corner of the quadrat. These points were georeferenced using *Google Maps* by saving GPS coordinates. This was where both soil and leaves were picked from. Within the quadrat, a composite soil sample was taken consisting of 10 soil cores taken to 20cm depth underneath the tea canopy (avoiding foot paths) (Figure 3). Soils were then transported to the laboratory for analysis. Within the same quadrat, young tender leaves (based on the picking standard of green tea; 2 leaves and 1 bud) were harvested. Leaves were sent to the university laboratory for preparation (0.3 grams of leaves were frozen fresh for secondary metabolites analysis and 5 kilograms were dried in an oven specifically used for plant material to be analysed for trace elements and nitrogen analysis).

Throughout the study, leaf samples were handled carefully, following the recommendations of Dahlin et al. (2012). This involved limiting the chances of contamination by keeping samples enclosed as well as avoiding harvesting from crops growing close to the roadside, the use of metallic tools, or placing the samples on dusty surfaces.

2.3 Analytical methods

2.3.1 Soil properties

Soil samples were analyzed by the Soil and Fertilizers Institute Hanoi (SFRI) laboratory after a month of sampling. The SFRI laboratory has provided detailed methodologies based on the national standards and have been adapted in the section below.

Table 1. Soil indicators analyzed in this study and the corresponding recommended Vietnamese standards (TCVN) used for their evaluation, for detailed explanations see Appendix 2: Soil analyses

Indicator	Reference	Principle
Soil texture	TCVN 8567:2010	Sedimentation
Soil pH_{KCl}	TCVN 5979:2021	1 M KCl
Soil Organic Carbon (OC)	TCVN 8941: 2011	Walkey and Black (wet oxidation)
Total Nitrogen (TN)	TCVN 6498:1999	Kjeldahl
Electric Conductivity (EC)	TCVN 6650:2000	Electrode
Cation Exchange Capacity (CEC)	TCVN 8568:2010	Saturation with NH_4^+
Exchangeable K	TCVN 8569:2010	Replacement by NH_4^+
Exchangeable Mg	TCVN 8569:2010	Replacement by NH_4^+
Exchangeable Ca	TCVN 8569:2010	Replacement by NH_4^+
Available P	TCVN 8942:2011	Bray II
Exchangeable Al	TCVN 4403:2011	1 M KCl
Total Cd	TCVN 6496:2009	Aqua regia
Total Cu	TCVN 6496:2009	Aqua regia
Total Zn	TCVN 6496:2009	Aqua regia

2.3.2 Leaf properties

The Central Analytical Laboratory at SFRI carried out the tea leaf analysis for N and trace elements, while Vietnam National University of Forestry laboratory carried out the analysis of secondary metabolites in tea. Both laboratories have provided detailed methodologies based on the national standards and have been adapted in the section below. For some of the analyses, leaves were dried immediately after plucking at the university laboratory while for some of the leaves, they were sent fresh to the tea processing facility.

Table 2. Leaf indicators determined in the study and the corresponding recommended Vietnamese standards (TCVN) and methods used for their evaluation. For detailed descriptions see Appendix 3:Leaf analyses. The following report was written and translated by Vu Kim Dung.

Indicator	Reference
Nitrogen	Kjeldahl
Aluminum	Microwave digestion and Atomic Absorption Spectrophotometry (AAS)
Copper	TCVN 8126:2009
Zinc	TCVN 8126:2009
Cadmium	TCVN 8126:2009
Total polyphenols	TCVN 9745-1:2013
Total catechins	HPLC-PDA
Caffeine	HPLC-PDA

2.3.3 Data Processing

Bioaccumulation factor (BCF)

The BCF describes a plant's ability to accumulate a substance, such as heavy metal, from the soil. It consists of an equation dividing the concentration of certain heavy metal in the plant by the concentration of heavy metal in the soil. BCF can offer insights of the extent to which trace element present in the soil is transferred to leaf tissue. Elevated levels of BCF may indicate higher bioavailability of a certain element in soils and increased dietary exposure risks for consumers.

$$\mathbf{BCF} = \frac{C\ plant}{C\ soil}$$

According to Malayeri (et al. 2008):

- Species that had BCF between 1-10 are classified as high accumulator plants.

- Species that had BCF between 0.1-1 are classified as moderately accumulator plants.
- Species that had BCF between 0.1-0.01 are classified as low accumulator plants.
- Species that had BCF <0.01 are classified as non-accumulator plants

Estimated daily intake and hazard quotient calculation

The estimated daily intake (EDI) equation was used to forecast a potentially hazardous agent if consumed daily. It uses data from a certain demographic's rate of ingestion (IR) of certain food, the average body weight (BW) and the concentration of the component (C) (in this case, trace element). The hazard quotient (HQ) uses the EDI and divides it by the tolerable daily intake (TDI) according to health organizations. The TDI, in this case, tells you the oral reference dose of each metal and is defined as mg/kg/day. This value differs per component and is measured by mg/kg/day; for Al it is 0.143 (European Food Safety Authority (EFSA) 2008), for Zn it is 0.36 (European Food Safety Authority (EFSA) 2014) and for Cu it is 0.5 (Joint FAO/WHO Expert Committee on Food Additives (JECFA) 1982).

The average person in Vietnam is 51 kg and consumes 0.9 kg of tea in a year (Phan Thi et al. 2020). This was used to calculate the risk of Zn, Al and Cu.

$$\mathbf{EDI} = \frac{C\ x\ IR}{BW}$$

The HQ value should be less than one to deduce that it is safe for consumption (Miranzadeh Mahabadi et al. 2020).

$$\mathbf{HQ} = \frac{EDI}{TDI}$$

2.3.4 Interview

The process of data analysis followed the basic principles of thematic analysis (Braun & Clarke 2013). The data were stored and labelled with an open code. Preliminary codes were then run through a refinement called focused coding, then a process of grouping which then made it possible to recognize and develop themes. The codes were puzzled together in new ways by making connections between groups which was a process coined by Strauss and Corbin (1990) called 'axial coding'.

The farmers were asked to describe their perception of organic farming in terms of benefits, disadvantages, government support and capital. Answers were grouped under a concept of “positionality” which describes where a farmer’s stance in relation to organic farming. In this paper positionality was understood as shaped by multiple social facts (Durkheim 1982) — such as institutional support, economic structures, market systems and broader farm-level conditions—that exist beyond the individual yet exert influence over their choices and perceptions.

2.4 Statistical Analysis

Using R studio Version 2024.12.1+563 (2024.12.1+563), the statistical analyses carried out in this study were aimed at investigating the differences between systems across locations.

2.4.1 Interview

To understand the Likert scale data, statistical method Wilcoxon rank-sum test (if $p<0.05$, the difference between group response is statistically significant) was used to identify statistical differences of the central tendencies of the responses between management systems.

2.4.2 Leaf and soil data

To summarize the overall distribution of the data, a principal component analysis (PCA) was conducted to identify patterns within the complex dataset and how they relate with each other. A correlation plot heatmap and Pearson correlation coefficients were also used to calculate and visualize the strength of correlation between important variables.

A linear model (LM) was developed based on the experimental design to quantify the dependence of the response variable on the independent variable. An analysis of variance (ANOVA) was carried out on the model to identify significance across variables (normality was assessed before the analyses). Where the assumption of normality was not met a non-parametric Wilcoxon rank-sum test was applied. In all cases, the least-squares means (LS- means) were used because they provide a more accurate comparison than arithmetic averages across location, since they estimate the values based on a linear fitted model (Cai 2014).

During preliminary data evaluation, slope position was considered a fixed effect. However, slope did not influence the results significantly and was therefore omitted from the model to preserve degrees of freedom. Instead, a simplified model including only system and location was used in the following analyses. While location was initially considered a random variable that accounted for site-level variation, exploratory statistical modelling and data analysis indicated that location influenced the results significantly. It was therefore considered as a fixed effect and used to seek interaction effects with the cropping system in the final model. All models were tested using a significance level of $\alpha = 0.05$.

3. Results

3.1 Interview analysis

3.1.1 The farmers and their system choices

The organic farms were significantly larger in size than the conventional farms, with a 62% ($p<0.05$) larger median (Figure 4). There was no significant difference between conventional and organic farms in terms of tea yield per area nor planting density.

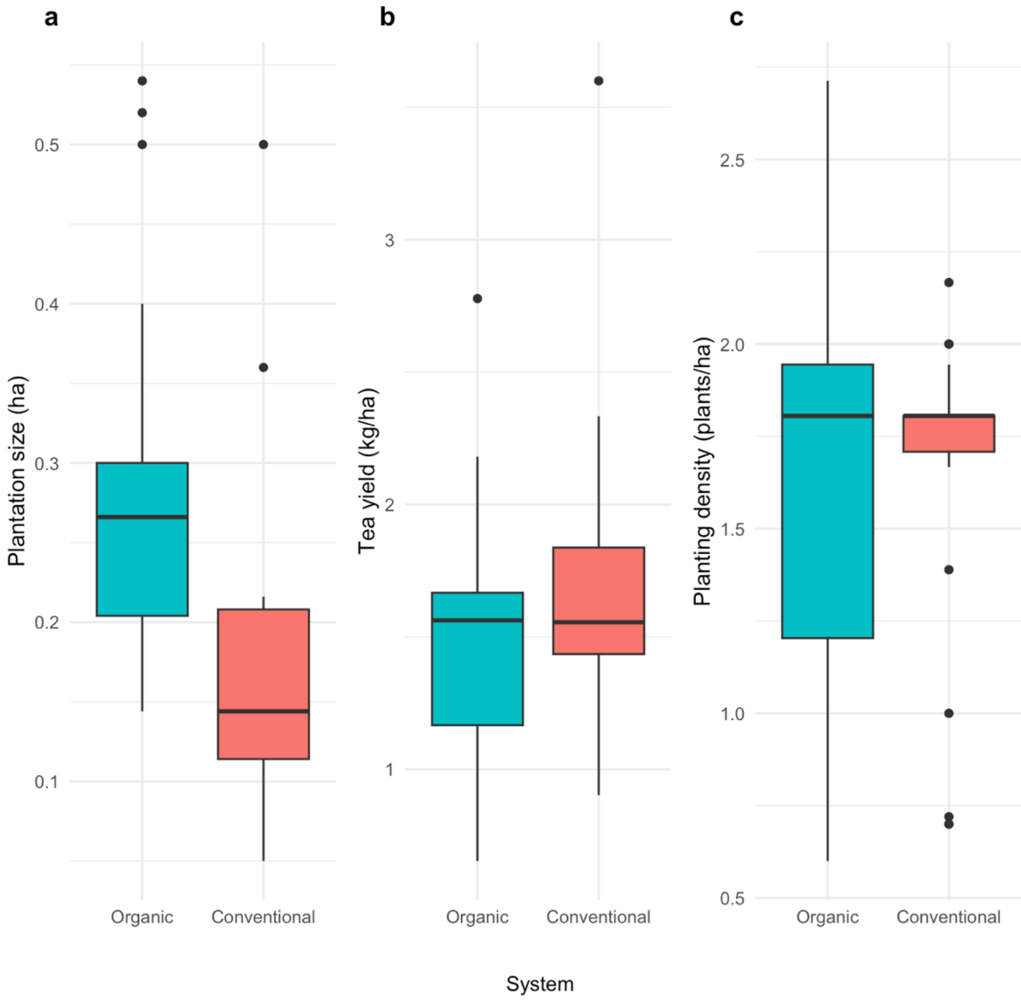

Figure 4. Boxplots comparing organic (blue) and conventional (red) tea farms: (a) Plantation size (ha), (b) Tea yield per area (kg/ha), and (c) Planting density (plants/ha). Each boxplot illustrates the median, interquartile range, and outliers.

There was a strong positive correlation between planting density and yield ($r=0.62$, $p<0.001$), implying that higher planting densities were generally associated with higher yields for both conventional and organic farms (Figure 5).

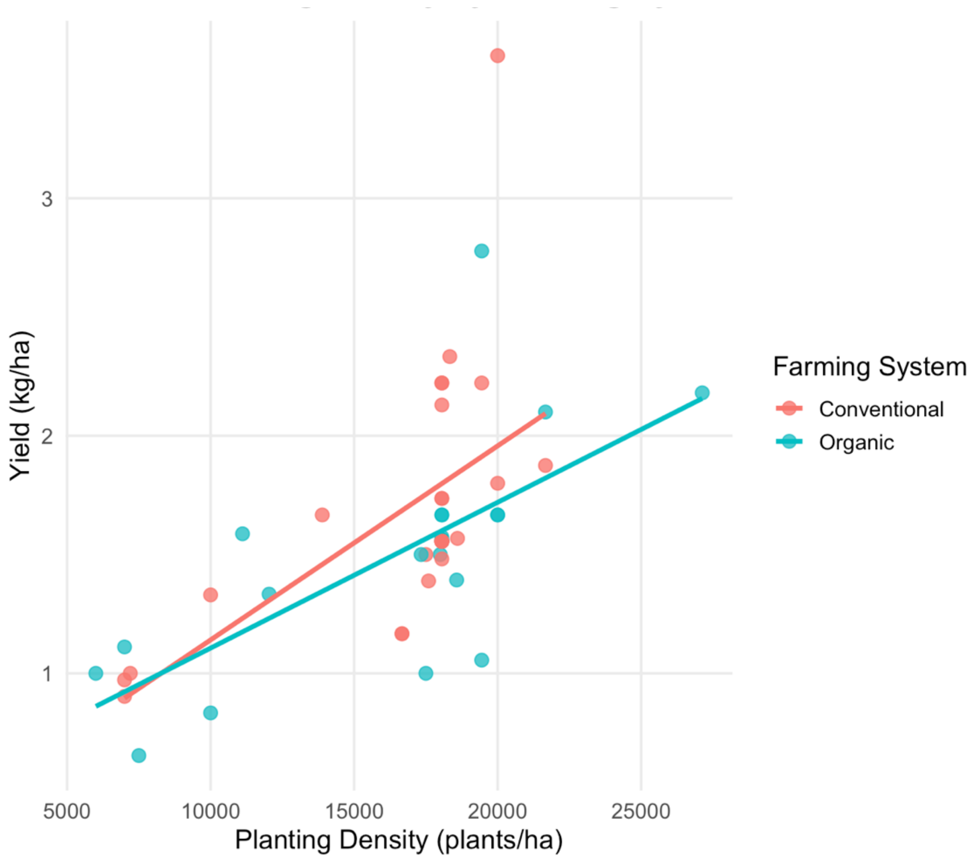

Figure 5. Relationship between planting density (plants/ha) and tea yields (kg ha⁻¹) under different farming systems. Data points represent observed yields for organic (blue) and conventional (red) tea farms, while fitted lines show the linear trend for each system. Planting density was calculated as the number of tea plants per hectare.

3.1.2 The farmers' attitudes towards farming practices

Surveys revealed some differences and similarities in attitudes across the organic and conventional farmers (Figure 6). The farmers across management systems mostly share similar beliefs regarding the statements they were presented with, indicated by the non-significant p-values. However, when discussing the perception of organic farming's potential, differences were seen. A majority of the organic farmers disagree with the statement "I do not see any potential of organic farming", while the response of the conventional farm is divided between disagreement and neutrality.

While the farmers agree that "Organic farms produce better quality tea than conventional farms", there was a difference across responses when debating whether "VietGAP farms produce better quality tea than organic farms". Most of the organic farmers disagreed, and the conventional farmers were divided between disagreement and agreement.

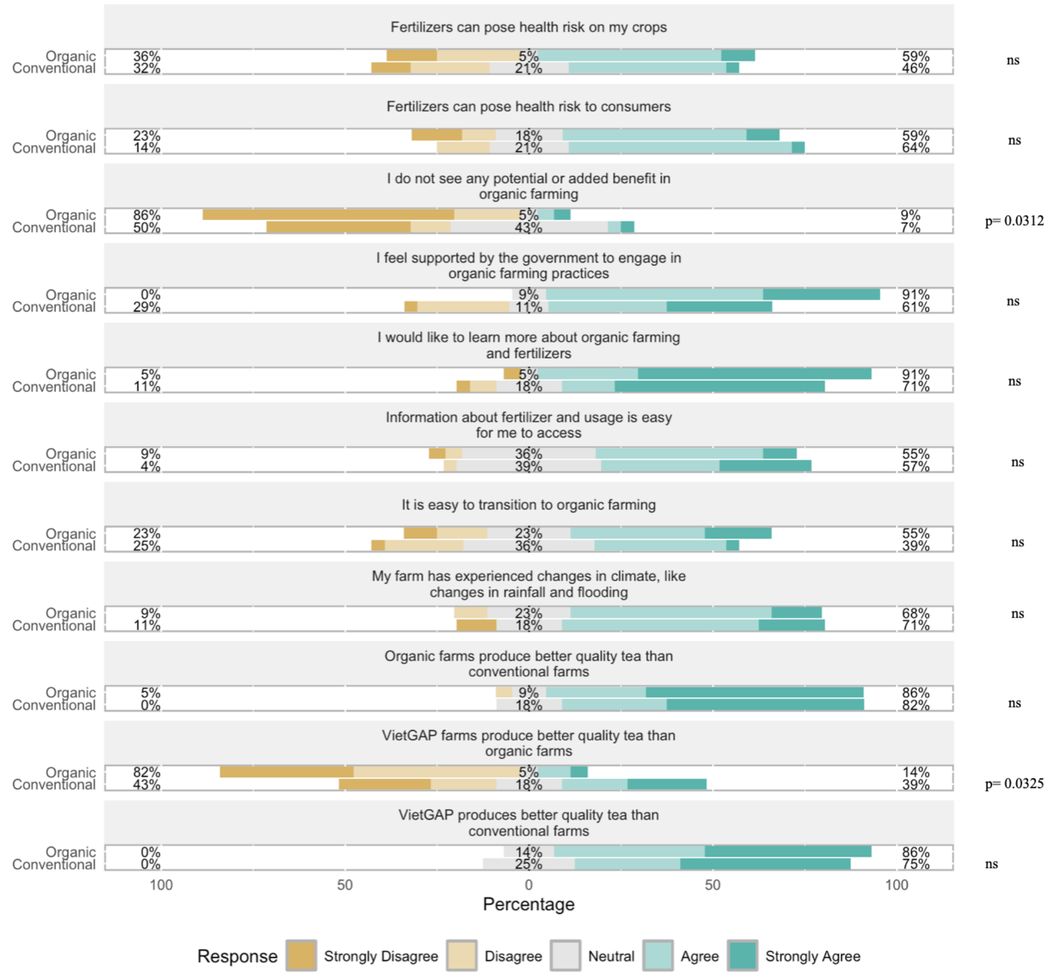

Figure 6. Distribution of the farmers' responses on a likert scale (organic n=22, conventional n=28). Percentages to the left are an agglomeration of 'strongly disagree' and 'disagree', to the right are 'agree and 'strongly agree' while the middle grey area represents 'neutral' responses. The significant difference between the answers of management systems are expressed as p-values to the right of the statement, where ns stands for non-significance.

3.1.3 Thematic analysis

The farmers' priorities and challenges

The underlying aspirations, motivations of respondents for their farming and other belief systems they may hold are captured in this analysis.

Priorities: The overarching goal of the farmers was profitability. Whether framed as high yields, superior quality (good taste or untainted by disease) or higher market value, profitability was frequently the main goal outlined by the farmers. Expansion of production and market reach was another concept that was mentioned often, as one farmer explains this goal as "to increase yield and improve quality so that more customers know about it". Several farmers expressed a similar powerful vision: “reaching new heights and expanding further” or “nâng tầm, vươn xa”.

Some farmers emphasized the importance of selecting varieties that match the local soil and climate conditions. One farmer explained that tea crops should remain productive for many years and be resistant to flooding.

Challenges: The most frequently reported challenges were insect pests; some noted a general increase in pest population and the growing resistance to pesticides. Related to this, timely pest control was another challenge noted. It is a demanding feat as the cost of pesticides is high and the application requires more labor (labor shortage is also expressed by farmers). The cost of investment for farm inputs such as fertilizers was also a major concern. Other challenges noted were low yields, nutrient deficiencies, climate pressures and aging tea plants.

Positionality on organic farming

Of the 28 conventional farmers, 22 expressed an openness towards organic farming, citing “I intend to apply” or “I have thought about applying”. Others expressed a reluctance in “It is good but not ideal” or more frankly, “I do not intend to apply, because my family does not have the capacity to do so”. Farmer responses under this theme disclosed external and internal drivers to adopting organic farming (Figure 7).

External drivers: Farmers frequently cited market trends as decisive in their consideration of organic farming, suggesting that market conditions strongly influence adoption. Tea produced organically was often described by farmers as being more competitive on the market, having a higher demand and being easier to sell. Its selling price was also said to be higher compared to conventionally grown tea. However, some conventional farmers still considered tea production worthwhile even when sold at a lower price and the demand for their product as unwavering.

When discussing governmental subsidies, organic farmers mentioned more targeted support like subsidized certification, and marketing assistance. On the other hand conventional farmers talked more about product-oriented support, like help with farm inputs, irrigation systems and technical training.

Internal drivers: Farmers using both systems often linked organic practices with improved health outcomes for farmers, consumers and the environment. Additionally, it was associated with the concept of sustainability.

When considering plant-care, some organic and conventional farmers perceived the method of applying fertilizer in organic farming to be easier, though it results in “reduced yields and productivity”. A conventional farmer remarked that there were technical barriers when learning new ways to care for the plants, “particularly in fertilization and pest control”. The transition was often described as difficult, requiring farmers to relearn both farming ideologies and operations due to the “strict regulations” of organic certification. Some considered organic farming to be more time-consuming and labor-intensive, e.g. since it required more weeding by hand, and therefore, a couple of farmers declared that it was out of their family’s capabilities to make the switch.

One key motivation for adopting was their personal perceptions of the transition. Most conventional farmers expressed interest in applying for certification and organic farmers said they adopted the practice because it has a good reputation. Organic farmers generally expressed personal satisfaction and pride, believing they produced good-quality crops with satisfactory yields. Additionally, it was observed during the fieldwork that the organic farmers were often part of a cooperative or network, which provided social and logistical support during the transition to organic management. When asked about their decision to adopt organic farming, most farmers reported doing so voluntarily, while others indicated that the cooperative made the decision for them.

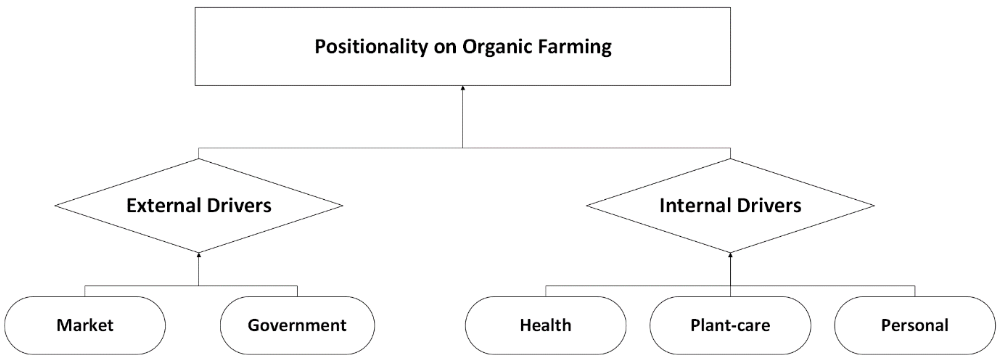

Figure 7. External and internal drivers to adopting organic farming described by the farmers. Illustration by author.

Fertilizer Philosophy

Ultimately, farmers applied fertilizers based on their farming goals with preferences shaped by both personal experiences, philosophies and external constraints. A majority of the organic farmers believed that using only organic fertilizers was the best for their tea crop while a smaller group perceived a combination of both mineral and organic inputs as better for crop growth (Table 3). Among conventional farmers only a few believed getting nutrients from solely organic fertilizers were ideal, while some considered mineral fertilizers to be superior. However, a majority favored a combined approach, revealing a broader trend across both groups: a belief in the complementary benefits of organic and mineral inputs.

Table 3. Farmers' fertilizer philosophy by farming system. The table presents out of 50 respondents, the number of conventional (n = 19) and organic (n = 21) who identified organic, mineral, or a combination of both fertilizers as the best option

Fertilizer Philosophy	Conventional (n= 19)	Organic (n=21)
Organic is best	2	12
Mineral is best	4	0
Combination is best	13	9

The Sankey diagram (Figure 8), used to further unpack the reasoning behind the farmer fertilizer preferences, show that the main unifying belief across all fertilizer philosophies was that the chosen practice should ultimately lead to increased yields. Among those who favor a combined approach, many regard mineral fertilizers as essential for stimulating plant growth and bud production, while organic fertilizers are seen as vital for enhancing soil quality. Other farmers explicitly attribute higher yields to mineral fertilizers, due to their higher concentration of nutrients. The perception that organic fertilizers enhance the soil fertility is widely shared across both organic and conventional farmers, with organic fertilizers often described as making the soil "loose and airy" or fostering a "resilient soil".

Another recurring theme was the perceived improvement in tea quality. Both organic and combination fertilizer advocates linked their fertilizer philosophies to producing tea with superior quality. For organic farmers, quality was described in terms of thicker leaves, healthier plants and safer products (for consumers, workers and the environment)—often characterized as "clean" and "sustainable". Meanwhile, farmers who support a combined approach, associated it with better-tasting tea and longer plant lifespans. One farmer also emphasized the economic efficiency of combining fertilizer types. Financial considerations were particularly prominent among mineral fertilizer users, who valued the high nutrient density and lower labor demands compared to labor-intensive organic fertilizer management.

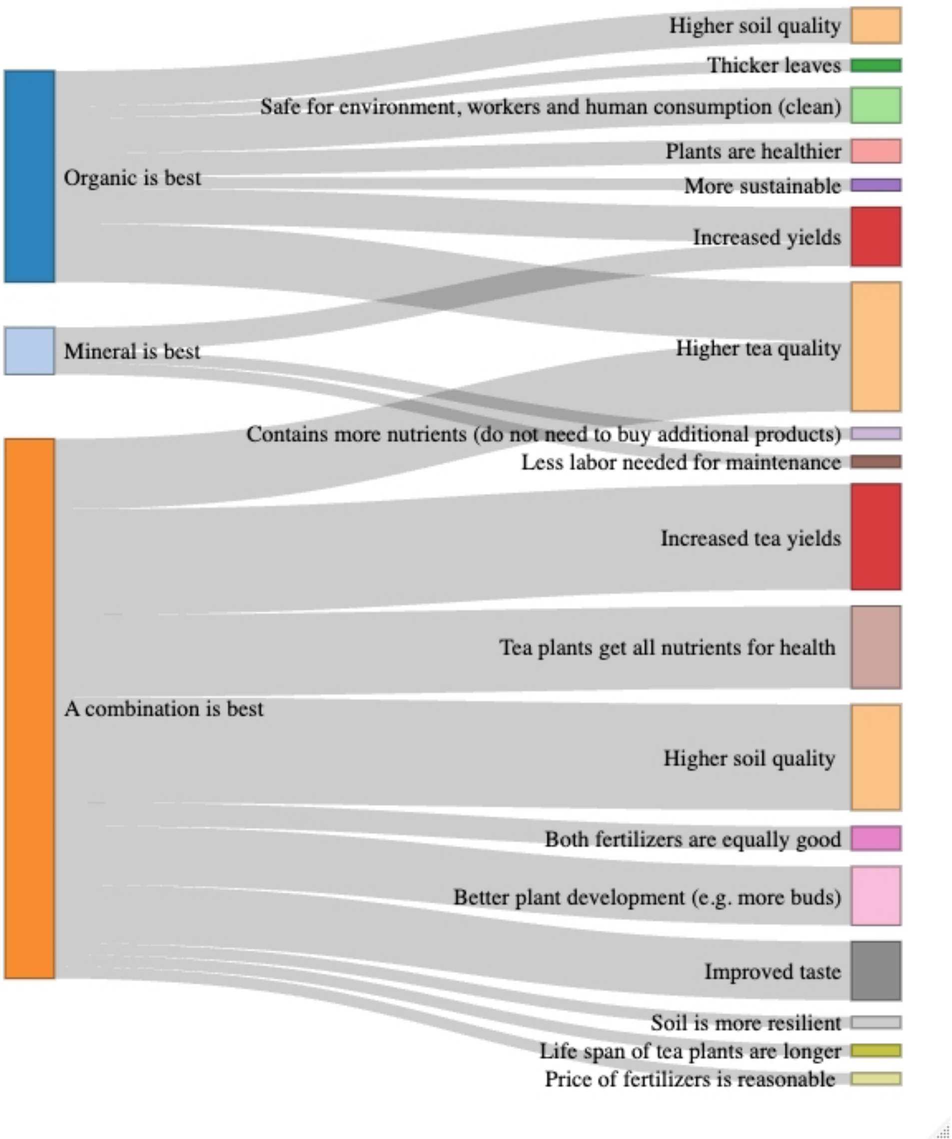

Figure 8. Sankey diagram showing the distribution of farmers' fertilizer philosophies and how their beliefs flowed between categories. Farmers were asked whether they considered organic, mineral, or a combination of fertilizers as best. The width of each flow is proportional to the number of mentions, illustrating how beliefs are distributed across conventional (n = 19) and organic (n = 21) farmers.

In practice, the conventional farmers tended to use a wider range of branded fertilizers while the organic fertilizer options appeared more limited in the market (Figure 9). Among both farm types, it was general farm practice to use composted animal manure from either chicken, cow, pig or buffalo (or a mix of a few). One organic farmer shared a homemade recipe using a fermented mixture of fish emulsion, eggs and soybeans. Some conventional farmers also reported creating their own fertilizers such as a fermented blend of grass and bananas or a similar mixture using bananas, eggs and honey.

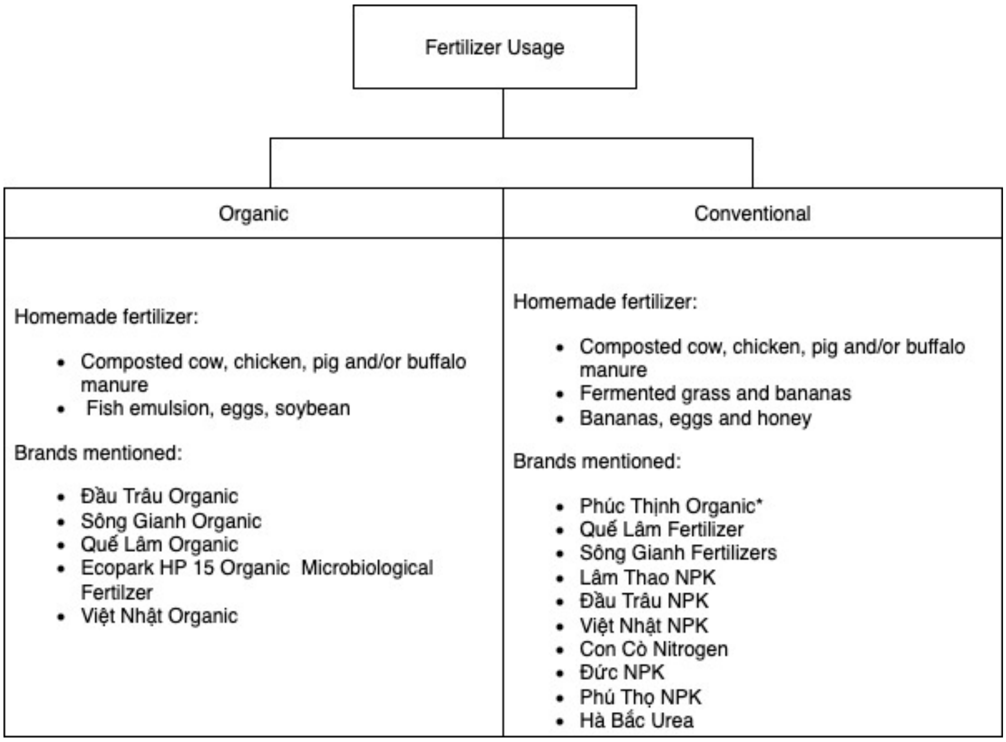

Figure 9. Types and brands of fertilizers used by the tea farmers. Commercial fertilizers are labeled by brand, while homemade or farm-prepared fertilizers are indicated accordingly. The figure shows the distribution of fertilizer types across conventional and organic farms.

Intersectionality of gender-based division of labor

The respondent group included 32 female farmers and 18 male farmers. This section of the interview illuminated the deeply ingrained perceptions of “natural” physical abilities that dictate the roles men and women assume on the farm. Men did the heavy and technically intensive work (such as carrying fertilizers and pesticides, irrigating and operating machinery)—under the assumption that women are “physically weaker”. Meanwhile women’s work was often framed as meticulous, detail-oriented and nurturing. Their roles often involved delicate tasks such as harvesting, sales and packaging. One farmer noted how women “take better care of plants because they pay more attention to detail”. The interviews also exposed a notable tension in ideologies with some respondents simultaneously denying the existence of gendered differences in tea cultivation while describing a clear gender-based division of labor. One farmer remarked that men “do most of the work” because they are responsible for heavy work. Conversely, other farmers expressed a different narrative claiming that women are the primary workers in tea cultivation. One responded candidly, “the wife does the main work, the husband helps” especially during times of climate stress when irrigation is needed, adding “drought has an impact, and the husband assists with watering”.

Table 4. Summary of the farmers' perceptions of gendered labor in tea farming. Themes capture common statements on task division, capability, and workload. "Mentions (total)" indicates the number of farmers who expressed each theme (n = 45/50 respondents), and "By gender" shows the proportion of female (F) and male (M) respondents who mentioned them.

Theme	Mentions (total)	By gender	Summary of gendered labor perceptions
Non-Gendered Division of Tasks	14	F: 64% M: 36%	No perceived difference: both genders can do the work equally
Gendered Division of Tasks	31	F: 65% M: 35%	Men carry heavy items (tea/pesticides/ fertilizer/ machinery) while women harvest, manage sales, labor, marketing. "Strong vs meticulous" roles Women either lead most tasks with husbands help or women do all the farmwork Farmers initially claim no gendered division of labor, but later describe clearly gendered roles Men do more work

Climate change perceptions

The farmers were asked to reflect on their experiences of climate change, revealing a consistent narrative of increased hardship and vulnerability when caring for tea (Table 5). There was a diverse range of perspectives amongst the farmers, yet they converged on a shared sense of environmental uncertainty. While some of the farmers reported that climate change had had a minimal impact on their tea production, the broader narrative pointed to a growing sense of urgency. Several respondents emphasized the need to adapt cultivation techniques as the lifespans of tea plants are decreasing rapidly and crops are becoming more difficult to care for. These testimonies portray climate change as a present and intensifying stressor that is shaping tea farming systems.

The farmers frequently identified extreme weather as a growing threat to tea cultivation like heavy rainfall, drought and heat. Heavy rain was said to cause waterlogging and root rot, as one farmer reflected "too much rain damages the roots, and too much sun damages the branches". Particularly during the 2024 floods in northern Vietnam, one farmer observed their tea crop turning yellow and dying back, therefore decreasing the tea yield and quality, and ultimately fetching a lower price on the market.

The farmers experienced droughts arriving earlier than before and happening more frequently, threatening the budding of plants as it was said to cause plants to wither and not sprout. The farmers reported experiencing lower yields during periods of climate stress. They also noted that managing crops under these conditions required additional labor and other inputs

Rising temperatures was another concern. The respondents noted that winter was shorter in the recent times. Another farmer shared his observation that the excessive heat had caused the soil quality to degrade and a reduction in plant productivity.

Table 5. Climate change observations reported by conventional (n=28) and organic (n=22) farmers

Climate Change	Conventional (n=28)	Organic (n=22)
Droughts (frequent and longer dry spells)	16	12
Heavy Rains (and flood)	14	11
Intense Sun (Temperature has increased)	5	7
Weather is unpredictable (alternating rain and sunshine)	1	1
Winter is shorter	2	
Experienced climate change	3	3
No changes	2	2

Intercropping and agroforestry potential in tea farms

When asked whether they would consider intercropping tea with trees or other crops, 49 out of the 50 farmers responded negatively. Only one farmer expressed interest in intercropping, specifically with moringa trees, citing the perceived benefit of shade. The most common justifications for rejecting intercropping were fears of competition for sunlight and nutrients between tea and the other crops, ultimately reducing both yield and quality. In some cases, the farmers also expressed that tea alone provided sufficient income, implying the little perceived need to diversify.

3.2 Soil properties

The farms all had high sand and clay content and were low in silt (Figure 10). Soil textures cluster around sandy-clay-loam to clay loam and sandy clay. Data points from the same location cluster together in the soil triangle but differ between locations. In general, there were no significant differences in soil texture between systems, but the conventional plots at Phu Xuyen had lower clay content than the organic ones, causing a significant interaction between location and system (Table 6, Figure 13).

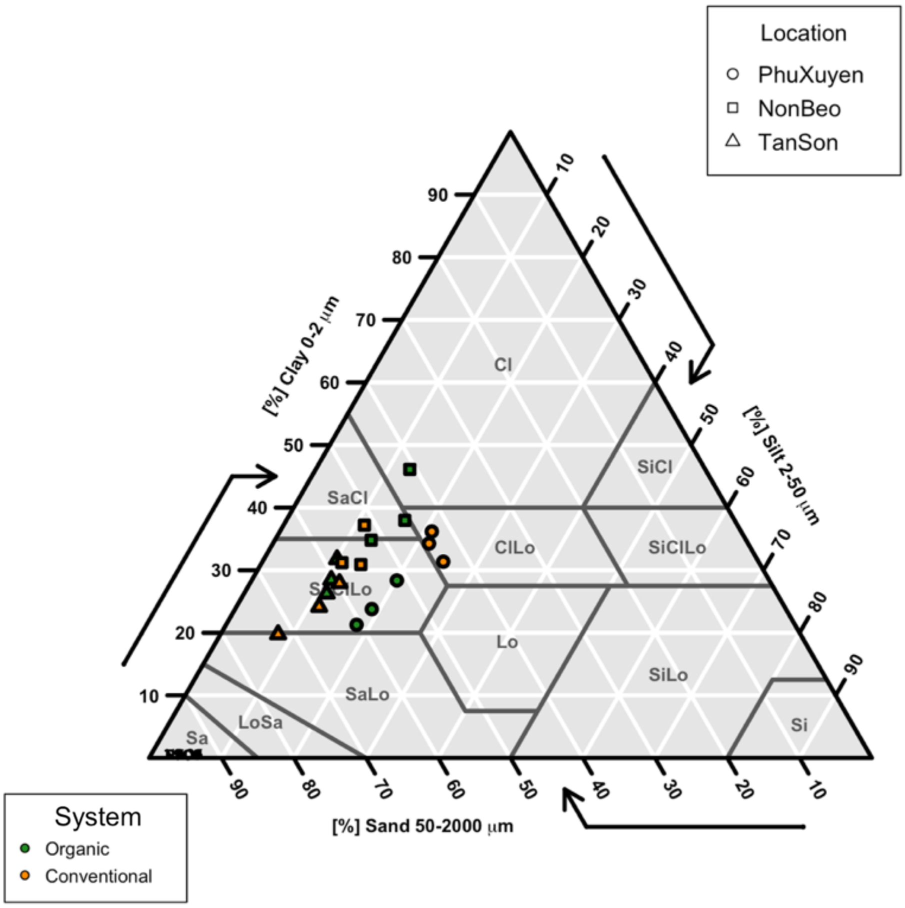

Figure 10. Distribution of soil texture in organic and conventional farms across three locations. Symbols indicate location—Phu Xuyen (circle), Non Beo (square), and Tan Son (triangle)—while colors represent farm type: organic (green) and conventional (red).

Among all the measured soil indicators, only aluminum (Al), organic carbon (OC), copper (Cu), and zinc (Zn) contents were significantly affected by system, where conventional soils had concentrations that were, respectively, -30%, -20%, +48% and +129% of that in the organic systems (model-based means after accounting for location effects). However, the effect of system on two of those indicators, OC and Zn, differed between locations, which caused a significant interaction. The pH showed no significant general difference between systems, but pH showed to be significantly different across locations and caused a significant interaction effect. Electric conductivity (EC) and total nitrogen (TN) were both near the threshold of statistical significance. While only close to significant, there could be a possible trend which would need more data to confirm any pattern. Overall, organic farms tended to exhibit a narrower range of variability across key soil indicators such as pH, EC, cation exchange capacity (CEC), calcium (Ca), and nitrogen (N) compared with the conventional systems. In terms of micronutrients, Cu and Zn appeared slightly higher in conventional systems, whereas Al concentrations are marginally higher in soils of organic farms.

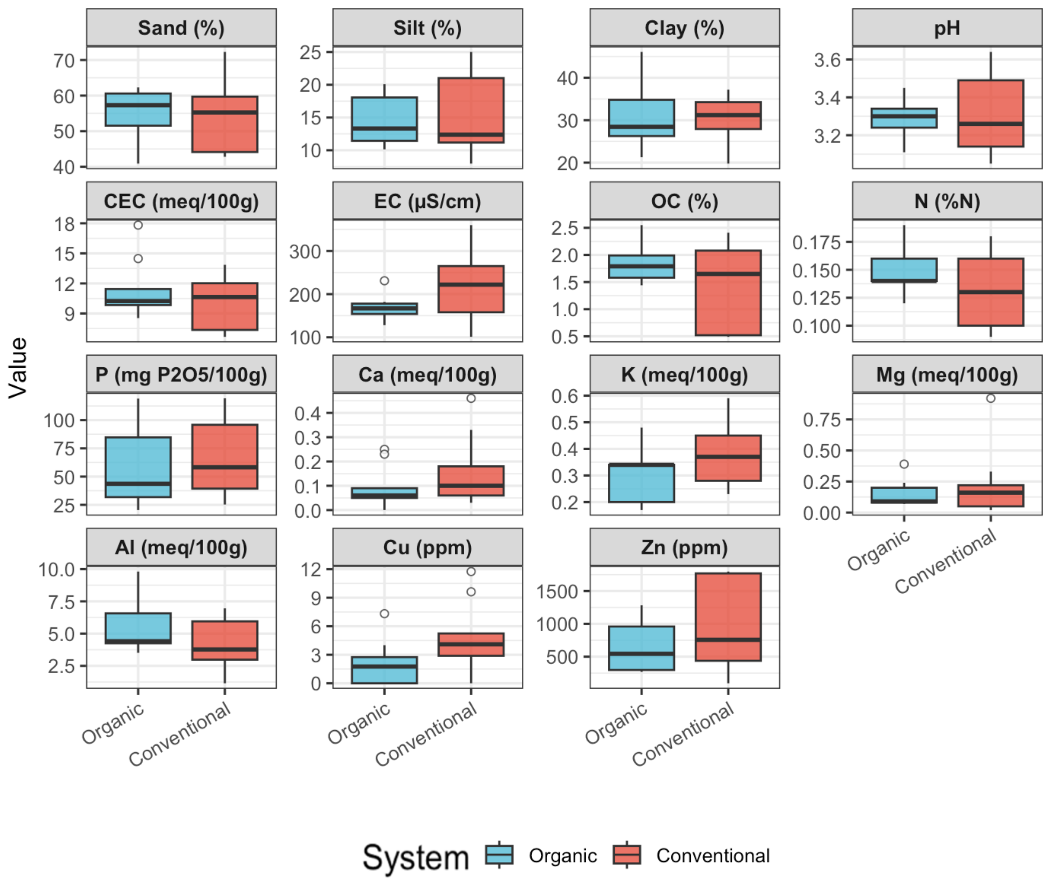

Figure 11. Comparative boxplots showing the distribution of soil chemical and physical properties in organic (blue) and conventional (red) farming systems. Each boxplot represents a soil property indicator, illustrating the median, interquartile range, and outliers. For Cu, six samples had concentrations below detection and were assigned a value of half the lowest detected concentration.

Table 6. Results of two-way analysis of variance (ANOVA), testing the effects of system, location and their interaction on soil chemical and physical properties (see Table 1). Values represent p-values for each source of variation, and those written in bold indicates a significant difference (for values see Table 7, Table 8 and Table 9)

Indicator	System	Location	Location: System
Sand	0.885	**p<0.001*** **	**0.002*** **
Silt	0.671	**p<0.001*** **	**0.038***
Clay	0.730	**0.002*** **	**0.007*** **
pH	0.422	**0.001*** **	**0.010*** **
EC	0.096	0.233	0.076
Al	**0.003*** **	**p<0.001*** **	0.615
CEC	0.142	**0.001*** **	0.444
K	0.125	**0.024***	0.576
Ca	0.180	**0.035***	0.129
Mg	0.408	0.095	0.079
OC	**0.034***	**p<0.001*** **	**0.035***
N	0.063	**0.007*** **	0.165
P	0.456	0.865	0.072
Cu	**0.050***	0.070	**0.039***
Zn	**p<0.001*** **	**p<0.001*** **	**p<0.001*** **

The strongest negative correlation found in the analyzed soils are OC with pH, sand with Zn, and CEC with pH level (Figure 12). The pH also had a strong negative correlation to CEC, N and Al meaning that as pH decreases, these variables, and OC increase. The strongest positive correlations found are Al with CEC, magnesium (Mg) with Ca and Cu with Zn. Aluminum was also positively correlated to OC and clay content. The base cations potassium (K), Ca, Mg behave similarly to each other, as they are all positively correlated to one another and are all also positively correlated to the cations Zn and Cu. However, OC was negatively correlated to Mg, and Ca while there was not a significant relationship between OC and K.

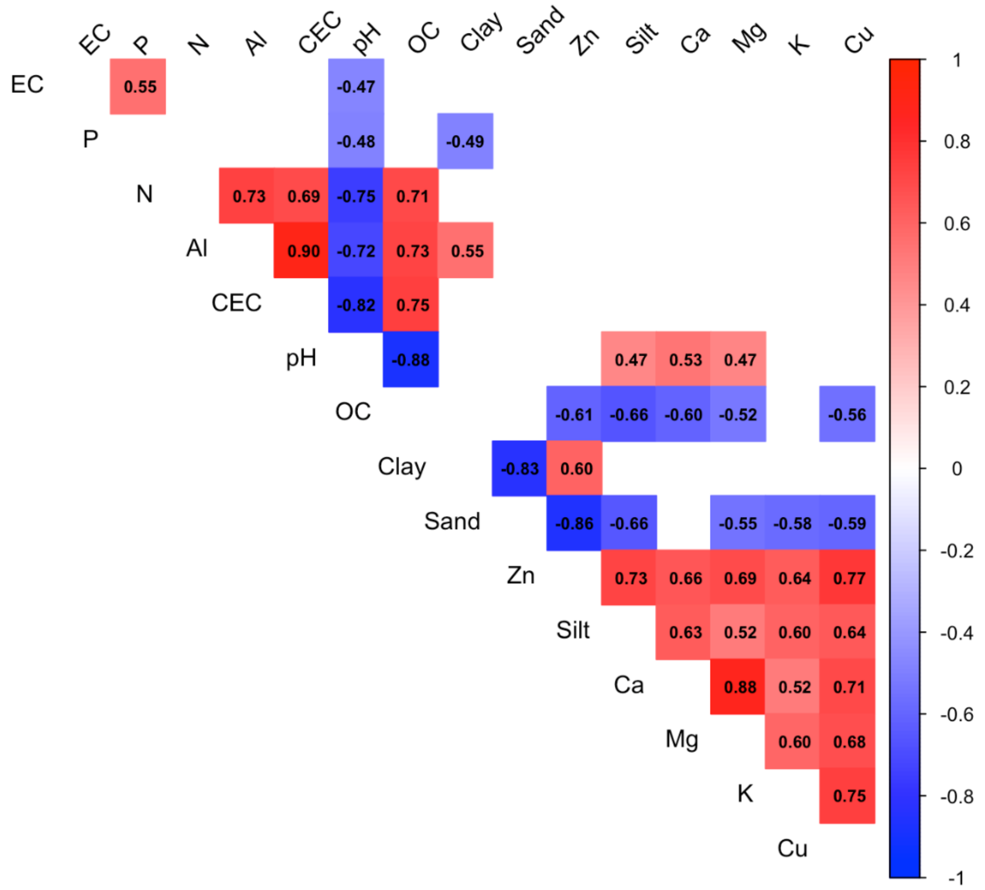

Figure 12. Correlation plot heatmap with significant Pearson coefficients (p<0.05). P is expressed as the available concentration, Mg, K, and Cu represent the exchangeable concentrations, N and OC are their total concentrations.

The first principal component (PC1) captured variation primarily in OC, Zn, Ca, silt, Mg, pH and Cu, while PC2 was associated with CEC, clay, Al, sand, K, N and pH (Figure 13). The pattern shows a clustering of locations Non Beo and Tan Son of both systems, while at Phu Xuyen, the conventional farms have a clear difference in PC1. Nevertheless, conventional farms showed a wider spread across both PC1 and PC2, suggesting greater heterogeneity in soil condition. On the contrary, organic farms were more tightly clustered near PC1=0, indicating that they expressed the PC2-associated variables more strongly than PC1. As organic farms were spread along the Y-axis (PC2), this implies that they were more differentiated by soil texture and content of exchangeable Al rather than nutrient concentrations.

In terms of variable representation, CEC, sand, pH and clay have the longest arrows in the biplot, implying they are well-represented variables across both PCs. Small angles between vectors of Ca, silt, Mg, Cu and Zn indicate positive correlations between the variables.

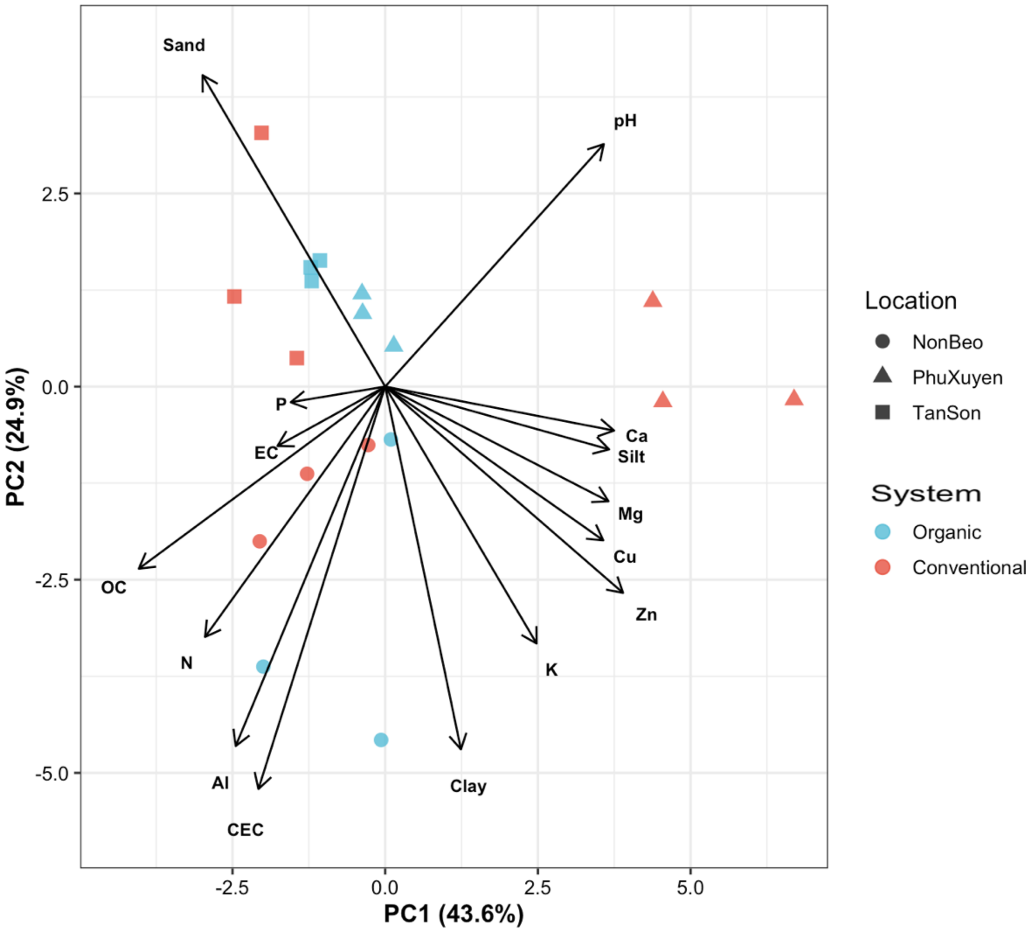

Figure 13. Principal component analysis biplot of soil indicators data points colored by farm type organic (blue) and conventional (red) and shaped by location.

3.2.1 Organic carbon and total nitrogen

Across all sites, organic systems tended to have slightly higher OC and N values compared to conventional systems, although the magnitude of this effect differed across locations (Table 7). The difference was most pronounced in Phu Xuyen, where organic farms had substantially higher OC than conventional farms, and higher N. In Non Beo, OC and N were similar in both systems, with organic farms showing a modest increase. Meanwhile, Tan Son displayed nearly identical OC and N levels in both systems .

Table 7. Least-squares means (LS-means) of soil organic carbon (OC, %) and nitrogen (N, %N) in different farming systems for each of the three locations. Values are shown for conventional and organic systems at Non Beo, Phu Xuyen, and Tan Son, with corresponding standard errors (SE) reported for each LS-mean.

Location	System	OC LS-mean (%) SE 0.2	N LS-mean (%N) SE 0.0126
Non Beo	Conventional	2.03	0.160
	Organic	2.15	0.173
Phu Xuyen	Conventional	0.51	0.093
	Organic	1.59	0.143
Tan Son	Conventional	1.93	0.133
	Organic	1.90	0.133

3.2.2 Soil acidity and cation exchange capacity

The results of calculating the pH LS-means per system across all locations show that the soils are acidic ranging from 3.15 to 3.57 (Table 8). There was no statistically significant difference in soil pH between organic and conventional farms ($p>0.05$). In this study, CEC was measured using a standard method at pH 7.0. Potential CEC ranged from 7.66 to 12.93 meq/100g.

Table 8. Least-squares means (LS-means) of soil pH level and CEC in different farming systems across three locations. Values are shown for conventional and organic systems at Non Beo, Phu Xuyen, and Tan Son, with corresponding standard error (SE) reported.

Location	System	pH LS-mean SE 0.06	CEC LS-mean SE 1.03
Non Beo	Conventional	3.15	12.9
	Organic	3.18	14.6
Phu Xuyen	Conventional	3.57	7.66
	Organic	3.30	10.1
Tan Son	Conventional	3.24	9.64
	Organic	3.37	9.47

3.2.3 Trace elements assessment in soil

Trace elements of Zn and Cu were assessed across farming systems and locations. Aluminum is also reported here (Table 9) due to its relevance in acidic soils and tea plantations. It is important to highlight that the laboratory analyses of Cd were all below detection limit of the laboratory (<1.5 ppm) and therefore were omitted completely from the analysis. Zinc LS-means in all farms exceeded the legal limit of 200 ppm, ranging from 270 to 1785 ppm. A very strong interaction between system x location was observed ($p<0.001$***, see Table 6). The highest Zn concentration was recorded in the conventional farm of Phu Xuyen while the lowest values were found in Tan Son. In contrast, Cu levels were well below the legal limit of 100 ppm, with values ranging from 1.34 to 8.87 ppm.

Table 9. Least-squares means (LS-means) concentrations of zinc (Zn), copper (Cu), and aluminum (Al) are shown for conventional and organic tea farms at three locations (Non Beo, Phu Xuyen, Tan Son). LS-mean values are compared to regulatory reference levels (QCVN), with an indication of whether concentrations exceed recommended thresholds. Al values are provided for context, though no regulatory limits exist.

Location	Heavy Metal	System	LS-mean (mg/kg)	Regulatory limit	Excess in relation to the limit
Non Beo	Al	Conventional	6.47	Not specified	N/A
		Organic	8.67		N/A
Phu Xuyen	Al	Conventional	2.06		N/A
		Organic	4.06		N/A
Tan Son	Al	Conventional	3.67		N/A
		Organic	4.78		N/A
Non Beo	Cu	Conventional	3.57	100 (QCVN)	No
		Organic	3.36		No
Phu Xuyen	Cu	Conventional	8.87		No
		Organic	1.35		No
Tan Son	Cu	Conventional	1.37		No
		Organic	1.34		No
Non Beo	Zn	Conventional	761	200 (QCVN)	Yes
		Organic	1105		Yes
Phu Xuyen	Zn	Conventional	1785		Yes
		Organic	514		Yes
Tan Son	Zn	Conventional	270		Yes
		Organic	281		Yes

3.3 Tea leaf analysis

Aluminum levels in tea leaves from the conventional systems were generally higher than those from the organic systems where the latter had a wider, lower range (Figure 14; Table 10). Nitrogen levels on the other hand, were higher in leaves from the organic systems than from the conventional farms. The Zn range was larger for organic systems. However, like the Cu levels, they were not significantly different between systems. Cadmium levels were below the detection limit (0.02 mg/kg) and therefore omitted from further analyses.

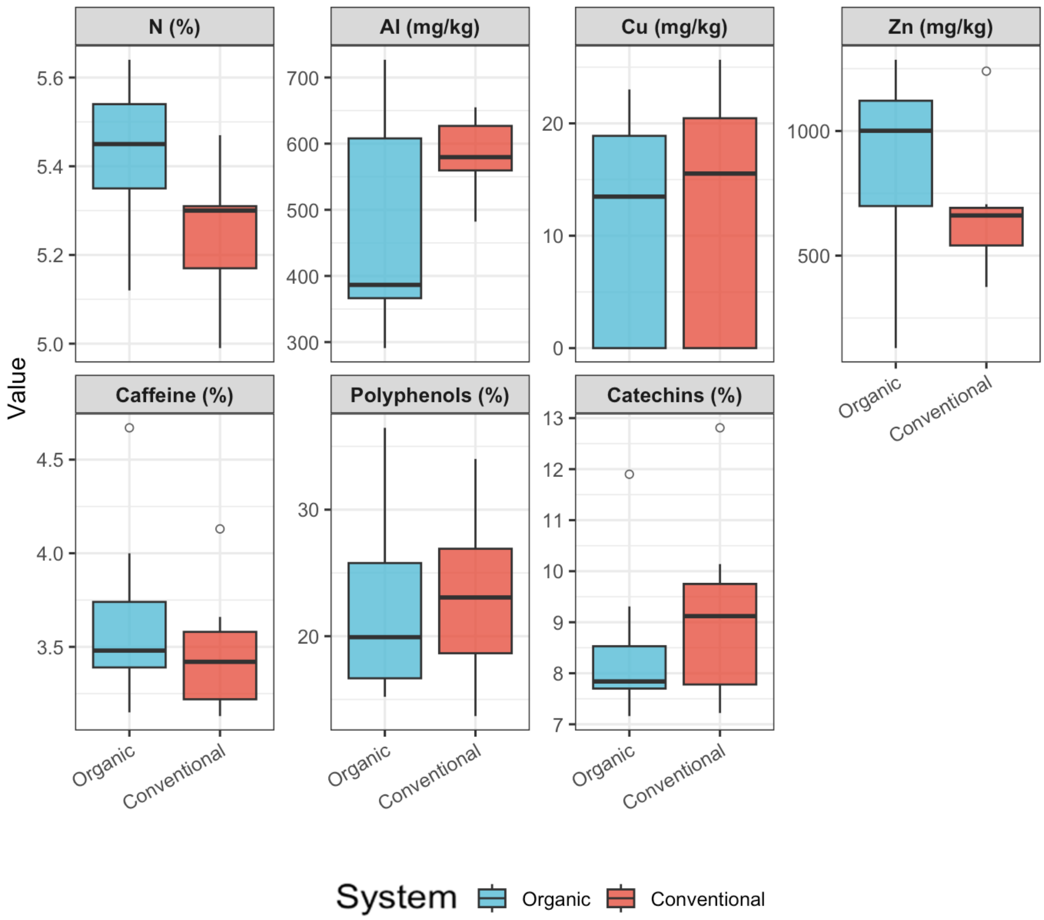

Figure 14. Comparative boxplots showing the distribution of element concentrations and secondary metabolites found in the teas in organic (blue) and conventional (red) farming systems. Each boxplot represents a soil property indicator, illustrating the median, interquartile range, and outliers. Six samples of Cu had concentrations below detection and were assigned a value of half the accreditation's lower limit.

Table 10. Results of two-way analysis of variance (ANOVA) on element concentrations and secondary metabolites found in the teas, testing the effects of system, location and their interaction. Catechins and polyphenols are expressed as total values. Values represent p-values for each source of variation.

Indicator	System	Location	Location: System
Zn	0.358	0.787	0.953
Cu	0.550	0.00795**	0.0549
N	0.00932**	0.734	0.0227*
Al	p<0.001***	p<0.001***	0.00115**
Caffeine	0.277	0.161	0.214
Catechins	0.331	0.269	0.945
Polyphenols	0.960	0.0427*	0.961

Copper concentrations in leaves was strongly negatively correlated with caffeine content ($r=-0.83$, $p<0.001$) and Al concentration in leaves was positively correlated with Cu concentration in tea leaves ($r=0.61$, $p=0.034$) (Figure 15).

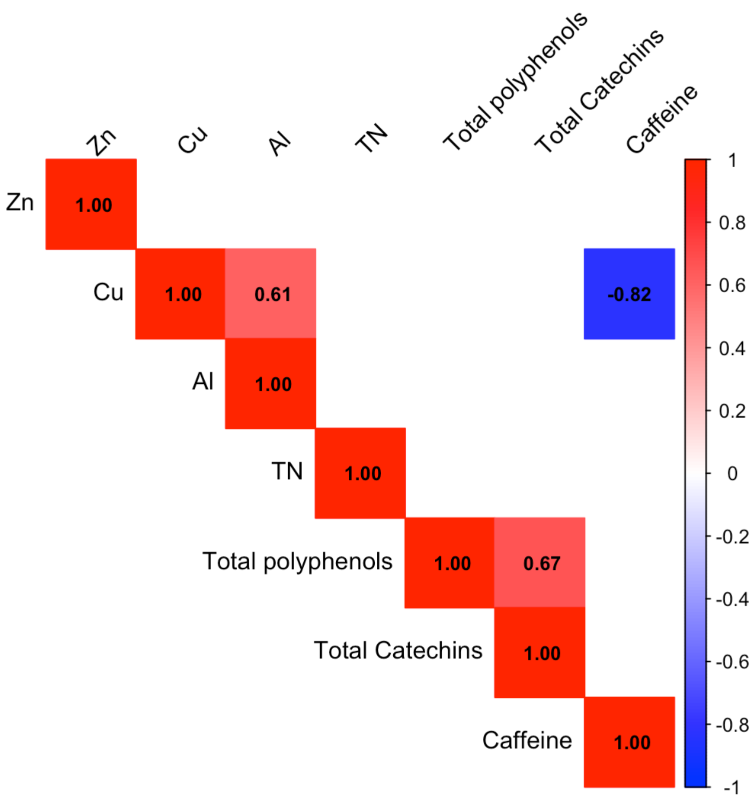

Figure 15. Correlation plot heatmap of leaf variables with significant Pearson coefficients (p<0.05). TN represents total nitrogen.

3.3.1 Secondary metabolites

The total polyphenol content in the 18 tea leaf samples ranged from 14% to 37% of dry weight (Table 11). The cropping system apparently did not affect the concentration but there were large differences between the locations. The highest total polyphenol content was found in Non Beo (36.5%) – organically grown tea, while the lowest was found in sample Phu Xuyen (13.7%) – conventionally grown tea. The caffeine content was relatively stable across the samples, ranging from 3.15% to 4.67%. The catechin content did not significantly differ between cropping systems or locations and ranged between 7.16% and 12.8%.

Table 11. Comparison of least-squares mean (LS-means) of secondary metabolites including caffeine, catechins and polyphenols (the latter two are expressed as total values) are shown for three locations (Non Beo, Phu Xuyen, Tan Son) under conventional and organic management systems.

Location	System	Caffeine	Catechins	Polyphenols
Non Beo	Conventional	3.31	7.84	19.8
	Organic	4.04	8.34	20.1
Phu Xuyen	Conventional	3.42	8.15	20.0
	Organic	3.34	8.88	19.1
Tan Son	Conventional	3.67	9.10	28.0
	Organic	3.58	10.23	29.1

3.3.2 Potential risk of Al, Cu and Zn

All farms had notably high bioaccumulation factor (BCF) values for Al (Table 12). Across all locations, conventional farms showed higher BCF values for Al than organic farms, particularly in Phu Xuyen's conventional systems (350). The hazard quotient (HQ) for Al was less than 1. The BCF values suggest that tea is in between moderately and high accumulators of Zn with maximum levels of 4.0. The HQ of Zn from all locations and systems falls below 1. Tea leaves show high Cu accumulator tendencies with the BCF values being elevated, ranging from 1.2 to 11.7. The HQ values for all locations were also below 1. Notably, conventional systems in Tan Son had undetectable levels of Cu in tea leaves. Furthermore, the ANOVA results indicated no significant difference in BCF of Cu and Zn between systems.

Table 12. The table shows values for conventional and organic farms across Non Beo, Phu Xuyen, and Tan Son for each heavy metal (HM) tested (Al, Cu and Zn), their trace element bioaccumulation factor (BCF), estimated daily intake (EDI), and hazard quotient (HQ) of tea leaves from different farm systems and locations. An HQ value less than one suggests that the substance is safe for consumption with regards to the trace element. bd = below detection limit)

Location	HM	System	BCF	EDI (mg/kg bw/day)	HQ
Non Beo	Al	Conventional	85	0.026	0.184
		Organic	48	0.020	0.137
Phu Xuyen	Al	Conventional	350	0.030	0.210
		Organic	162	0.032	0.221
Tan Son	Al	Conventional	158	0.028	0.193
		Organic	70	0.016	0.109
Non Beo	Cu	Conventional	5.7	0.001	0.002
		Organic	3.4	0.001	0.002
Phu Xuyen	Cu	Conventional	2.6	0.001	0.002
		Organic	3.9	0.000	0.001
Tan Son	Cu	Conventional	bd	-	-
		Organic	1.2	0.000	0.001
Non Beo	Zn	Conventional	0.81	0.030	0.083
		Organic	0.72	0.037	0.11
Phu Xuyen	Zn	Conventional	0.36	0.031	0.087
		Organic	1.7	0.036	0.101
Tan Son	Zn	Conventional	2.9	0.035	0.097
		Organic	3.4	0.047	0.13

4. Discussion

4.1 Socioeconomic dimensions of tea farming systems

4.1.1 Farmer engagement with organic farming

The organic farming areas were, on average, 62% larger than the conventional farming areas, but tea yield per hectare and planting density did not differ significantly between systems. This indicates that organic farming maintains comparable productivity per unit area. Most conventional farmers (79%) expressed an intention to transition to organic system in the future. The appeal of organic certification is driven by the market incentives (higher demand and market prices and therefore profits) and the perceived environmental and consumer health benefits of organic tea management. The greater interest towards organic certification aligns with the broader goals of the country's tea industry.

The fewer percent of farmers that shared a disinterest or inability to transition ascribed this attitude to the high requirements of organic certification. The transition is explained to be a costly investment, considering the time and energy needed to learn the strict regulations and relearn their management practices. While these barriers to enter the organic market mentioned are often discussed at the farm level, they also reflect deeper structural issues within certification systems. In political ecology, environmental certifications such as organic or VietGAP certification are understood not only as tools to promote sustainable practices, but also as mechanisms to influence farmer behaviors. According to Otto & Mutersbaugh (2015), by providing incentives and redefining production standards, these schemes subtly shape farmers' (and consumers´) thoughts and behavior as certification tends to reproduce a marketable version of nature. This reinforces the idea that organic produce is worth more than conventional. Some farmers in this study explained that they lacked the financial means to make the shift on their own, and while cooperatives help to ease the transition by pooling resources, this also highlighted how access to such networks and more resources determines who can participate in organic farming and who is left behind.

4.1.2 Gendered dynamics in the tea farms

The female and male respondents from Dai Tu reported patterns of gendered and non-gendered labor in relatively similar proportions, indicating broadly shared perceptions of task division. The findings suggest that traditional gender norms continue to shape roles: men were associated with strength and machinery, while women were linked with meticulousness, harvesting, and marketing —reflecting patriarchal frameworks that tie masculinity to technology and symbolic power

(Fischer et al. 2021). Even when some of the respondents described gender divisions as complementary or equal, the observed pattern across farms of the division of labor suggest persistent gendered expectations and culturally embedded assumptions about strength, skill, and task appropriateness that help sustain these gendered hierarchies.

Future research should examine these dynamics, as overlooking them could perpetuate inequalities and affect both rural livelihoods and agricultural sustainability (Kawarazuka & Prain 2019; Nhat Lam Duyen et al. 2021). Addressing the gendered labor requires holistic strategy: transforming societal and household norms that enforce gender roles, implementing affirmative measures like quotas, targeted training and equitable access to resources for women farmers, and strengthening of gender-mainstreamed policies through gender-responsive design and continuous intersectional labor market monitoring (United Nations in Viet Nam 2023). While this study only briefly touches on gender dynamics in Northern Vietnamese tea farms, the observations suggest that these dynamics may influence the adoption and sustainability of farming systems (like organic farming).

4.1.3 Climate change perception in tea farms

Farmers in this study consistently reported more intense sunshine, increased temperatures, shorter winters, longer droughts and more intense rainfall—stressors that directly affect tea productivity and quality. Recent climate projections have highlighted significant risks for tea production, a climate-sensitive crop and a vital livelihood in many areas. In the face of extreme drought events, irrigation is inevitably going to be of higher demand, especially for tea plants that are predominantly rain-fed or dependent on water from streams and ponds like the farms in this study. Projections estimate that by 2100, the water demand for Vietnamese agriculture is said to increase double to triple times that of 2000 (Food and Agricultural Organization 2012). Another study on tea suitability under various climate change scenarios in Van Chan district, Northwestern Vietnam, found that by 2050, low-elevation areas will likely become less suitable for tea cultivation because climate change is forecasted to cause greater mean diurnal range, moving temperature fluctuation outside the optimal range required for tea cultivation (Pham et al. 2023). This shift raises critical concerns for tea-growing areas like those in this study region where tea is predominantly cultivated at lower altitude(farms in studied were all located <200m). These areas may face rising pressure as climate suitability declines, potentially threatening the region's long-standing tea legacy and smallholder incomes.

4.1.4 Agroforestry potential in tea farms

Nearly all farmers (49/50) rejected the idea of agroforestry, primarily due to concerns that intercropping with trees would lead to light and nutrient competition, ultimately lowering yields. Tea is predominantly cultivated as a monocrop, particularly in Vietnam, shaped by market pressures and input-intensive production models. However, in regions like Thai Nguyen, where climate variability is increasing, integrating shade trees within climate-smart agriculture frameworks may offer a promising approach to enhance resilience (Mohotti, Pushpakumara & Singh 2020). Tea is naturally an understory plant, and early observations noted that shade trees in plantations mimic its natural habitat (Eden, 1958). Intercropping tea with shade-providing species like loquat, citrus, gingko have shown positive effects on soil quality— raising soil pH, organic matter, and nutrient availability (N, P, and K) — and regulates microclimate by buffering temperature fluctuations and regulating tea pests) (Tian et al. 2013; Zhang et al. 2017b; Wen et al. 2020), which is especially relevant under climate related challenges described by the farmers. Tea requires shade and is susceptible to photoinhibition under high photosynthetically active radiation (PAR) which reduces photosynthetic efficiency. Moderate shading (e.g. 35%) increases photosynthetic rates, whereas tea exposed to strong sunlight shows photoinhibition on sunny days as opposed to cloudy days. Furthermore, shade cultivation can alter metabolite profiles, enhancing antioxidant activity compared to monoculture tea (Ku et al. 2010). Overall, moderate shading may mitigate extreme climate effects and improve tea physiological performance.

Despite these ecological arguments, farmer resistance to intercropping reflects more than just agronomic considerations—it also reveals the persistence of a deeply rooted monocultural logic. As Kumpf (2021) argues, the adoption of organic practices does not necessarily challenge the "plantation" system's underlying logic; rather, it can reinforce it. In fact, yield and reputation remained the farmers' primary concerns across all systems. This suggests that even within organic frameworks, production continues to follow a monocultural, yield-driven logic. When organic transitions prioritize productivity and the removal of "unprofitable" species such as pests or weeds, they risk replicating the same extractive mindset as conventional farming. Similarly, Tsing (2015) discusses how practices framed as ecological or sustainable often remain entangled in capitalistic supply chains that prioritize control and marketability. Organic agriculture, in this view, becomes not a radical ecological alternative, but a rebranded product marketed as sustainable while still operating with monocultural ontology. This persistence of monocultural logic has broader societal implications. It limits the transformative potential of sustainability, reinforcing systems that prioritize market conformity and short-term yield over ecological diversity and long-term resilience.

4.2 Chemical compositions

4.2.1 Effects of farming systems

The principal component analysis biplot showed distinct clustering patterns between locations. The differences seen between systems was particular for conventional farms at Phu Xuyen whose farms were situated on soils with different texture than the organic farms, and which also had disproportionately higher zinc levels than the other farms altogether. Organic farms in general had more homogenous soil properties, clustering more tightly along PC1 (probably due to shared management styles following the strict regulations of organic system). Organic carbon was significantly higher in organic farms, likely due to the use of organic inputs such as manure and compost. While soil acidity and organic carbon showed interaction effects between system and location, soil texture evidently cannot be altered by management. The observed differences in soil texture therefore are more likely due to the natural properties of the soil, not the type of farming system. This suggests that the observed differences depend on the combination of location and system rather than the system itself.

The pH of the sampled soils in this study, measured using potassium chloride (KCl) extraction, ranged from 3.05-3.64. pH KCl values are typically lower than pH measured in water (H_2O), and a study on Acrisols in Vietnam reported an average difference of approximately 0.4 units between the two methods (Tho & Hoa 2017). This suggests corresponding pH H_2O values of approximately 3.5-4.1, which remain below the commonly reported optimal pH range for tea-growing media of 4.5-5.6 (Hajiboland 2017). Tea roots acidify the culture it grows in through a process of proton release during aluminum uptake (Saito & Ikeda 2012; Wan et al. 2012)—reducing the soil's adsorption capacity for heavy metal ions. The enhanced bioavailability of heavy metals in these conditions underscores the need for greater attention to such risks in tea cultivation. The continuous use of ammonium-based fertilizers is another known cause of higher soil acidity in tea plantations (Wang et al. 2020; Rebello et al. 2022). Although organic inputs can contribute to buffering soil acidity, their effect may be insufficient to counteract cumulative acidifying impact of long-term nitrogen fertilization. On the other hand, high acidity in organic soils could be a result of newly established farms not yet accumulating the benefits of organic inputs and its buffering capacity for acidic soils (Ye et al. 2022).

The low potential cation exchange capacity levels found in the soils is typically indicative of sandy or kaolinitic soil like those usually found in the study region (Weil 2017; Chien et al. 2020). These expected low levels of cation exchange capacity are likely even lower due to the highly acidic conditions observed. This means the results represent the potential cation exchange capacity—the exchange sites that become active only under less acidic conditions. As a result, the reported cation exchange capacity values likely overestimate the soil's true nutrient-holding capacity in its native acidic state. Given that most soils in the study were classified as sandy clay loam, they are inherently low in nutrient -holding capacity. Moreover, when combined with low pH and base saturation, these properties increase the soil's vulnerability to nutrient leaching and aluminum-dominated exchange sites. Such conditions highlight the importance of organic matter management and the potential need for liming to improve soil fertility and nutrient retention.

4.2.2 Effects of farming systems on trace elements in soil

There was a significant difference between organic and conventional soils in the available or total concentration of metals aluminum, copper and zinc. Organic soils in general had a greater content of aluminum in the soils. While the QCVN does not advise a limit for aluminum level in soil, it is a cornerstone trace element for the tea plant as tea has an affinity for aluminum , meaning that it accumulates aluminum without exhibiting toxicity symptoms (Carr et al. 2003). In fact, the presence of Al promotes the growth of tea bushes and total root length is positively correlated with aluminum concentrations in the root system (Hajiboland 2017). The mechanism by which tea plants tolerate aluminum involves storing it either in chelate complexes or adsorbed in organic matter (Zhang et al. 2018), which could explain why organic systems—with higher soil organic —showed higher exchangeable aluminum in their soil.

The levels of copper in soil found in this study are considered low concentrations, ranging from 1.34-8.87, typical of highly acidic, leached, and weathered agricultural soils (Antoniadis & Golia 2015). Copper is an essential trace element for both plants and animals and the acidic tea soils can increase copper bioavailability, thereby influencing plant uptake (Zhang et al. 2006). Conventional systems in this study showed higher levels of copper than organic soils, which could be due to the accumulation of copper from agricultural inputs such as fertilizers, animal manure and fungicides (Jin et al. 2008).

While total zinc content can indicate the extent of soil contamination, it is less useful assessing environmental impact due to the plenty chemical forms zinc can take—each differing in bioavailability, phytotoxicity and mobility (Baran et al.

2018). Zinc is a necessary element for the growth of plants and animals when not found in excessive concentrations (Li et al. 2021). Identifying the source of zinc in this study is challenging due to the lack of baseline data and no significant correlation was observed between soil pH and zinc concentration, suggesting that acidity alone does not explain the elevated zinc levels. Zinc levels were high across all locations and systems relative to the QCVN permissible limit. While zinc concentrations differed significantly among systems and locations, the effect of system varied depending on the site. This suggests that the influence of cropping system on zinc may be confounded by inherent soil properties. The study region has plenty metallurgy potential, and it is also possible that the high level of zinc originates from the natural turnover in rock-soil plant systems. In fact, 20 km away from the study areas is Nui Phao Tungsten mining site situated. Hoang et al. (2020) found that the soils in Thai Nguyen were naturally of high concentration of zinc (and copper), reaching levels of ecological risk, and that the origin of the zinc most likely is from the sedimentary rock. In extreme exposure levels of zinc not only are microorganisms disrupted in nutrient cycling and soil fertility but so is aquatic life if zinc makes its way into water bodies (Zhang et al. 2012). However, fertilizers, waste disposal or sewage sludge applications and industrial pollution are the main source of zinc pollution in agriculture (Alloway 2013; Van et al. 2024), thus management cannot be ruled out as an explanation to the high zinc levels. At Phu Xuyen, where zinc levels were nine times above the permissible limit, the high levels are consistent with the confirmed use of pig manure, which is commonly enriched with zinc in Vietnam. Some farmers were even observed applying 2–10 times more zinc than the pigs require (Sơn 2020).

4.2.3 Soil correlations

As expected, organic carbon showed a strong negative correlation with pH, suggesting that more acidic soils tend to accumulate organic matter—likely due to slower decomposition rates and greater stabilization of organic complexes under low pH (Hassink 1997; Baldock & Skjemstad 2000).

The positive correlation of aluminum with potential cation exchange capacity, organic carbon, and clay content is consistent with its affinity for fine particles and organic surfaces in acidic environments. Aluminum was also positively correlated with total nitrogen, which may reflect their common association with soil organic matter, as nitrogen is a major constituent of organic matter.

The base cations potassium, calcium, magnesium exhibited strong positive correlations with each other and with zinc and copper. The Phu Xuyen farms, particularly those under conventional system, strongly influence the overall zinc–copper correlation, indicating that the observed relationship may be largely driven by these specific farms rather than representing a general pattern across all locations and systems. The strong correlation between zinc and copper also suggests that they may originate from similar sources, such as pig manure-based fertilizers or feed additives commonly used in livestock production. However, the negative correlation between organic carbon and both calcium and magnesium may indicate cation leaching or competitive binding under strongly acidic conditions where aluminum and hydrogen dominate exchange sites. This pattern suggests that these soils with could be prone to multiple nutrient deficiencies in the future, highlighting the importance of monitoring and managing soil fertility to sustain tea productivity.

4.2.4 Effects of farming systems on tea leaf composition

The tea analyzed in the study showed relatively stable levels of secondary metabolites across the systems and locations. Total polyphenols, however, were significantly different across the locations. Secondary metabolites, amino acids and caffeine are widely associated with flavor and health benefits (Yu et al. 2014) though interpreting their absolute concentrations is not always straightforward and there is no global standard that defines tea quality. The optimal balance of compounds and the flavor profile it lends to tea is highly dependent on cultural and consumer preference. Caffeine is an important secondary metabolite produced in tea plants. While there is no Vietnamese standard for how much caffeine there should be in green tea, the common finding is that green tea leaves contain about 2-5% is like the caffeine content found in this study with levels ranging from 3.15% to 4.67%. According to TCVN 9740:2013 - the national standard for green tea, all tea samples in this study met the quality requirement of polyphenol content in dried tea ≥ 11% of dry tea weight). The same can be said for catechin content, wherein the levels in the study all met the minimum standard of 7% total catechins required by TCVN 9730 for tea quality. It's important to note that secondary metabolites may change with the season the tea is picked. For example in a study by (Mai et al. 2012) on teas from Thai Nguyen, Phu Tho, and Moc Chau it is found that polyphenol content varied by season, being highest in summer - autumn and lowest in spring.

In terms of metal concentrations, copper levels were significantly different across the locations. In plants, disease may arise from both copper deficiency and excess. When copper in plant tissue fall below 4ppm, deficiency symptoms occur, potentially affecting photosynthesis, respiration, disease resistance and other physiological processes (Hodges 2010). Yet, most leaves in this study showed moderate accumulation of copper and contained sufficient copper concentrations above the deficiency threshold. It is important to highlight that the conventional farms at Tan Son showed copper levels in leaves below the limit of quantification (and are at risk of copper deficiency). Even with more exchangeable aluminum in the soils of organic farms (than in the conventional ones), the tea leaves from these farms contained lower aluminum concentrations. The significant differences between systems, locations and their interactions further show that aluminum behavior is highly context dependent. Thus, the lower aluminum in organic leaves may reflect not only that organic management may promote stronger aluminum binding in the soil, reducing its bioavailability and subsequent uptake by plants, but also the influence of site-specific conditions that limit this bioavailability. In this study zinc concentrations in tea leaves ranged from 129-1286 ppm, far exceeding the critical toxicity threshold of approximately 83 ppm for plant leaves; such elevated zinc levels are known to significantly affect plant metabolism, including the biosynthesis of flavonoids in tea leaves (Venkatesan et al. 2006; Zhang et al. 2017a).

Nitrogen levels were significantly higher in organic tea leaves; however, this effect was not consistent, which is indicated by a significant interaction effect of system x location. Further research is needed to assess the nitrogen uptake and use efficiency (NUE) of tea plants in organic versus non-organic systems. However, these results could reflect enhanced soil fertility under organic management and a shift in the primary source of nitrogen after fertilization. In a study by Lu et al. (2025), organic fertilizer was found to be correlated with ammonium (NH_4^+), and the gradual release from decomposing organic matter was linked to higher leaf nitrogen concentrations.

4.2.5 Leaf correlations

The negative relationship between leaf copper and caffeine content could be explained by the effects of copper toxicity on nitrogen metabolism in tea plants. Excess copper in leaves can disrupt cellular homeostasis by generating reactive oxygen species, thus damaging the cellular membrane, enzymes and other components essential for normal metabolic function (Akhtar et al. 2025). Under copper toxicity, plants typically show overall weakening of nitrogen metabolism and assimilation (Dai et al. 2024). Since caffeine is a nitrogen rich alkaloid, the plant becomes less capable of sustaining high caffeine production (Ashihara et al. 1997).

The observed positive correlation between aluminum and copper in tea leaves likely reflects their shared environmental availability and overlapping physiological pathways. Both metals become more soluble in acidic soils typical of tea plantations like the ones in this study, thus increasing root uptake (Dai et al. 2024). Tea plants manage both metals using similar defense systems to detoxify metal ions thus leading to co-accumulation (Yadav & Mohanpuria 2009).

These results suggest that the accumulation of metals such as copper and aluminum, together with their impact on nitrogen- rich secondary metabolites like caffeine, may influence tea leaf chemistry and quality. Understanding these metal interactions could help guide soil and fertilization management to ensure or regulate the presence of compounds and improve tea quality.

4.2.6 Effects of farming systems on the bioaccumulation factor of trace elements in leaves

The bioaccumulation factor of aluminum, zinc, and copper indicated moderate to high accumulation potential, most likely influenced by the low soil pH. While the hazard quotient (HQ) values indicate that current metal levels are within safe limits for consumption, the high BCF values imply potential risks if soil heavy metal concentrations were to increase over time.

4.2.7 Challenges in current land management

Soil pH was low, and zinc and aluminum levels were excessively high across all soils, which can negatively affect crop growth, soil health and pose risks to human consumption. Solutions could include improving agricultural input efficiency by increasing pH levels through liming (Tal 2018). Consequently, simply scaling up organic practices does not automatically ensure sustainable production; the interactions between soil chemistry, spatial variability, and environmental pressures must be carefully considered. Recognizing these constraints offers an opportunity to develop targeted, context-sensitive strategies that improve soil fertility, optimize tea quality, and support long-term sustainability in Vietnam’s tea sector. Sustainable transformation of Vietnam’s tea sector will not emerge from certification alone; it requires actionable and equitable agricultural policy and the deliberate integration of ecological, social, and economic realities.

5. Conclusion

This study explored tea production systems in Thai Nguyen, Vietnam, to evaluate the implications of organic and conventional management for soil and tea leaf composition, and farmer livelihoods. Through a mixed-methods approach combining chemical analyses, statistical testing, and farmer interviews. The findings reveal that while organic systems show some environmental advantages, the interaction between farming system and location ultimately is the strongest driver of whether a system delivers its intended benefits—meaning the same system can produce very different outcomes depending on local conditions. The study highlights the need for revising farm fertilizer regimes and adopting soil pH correction measures to maintain soil productivity, and mitigate heavy metal stress.

The findings show that farmers possess an optimistic attitude towards organic farming and generally perceive that organic management of tea produces a higher quality than conventionally grown tea. Market demand and higher profits generally drive farmers' motivations for adopting an organic system.The transition to an organic system is however not equally accessible to all farmers as participation is hindered by higher costs, including certification, increased labor demands, and efforts required to comply with strict certification regulations including modifying beliefs or practices. Gender roles in the tea community studied are shaped by traditional norms where men were typically associated with strength and machinery, and women were linked with meticulousness, harvesting, and marketing. The farmers reported a dual burden of climate stress—not only lowering tea yields but also having to adjust their practices in response to changing climate conditions, often without a choice. The study also emphasizes the high potential of tea agroforestry systems as a climate-smart approach; however, most farmers are hesitant to adopt them due to concerns about resource competition among crops.

Notably, organic farms tended to produce the same tea yield (kg ha^{-1}) as conventional farms. In terms of the soil properties, first and foremost, all the tea farms had highly acidified soils and had exceedingly high levels of Zn, underscoring the need to improve soil management and fertility. Newly established organic systems show promising environmental outcomes, with higher soil organic carbon and lower Zn and Cu concentrations, however organic fertilizers can be a source of heavy metal pollution.

Although Al levels were higher in organic farm soils, there was lower bioaccumulation in organic tea leaves. While secondary metabolite levels did not differ significantly among cropping systems, Cu accumulation in tea leaves may affect caffeine content, highlighting the role of metal stress in shaping leaf chemistry and tea quality. The calculations showed that there is no heavy metal risk to humans from consumption of the teas analyzed.

6. Limitations

Several limitations of this study should be acknowledged.

First, while farmer interviews were successfully conducted, they were constrained by language barriers. The interviews were carried out in written form with the support of a translator, which limited the researcher's ability to engage via spontaneous dialogue and follow-up questions. Although the researcher was present during the interviews, real-time interaction was minimal, potentially limiting the depth and nuance of qualitative data collected.

Second, due to limited time, leaf and soil sampling occurred at different seasons. While soil samples were collected directly by the researcher following a standardized protocol, assistance from local collaborators was required for leaf sampling.

Third, the organic farms are considered newly established and may not fully reflect the system's effect on soil and tea properties.

Fourth, information on the components of each fertilizer, as well as the volume and frequency of their application by farmers, is unavailable. Although these details were included during the interviews, the responses were unclear and therefore could not be used for drawing conclusions.

Fifth, infusion rate was not considered when calculating the EDI. Thus, the EDI might be less depending on the rate of heavy metal seeping into the water.

Lastly, due to communication challenges and limited access to laboratory specifications in advance, the detection threshold for cadmium was discovered to be higher than the permissible level set by TCVN. Had this limitation been identified earlier, the budget allocated for cadmium testing could have been redirected to another relevant heavy metal.

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Popular science summary

Organically Grown Tea: Better for the environment, not always for the flavor

Many people assume that organic tea is always tastier or healthier than tea grown by conventional methods. This research in Vietnam shows that while organic practices improve soil quality, they don't automatically make the tea leaves better in taste or chemical composition. In other words, when you pay extra for organic tea, you're investing more in environmental benefits and sustainability than in superior tea quality. Notably, the results suggest that the interaction between farming system and location is the strongest driver of whether a system delivers its intended benefits—meaning the same system can produce very different outcomes depending on local conditions.

Farmers are motivated by market incentives and perceived health benefits when considering organic farming. Yet, certification is costly and time-consuming and access to cooperatives and resources strongly influences participation. These challenges intersect with broader realities— including climate change and gender roles—that influence how farming systems perform on the ground. Farmers in the region face multiple environmental stressors: hotter temperatures, shorter winters, longer droughts and heavier rainfall. At the same time, labor patterns remain strongly influenced by tradition: men typically handle machinery and heavy work, while women focus on harvesting and marketing. Together, these environmental and social pressures affect farmers' capacity to adopt organic practices which often require more labor, knowledge and resources to make the shift.

To improve resilience under climate stress, one potential response is agroforestry (integrating trees with tea), yet adoption remains low due to concerns about crop competition and deeply ingrained monocultural beliefs. In practice, all farms in the study— organic and conventional alike— follow a monocultural plantation model that prioritizes yield over ecological diversity. Nevertheless, yields were similar across both systems, even though organic farms in general required more land and labor. With climate projections indicating water stress and declining suitability in low-elevation tea growing areas, this greater land demand sharpens the management challenge for organic systems.

As farmers navigate these pressures aboveground, the plant and soil qualities play a decisive role in the effectiveness of organic farming. Tea grows best in slightly acidic soils and tea plants actively contribute to this acidity through a mechanism native to tea. In our study, soil pH was in fact even lower than recommended. As pH drops, heavy metals become more mobile and easier for plants to absorb. Such low pH not only risks increasing metal uptake but also threatens soil fertility, by enhancing leaching, losses of beneficial nutrients and in extreme cases— aluminum toxicity. Tea is unusual in that it tolerates high aluminum levels and can even be stimulated by them, storing the metal in its roots or binding it with organic matter. Interestingly, the organic farms in this study showed higher aluminum concentrations in their soils but lower aluminum in the leaves— suggesting that organic matter may help immobilize aluminum in the soil, reducing the amount that ends up reaching the foliage.

Zinc levels were strikingly high—well above the national safety limit— and were strongly correlated with copper, particularly on the Phu Xuyen farms which seemed to drive the relationship. The likely source is pig manure which the farmers claimed to enrich their soil with, given that pig feed additives are often applied in excess. Combined with the acidic soils, this poses clear environmental risks to soil and water. Despite these high soil concentrations, the tea leaves remained safe for consumption, so drinkers are not at risk. Copper in leaves also played a role in tea chemistry: tea leaves with too much copper had lower caffeine. Excess copper in the leaves stresses the plant and reduces caffeine production, making it important to keep an eye on copper for tea quality.

Ultimately, paying extra for organic tea may support soil health, environmental sustainability and long -term resilience, rather than guaranteeing superior leaf quality. Real transformation in Vietnam’s tea sector will require coordinated efforts in ecological diversity, soil management and holistic farmer support systems, alongside incentives for adopting sustainable practices.

Appendix 1

Interview questions

Farm collective name	
Family-owned farm?	**Yes / No**
Land-owner	
Sex and Age Bracket of Participant:	**M / F** Age : _______
Number of farm workers	
Tea Variety	
Harvest seasons	
Plantation Size (hectare)	
Number of Tea Plants in plantation	
Tea yield / year	
Location coordinates Slope of land	

Likert scale Agreements Statements:

Circle one answer per statement.

(1 - Strongly Disagree) (2- Disagree) (3 - Neutral) (4 - Agree) (5 - Strongly Agree)

I do not see any potential or added benefit in organic farming	1	2	3	4	5
Fertilizers can pose health risk on my crops	1	2	3	4	5
Fertilizers can pose health risk to consumers	1	2	3	4	5
My farm has experienced changes in climate, like changes in rainfall and flooding	1	2	3	4	5
I feel supported by the government to engage in organic farming practices.	1	2	3	4	5
I would like to learn more about organic farming and fertilizers.	1	2	3	4	5
It is easy to transition to organic farming.	1	2	3	4	5
Information about fertilizer and usage is easy for me to access.	1	2	3	4	5
VietGAP produces better quality tea than conventional farms	1	2	3	4	5
Organic farms produce better quality than conventional farms	1	2	3	4	5
VietGAP farms produce better quality tea than organic farms.	1	2	3	4	5

1. How long have you been growing here? Do you know what this land was before you started cultivating here?
2. How do you manage your farm based on age (ages of tea)? Do you plant them by seed?
3. How often do you harvest a single plant in a year? Which seasons?
4. What is your criteria of choosing species of tea to grow?
5. How many times do you prune your plants per year? How much biomass is removed?
6. Do you use the pruned biomass? Do you use mulch on your soil (e.g. plastic/ biomass/ grasses)?
7. Do you process and distribute the tea yourself?
8. If NO, do your distributors enforce any requirements on your production?
9. What is your main goal and priority of your tea harvest? For ex. yield

10. Do you use more than one kind of fertilizer? What are they? please be specific of brand name if you remember, and type of animal manure
11. How did you decide to use this fertilizer?
12. Why do you prefer organic / synthetic fertilizers? IF using both, why not only choose one type?
13. Can you tell me step by step how you prepare your fertilizer, **how and where you apply it?** Do you cover the fertilizer after?
14. Do you disturb the topsoil in any way at any time, for example, weeding or tilling How deep do you disturb the topsoil? ***
15. For each fertilizer you use please tell me, How much do you apply kg/ha during each application?
16. Do you have a fertilizer schedule? What do you take into consideration when building this schedule? What about climatic factors like weather?
17. How many times in a year do you fertilize?
18. Do you apply other inputs into your soil OR leaves?
19. How often do you irrigate your crops?
20. Do you experience droughts?
21. Have you noticed any climate changes? What kind?
22. How does this affect your farming practices?
23. Do you as a MAN or WOMAN experience any gendered differences like hardships, or advantages in farming? How does climate change affect this?
24. How long have you had your organic certification? What benefit does this have for you? Are there any drawbacks?
25. If NONE, are you interested in having this certification? Why or why not?
26. Have you noticed any changes in the market demand for organic tea and/ or conventional production? What are they?
27. Do you receive any government subsidies (benefits) for pursuing organic agriculture certification?
28. What is your main issue on the farm? Why do you think so? For example: pests, nutrient deficiency, less yield, labor intensive, expensive materials
29. What are the main pests you have an issue with? What do you do to combat them? For ex. Fungi, Insects, Bigger animals

Appendix 2

Soil analyses

Soil texture

The soil's texture was quantified in relative percentage of silt, clay, fine sand and coarse sand. The sand values were then combined to simplify the analysis. Each observation point was then classified on a USDA soil texture triangle.

Air dried soil that was sieved through a 2 mm mesh and 20 g was then placed into a 500 ml glass beaker and combined with 50 ml of water. After, 10 ml of 30% H_2O_2 was added and then the beaker was covered with a watch glass and left to soak overnight. When finished, the watch glass was removed, and the beaker was gently heated in a water bath of about 70-80 °C. While heating, 1 ml of 30% H_2O_2 was gradually added at a time until the color of organic matter has disappeared. Then a small amount of water was added and gently heated for 1 hour to remove the residual H_2O_2. After it has cooled down, the mixture was centrifuged, and supernatant was decanted to completely remove the H_2O_2. Finally, the treated sample was concentrated to dryness and oven-dried to constant weight at 105 °C. To separate the particle size fractions, the dried treated samples were soaked overnight in 20 ml dispersing solution ($Na_4P_2O_7$, 0.05 M). Then it was transferred to a 500 ml beaker, diluted with 250 ml water and shaken for 16 hours using a rotary shaker. The resulting suspension was used to determine the particle size fractions: coarse sand (2-0.2 mm), fine sand (0.2-0.02 mm), silt (0.02–0.002 mm), and clay (<0.002 mm), using the sedimentation method, following the TCVN 8567:2010 protocol.

Soil pH_{KCl}

Approximately 5 g of air-dried soil that has been sieved through a 2 mm mesh was weighed. This was then transferred into a 50 ml polyethylene bottle (with a tight-fitting cap) where 25 ml of 1 M KCl solution was added to obtain a soil-to-solution suspension at a 1:5 (m/V) ratio. The suspension was then shaken for 60 minutes at 20± 2 °C. The pH of the suspension was immediately measured using an electrode.

Electrical conductivity (EC)

Air-dried soil samples (20 g) were placed in a 250 ml polyethylene shaking bottle. Distilled water with a conductivity not exceeding 0.2 mS/m at 25 °C was added at a soil-to-water ratio of 1:5 (m/V) to dissolve the electrolytes. The bottle was sealed and placed horizontally on the shaker for 30 minutes. The suspension was then filtered through a medium-speed quantitative filter paper, following

TCVN 6650:2000. Lastly, the electrical conductivity was measured using a conductivity meter which was adjusted to 25 °C.

Exchangeable aluminum (Al^{3+})

A 1 M KCl solution (pH 5.8-6.0) was used to extract the soil at a soil-to-solution ratio of 1:10 (m/V). The suspension was shaken for 30 minutes and filtered through slow-flow filter paper. Then, exchangeable Al^{3+} in the extract was determined by acid-base titration with standardized 0.01 M NaOH, using phenolphthalein as an indicator.

Cation exchange capacity (CEC)

Five grams of soil was weighed (accurate to 0.01 g) and mixed with 5 to 10 g of clean sand (acid-washed quartz sand, following TCVN 8568:2010) and the mixture was transferred into an exchange column. The cation exchange sites were saturated with NH_4^+ using 200 ml of 1 mol/L ammonium acetate (NH_4CH_3COO) at a flow rate of about 25 drops/min for a continuous exchange period of 120 to 180 minutes. Then the excess, or non-adsorbed NH_4^+ cations were washed away using 100 ml of 80% ethanol at the same flow rate for 90-120 minutes. Immediately after the washing process, the adsorbed NH_4^+ was displaced by percolating 100 ml of 10% KCl solution (pH=2.5) through the column for 120 to 180 minutes at the same flow rate. The released NH_4^+ was then determined by Kjeldahl distillation and titration with 0.01 M H_2SO_4, and the CEC was calculated from the amount of acid consumed, expressed as cmol(+)/kg soil.

Determination of exchangeable potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+})

A minimum of 10g (accurate to 0.01g) of soil was weighed and mixed thoroughly with 10g of clean acid-washed sand. The mixture was then placed into an exchange column where the exchange sites were saturated with NH_4^+ using 100 ml of 1 mol/L ammonium acetate (NH_4CH_3COO) at a flow rate of about 25 drops/min for a continuous period of 120 to 180 minutes. The collected solution was then used to determine the concentrations of K^+, Ca^{2+}, and Mg^{2+} using a flame atomic absorption spectrophotometer (FAAS).

Total organic carbon (OC)

Soil was first weighed at 0.5 g using an analytical balance and placed into a 250 ml Erlenmeyer flask. Ten ml of 0.1667 M potassium dichromate solutions was added to the soil using a pipette then shaken to create a well-mixed solution. Quickly, 20 ml of concentrated sulfuric acid was added and shaken. After leaving it for 30 minutes, 100 ml of water and 10 ml of phosphoric acid (H_3PO_4) was added and then allowed to cool again. Lastly, 0.3 ml of N-phenyl anthranilic acid indicator was added, and the excess dichromate was titrated with a 0.5 M Mohr's salt solution ($FeSO_4(NH_4)_2SO_4.6H_2O$).

Total nitrogen (TN)

The Kjeldahl distillation technique was used to determine the TN. Firstly, 0.2 g of soil was weighed into a 100 ml digestion flask. Then, 4 ml of salicylic acid/concentrated sulfuric acid (prepared by dissolving 25 g of salicylic acid in 1 liter of concentrated sulfuric acid) was added and the mixture was let to stand overnight. After, 0.5 g of sodium thiosulfate was added to the flask where it was also carefully heated on a digestion block until the foaming ceased. When the flask had cooled, 1.1 g of a catalyst mixture (containing potassium sulfate) was added and heated again until the digest became clear. Finally, after cooling, 20 ml of water was slowly poured in to convert the insoluble residue into a suspension and transferred into a distillation apparatus used for N distillation. The distilled ammonia was collected in a boric acid solution and the total N content was determined by titration with standardized hydrochloric acid.

Available phosphorus (P):

Available phosphorus was determined following TCVN 8942:2011 (Bray II method). Five g of soil sample was placed in a 100 ml Erlenmeyer flask and 35 ml of Bray II extractant* was added. The mixture was shaken immediately for 40 seconds and quickly filtered using slow-filtering paper. The phosphorus concentration in the filtrate was determined colorimetrically: ascorbic acid was added as a reducing agent, and after the color was allowed to develop for 30 minutes and the absorbance of the colored solution measured using a spectrophotometer at a wavelength of 882 nm or 720 nm was measured.

*Bray II solution: mixture of 30 ml of 1 M ammonium fluoride with 200 ml of 0.5 M hydrochloric acid, then diluted with distilled water to 1000 ml.

Determination of soil cadmium (Cd), copper (Cu), and zinc (Zn):

This method was based on atomic absorption spectrophotometry (AAS) following the protocol TCVN 6496:2009. Approximately 2 g of soil sample (to the nearest 0.001 g) was weighed and placed into a 250 ml digestion flask. The sample was moistened with 0.5–1.0 ml of water while mixing, then 21 ml of 37% concentrated hydrochloric acid (HCl) was added, followed by 7 ml of 65% concentrated nitric acid (HNO_3). The digestion process was left to be carried out for 2 hours, then the resulting solution was filtered and collected for analysis. The concentrations of Cd, Cu, and Zn were measured using a flame atomic absorption spectrophotometer at wavelengths of 228.8 nm, 324.8 nm, and 213.9 nm respectively.

Appendix 3

The following report was written and translated by Vu Kim Dung.

Leaf analyses

Leaf preparation for metal content analyses

Samples were delivered to the laboratory, homogenized and placed in an oven at 105 °C for drying. Each bag had leaves with a weight of 300 g.

Determination of total nitrogen

A 0.1 g of milled leaf sample was used. Digestion and distillation followed the same Kjeldahl procedure as described for soil, except a smaller catalyst amount (¼ tablet) and 10 ml boric acid were used for ammonia collection. Total N was determined by titration with 0.01 M HCl.

Determination of metal contents

Approximately 0.2 g of dry sample (accurate to 0.1 mg) was weighed into a 100ml Teflon digestion vessel capable of withstanding a minimum pressure of 1.4MPa. Then, 5 ml of concentrated nitric acid (HNO_3, 65%) and 2 ml of hydrogen peroxide (H_2O_2, 30%) were added. The vessel was sealed, and placed into the microwave for 3 minutes at 250 W, followed by 5 minutes at 630 W, then, 22 minutes at 500 W.

The Cd content in the sample was measured using a PerkinElmer 900T atomic absorption spectrophotometer with graphite furnace technique (GFAAS) at a wavelength of 228.8 nm. The Cu, Zn, and Al contents were measured using the PerkinElmer 900T atomic absorption spectrophotometer with flame atomic absorption spectroscopy (FAAS) at wavelengths of 324.75 nm, 213.86 nm, and 309.27 nm, respectively.

Leaf preparation for secondary metabolites analyses

The samples were transported to the processing facility immediately after harvesting, based on the standard tea processing. Here the leaves were placed on a clean, well-ventilated surface where they were subject to withering for 2-3 hours. The leaves are monitored in case of over-withering. Then, samples were dried at 40 °C for to reduce the moisture contents while preserving their bioactive compounds. Plants were monitored for 72-86 hours depending on their moisture level and thickness of the buds, avoiding tea becoming burnt. After drying, leaves were left to cool at room temperature and finally stored in airtight packaging to avoid exposure to light and high humidity. Each bag had leaves with a final weight of 0.5 kg.

Determination of dry matter content

The dry matter content of the tea samples was determined according to TCVN 9738:2013 (ISO 1572), applicable for green tea or black tea. The principle involved drying the tea samples at a temperature of 103 °C ± 2 °C until a constant weight was achieved. The difference in sample weight before and after drying was used to calculate the dry matter content and moisture content by mass.

Determination of caffeine content

The caffeine content of the samples was determined using high-performance liquid chromatography (HPLC). First, 1.0 g was weighed (accurate to 0.001 g) into a round-bottom flask, and 4.5 g of magnesium oxide and 300 ml of water was added into the flask and mixed well. The flask was then weighed with its contents (accurate to 0.1 g) – this was m_0. A condenser was attached, then the flask was placed on a heating plate, and heated quickly to boiling. Then, the heat was reduced and simmered gently for 20 minutes, occasionally the flask was swirled. The flask was removed from the heat, allowed to cool to room temperature, and weighed again (accurate to 0.1 g). *(Note: The mass of the cooled flask and its contents must match the previously recorded m_0. If there was any discrepancy, water was added to reach m_0, then mixed thoroughly.)* The mixture was let to settle, then approximately 10 ml of the supernatant was taken and centrifuged at 6000 rpm for 5 minutes. 1.0 ml of the filtrate was pipetted into a volumetric flask, diluted to 10 ml with distilled water, mixed well, and filtered through a 0.45 µm membrane. HPLC analysis was then performed under the following conditions:

- Flow rate of mobile phase: 1.0 ml/min
- Column temperature: 40°C
- Mobile phase: Tetrahydrofuran - acetonitrile - buffer solution pH 4.5 (20:25:955), where the buffer was 0.082% sodium acetate adjusted to pH 4.5 using glacial acetic acid
- Column: C18-RP (250 × 4.6 mm, 5 µm)
- UV detector: Set at a wavelength of 275 nm
- Injection volume: 10 µL
- Analysis time: 70 minutes

A linear calibration curve was constructed based on the peak area of the caffeine standard using the HPLC system. The caffeine concentration in the sample was then determined automatically by the system's software.

Determination of catechin content

A 0.2 g of the sample were weighed into an extraction tube, 5 ml of 70% methanol was added, and placed in a thermostatic water bath at 70 °C. The extraction mixture was allowed to equilibrate for 30 minutes, then it was mixed using a vortex mixer. The tube continued to incubate for another 10 minutes in the water bath, mixing again after 5 and 10 minutes. The tube was removed from the water bath and let cool to room temperature. Then, centrifuged at 3500 rpm for 10 minutes. The supernatant was then collected, and the extraction steps were repeated once. The two extracts were combined, 70% methanol was added to make the volume up to 10 ml, and the extract mixed thoroughly. 1.0 ml of the sample extract was taken and diluted to 5.0 ml with a solution of 10% acetonitrile (v/v) containing ascorbic acid and EDTA at 500 mg/ml. Then, filtered through a 0.45 µm membrane. HPLC analysis was performed under the following conditions:

- Flow rate of mobile phase: 1.0 ml/min
- Column temperature: 40 °C
- Mobile phase composition: Channel A: 9% acetonitrile + 2% acetic acid
- 20 µg/ml EDTA; Channel B: 80% acetonitrile + 2% acetic acid + 20 µg/ml EDTA
- Gradient program: 100% Channel A for 10 minutes → 68% A + 32% B for 10 minutes → back to 100% A for 50 minutes
- Column: C18-RP (250 × 4.6 mm, 5 µm)
- UV detector: Set at a wavelength of 275 nm
- Injection volume: 10 µl

A linear calibration curve was created based on the peak areas of the catechin standards (EGCG, EGC, ECG, EC) using the HPLC system. The total catechin content in the analyzed sample was calculated as the sum of the concentrations of EGCG, EGC, ECG, and EC.

Determination of polyphenol content

A total of 100g of each powdered tea sample was extracted using the cold maceration method with 96% ethanol. The extraction was carried out over 72 hours per extraction cycle, repeated three times. The polyphenol content was determined using the Folin–Ciocalteu method and standardized in TCVN 9745-1:2013 (Total Polyphenol content in tea – Colorimetric method using Folin–Ciocalteu reagent). The Folin–Ciocalteu reagent contains phosphotungstic and phosphomolybdic acid complexes, which were reduced by Polyphenols to form a blue colored compound, with maximum absorbance at 758 nm. The Polyphenol content in the sample was directly proportional to the intensity of the color and was calculated as gallic acid equivalent.

Both the extract and the gallic acid standard solution were diluted to concentrations of 10, 20, 30, 40, and 50 µg/ml using methanol. Then the Folin–Ciocalteu reagent was diluted to 10% with distilled water. 1 ml of the sample extract was added to a 10 ml volumetric flask containing 6 ml of distilled water, mixed well, then 2.5 ml of Folin–Ciocalteu reagent was added, shaken thoroughly and let to stand. After 5 minutes, 4 ml of 7.5% Na_2CO_3 solution was added, mixed well, and filled up to 10 ml with distilled water. The mixture was allowed to stand in the dark for 1 hour, then the absorbance was measured at 765 nm. The extraction was repeated three times, and the recorded absorbance values were used to plot a calibration curve for determining the total Polyphenol content in the tea extracts.

The total polyphenol content (TPC), expressed as a percentage of the dry sample weight and measured as gallic acid equivalent (GA), was calculated using the following formula:

$$TPC\ (\%) = \frac{\mathrm{CxVxFx10\hat{}-2}}{m\mathrm{xWk}}$$

Where,

C: Concentration calculated from the standard calibration curve (µg/ml)
V: Volume of extract (ml)
F: Dilution factor
m: Weight of the sample (g)
Wk: Dry matter content of the sample (percentage, %)

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