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The study of the effect on soil fertility and Arabica coffee seed quality under monoculture and integrated farming in Ban Pang Khon, Chiang Rai Province

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ABSTRACT: This research aimed to study the soil properties and the quality of Arabica coffee seeds of the Catimor variety under the agroforestry system with temperate fruit trees in a naturally regenerated mixed and monoculture area at Ban Pang Khon. It was focused on promoting high-quality coffee cultivation in highland areas and maintaining sustainable environmental systems. Randomly arranged sample plots of size 50x20 square meters were established. Soil samples were collected from the same level of depth (0-15 cm) in both monoculture and agroforestry areas. Coffee seeds were randomly collected from each plot, totaling 600 seeds per plot. The results showed that the soil of the single-crop coffee garden is loamy sand, while the mixed-crop soil is a loam soil mixed with sand. The soils in the monoculture and agroforestry areas were slightly acidic to moderately acidic (pH 5.42-5.35). The electrical conductivity (EC) of the soil was between 25.79-27.61 µS/cm, indicating a non-saline soil. The organic matter content (%OM) in the soil ranged from 6.55% to 6.08%. The organic carbon content (%OC) was high, with main nutrient levels: N = 0.38-0.50%, P = 10.37-14.43 mg/kg, and K = 215.04-508.95 mg/kg. The cation exchange capacity (CEC) ranged from 18.53 to 20.22 meq/100g. Soils from the agroforestry area exhibited higher CEC and moisture content compared to monoculture soils, indicating the ability to retain nutrients in the soil and higher soil fertility. Fresh coffee beans from the agroforestry area contained 1,082.56 mg/kg of caffeine, 188.09 mg Gallic acid/g dry weight (DW) of total phenolic compounds, and higher antioxidant activity than coffee beans from the monoculture area, which contained 783.43 mg/kg of caffeine, 135.54 mg Gallic acid/g DW of total phenolic compounds, and 8.60 mg Vitamin C/g DW. Therefore, the agroforestry system for Arabica coffee cultivation has positive effects on soil properties and soil fertility, making it suitable for producing high-quality coffee beans while practicing organic farming principles.

Keywords: soil quality; Arabica coffee; monoculture; integrated farming

Introduction

Coffee is an important economic crop worldwide. Thai farmers have been cultivated coffee as an economic crop in both the northern and southern regions in Thailand. In the northern region, Arabica coffee (*Coffea arabica* L.) is commonly grown, while in the southern region, Robusta coffee is preferred. Specifically, the province of Chiang Rai provides suitable topography and climate conditions for robust coffee growth. The region has over 4,200 farmers cultivating coffee across approximately 41,200 Rai, with an estimated total annual production of 7,525 tons. This

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contributes to income generation through the sale of fresh coffee cherries and processed coffee products, benefiting local farmers. Arabica coffee, known scientifically as *Coffea arabica* L., belongs to the Rubiaceae family. This variety is favored in the northern region and specifically, the Catimor CIFC 7963 variety has been selected by the Department of Agriculture. The global trend in producing Arabica coffee indicates a shift towards more environmentally friendly production systems. Certification systems such as Fair Trade Rainforest, or UTZ has been established to set standards for Organic coffee production (Rengchai, 2015).

The coffee cultivation source, Ban Pang Khon, is located in Huai Chom Pu Subdistrict, Mueang District, Chiang Rai Province. It serves as the origin of the "Pang Khon Coffee" development project, inspired by the royal initiative of Her Majesty Queen Sirikit, the Queen Mother of Thailand, also known as "Mae Fa Luang". Also, the "Father of the 9th Reign", His Majesty King Bhumibol Adulyadej bestowed knowledge of coffee and coffee varieties for the hill tribe people. This transformed their lives, turning them into high-quality coffee cultivators, producing exquisite and uniquely aromatic Arabica coffee of premium quality, recognized worldwide between the years 1974-1979. During the reign of King Rama IX, the Royal Agricultural Research Center was granted royal funds to develop coffee varieties suitable for Thailand's high-altitude conditions, aiming to replace opium cultivation on highland areas. Currently, the Royal Project Foundation continues to promote Arabica coffee cultivation in 24 development centers, including agricultural highland development stations, following the royal initiative, in Ban Pang Khon, Chiang Rai Province.

Various factors, including elevation above sea level, soil fertility, climate, and the surrounding vegetation, influence the flavor of coffee. Therefore, the cultivation process is essential in promoting the unique flavor profile of coffee beans, often referred to as "terroir." However, over the course of 10-20 years of coffee cultivation, challenges arise from intensive chemical usage and pest-related issues like coffee leaf rust, leading to significant deterioration. Farmers may be forced to cut down and replant coffee trees, which typically have a productive lifespan of up to 50 years. Replanting introduces substantial costs to face another critical period of vulnerability in the 4th to 5th year, thus elevating production expenses. This can prompt buyers to seek alternative sources for coffee beans. For successful coffee cultivation, suitable soil conditions are crucial. The ideal soil should allow proper aeration and drainage, as well as prevent waterlogging. It should be loamy with adequate levels of potassium (K) and a pH level ranging from 4.5 to 6.5. Other factors, such as climate, rainfall, humidity, and light intensity, also influence coffee plant growth and productivity.

Given these considerations, it is vital to study soil conditions, chemical properties, and physical attributes within the context of coffee cultivation under the agroforestry system with temperate fruit trees in rehabilitated natural forests (mixed gardens) and single-crop coffee areas. This research aims to evaluate soil fertility and suitability. The gathered data is then used to investigate soil improvement strategies and restoration methods that are suitable for optimizing coffee cultivation outcomes, all within the framework of sustainable agriculture. The objective is to promote good and appropriate agricultural practices (Good Agricultural Extension Practice, GAEP) that align with the significant operational guidelines set by the Department of Agricultural Research, focusing on enhancing productivity and agricultural practices, while also conserving, developing, and utilizing natural resources efficiently as vital factors in valuable production processes. This will lead to strategies for optimizing soil conditions tailored for efficient and effective coffee cultivation. The knowledge gained from this study will be disseminated to coffee farmers in the Huai Chom Phu Sub-district, Chiang Rai Province, aiding them in making informed decisions about coffee cultivation practices and soil improvement. This endeavor strives to enhance the sustainability of coffee farming, elevate the quality of coffee production, and ultimately increase income for farmers in the future.

Methodology

Research area

The research area serves as a prototype cultivation plot in the vicinity of Ban Pang Khon, Huai Chom Pu Subdistrict, Mueang District, Chiang Rai Province. This area belongs to the coffee garden of the community enterprise group 'Ata Farm,' which cultivates Arabica coffee of the Catimor CIFC 7963 variety. The land is utilized for coffee production in two formats, including the agroforestry approach involving cold climate fruit trees in naturally rehabilitated mixed gardens and the single-crop coffee cultivation format in open and spacious surroundings, as presented in Figure 1. These activities were carried out during the period from October 2022 to April 2023.

The method of soil sample collection in the field, the laboratory analysis of soil properties and the detection of residual chemical pesticides in the soil

A soil pit was dug at a distance of 0.5 meters from the coffee tree canopy. The size of the soil pit was 1.0x1.0x1.0 meters (width x length x depth), extending down to the bedrock layer. Soil samples were collected from both the agroforestry and the single-crop coffee plantation area. Each coffee garden provided five soil samples. The collected soil samples from each garden were mixed together, air-dried, and then divided into three piles. Each pile was further divided into four equal portions, from which 1 kilogram was taken and placed in plastic bags. This process was repeated three times for each garden. The laboratory analysis included physical and chemical properties of the soil. The physical properties comprised soil texture and moisture content (%). The chemical properties included pH (soil:water; 1:2), electrical conductivity (EC meter, soil:water; 1:5), organic matter content (%OM; Walkly&Black), organic carbon content (%OC), cation exchange capacity (CEC by NH4Oac pH 7/dilstillation), total nitrogen content (N% by Kjeldahl), available phosphorus content (Bray II extraction), and exchangeable potassium content (AAS). Additionally, the laboratory tests were conducted to detect residual chemical pesticides from the organophosphate, carbamate, organochlorine, and pyrethroid groups in the soil. All laboratory analyses were performed at the Quality Inspection and Standards Product Service Institute, Maejo University, Chiang Mai Province.

The process of collecting coffee bean samples for quality analysis and detecting residual chemical pesticides

Coffee bean samples were collected from within the sample plots, both in the agroforestry and the single-crop coffee plantation area. This sampling was conducted from January to April 2023. In each garden, coffee beans were randomly collected, 600 beans per garden in total. These beans were then weighed and the size of the fresh coffee bean (cherries) was measured for analysis. The purpose of this analysis was to determine the quantity of caffeine, key compounds, antioxidant properties and residual chemical pesticides in the coffee beans. For the pesticide analysis, both fresh coffee beans (cherries) and unroasted green coffee beans that had not undergone the roasting process were used. These green coffee beans were analyzed to determine the quantity of residual chemical pesticides from the organophosphate, carbamate, organochlorine, and pyrethroid groups. The test was conducted using the In-house method: T-005 based on AOAC Official Methods of Analysis, 21st edition, 2019, method 2007.01.

Results

Soil physical and chemical properties

The analysis of the physical properties of soil samples from both single and mixed-crop coffee gardens revealed that the color of the soil is reddish-brown. Due to the elevated terrain of the hilly area, this soil originates from the decomposition of parent materials, which contain a proportion of iron oxide compounds. The soil composition from single and mixed-crop coffee gardens consists of 80.37%, 80.04% sand particles, 6.26%, 6.66% silt particles, and 13.36%, 13.28% clay particles, respectively, indicating a variation in soil particle distribution when transitioning to single-crop coffee cultivation. The proportion of sand particles tends to increase when utilizing the land for single-crop coffee cultivation. The texture of the single-crop coffee garden soil is loamy sand, while the mixed coffee garden soil is loam mixed with sand. The sandy loam has better water retention and nutrient-holding capacity compared to loamy sand. Additionally, the soil moisture content of the mixed coffee garden is 30.90%, higher than that of the single-crop coffee garden, as shown in **Table 1**.

Figure 1 Monoculture and integrated farming coffee gardens in the vicinity of Ban Pang Khon

Table 1 The physical properties analysis of soil from the coffee plantation in Ban Pang Khon, Huai Chom Phu Sub-district, Mueang District, Chiang Rai Province

Property analysis	single-crop garden soil (Average for 3 replicates)	mixed-crop garden soil (Average for 3 replicates)	Analysis method
Soil Texture			Sieve/hydrometer
- Sand particles (%)	80.37	80.04	
- Silt particles (%)	6.26	6.66	
- Clay particles (%)	13.36	13.28	
- Type	Loamy sand	Sandy loam	
Moisture content (%)	23.71	30.90	Hot air oven

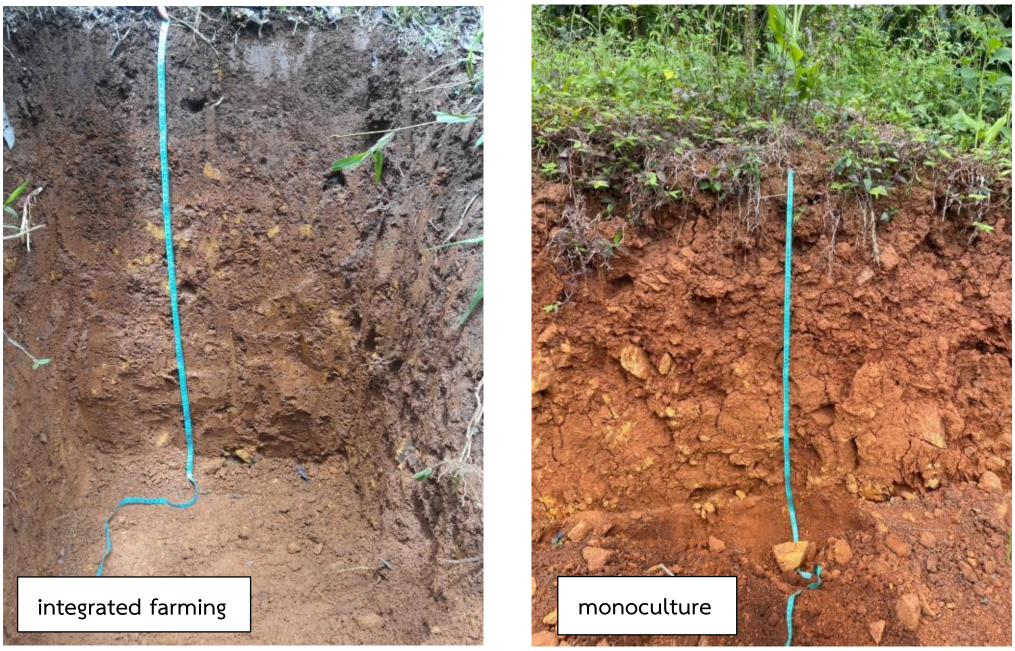

Figure 2 Soil samples from single-crop and mixed-crop coffee gardens in the vicinity of Ban Pang Khon

Regarding the chemical properties analysis of the soil, it was found that the pH of the soil from both the single-crop and mixed-crop coffee gardens ranged from moderately acidic to strongly acidic, with pH values of 5.42-5.35. The electrical conductivity of the soil, indicating salinity levels, ranged from 25.79-27.61 µS/cm, signifying a non-saline level suitable for cultivating various plant types (Ministry of Land Development, 2010). The organic matter content (%OM) in the soil ranged from 6.55% to 6.08%, and the organic carbon content (%OC) was considerably high, indicating soil fertility. The cation exchange capacity (CEC) ranged from 18.53 to 20.22 cmolc/kg, with the mixed-crop coffee garden having a higher CEC value compared to the single-crop coffee garden.

The results of the analysis of nutrient quantities in soil from single-crop gardens and mixed-crop coffee gardens indicate that the mixed garden soil has higher nutrient levels compared to the single-crop garden soil. The essential primary nutrients for coffee growth, including N in very high quantity = 0.38-0.50% (the standard value > 0.18%; very high), P in moderate quantity = 10.37-14.43 mg/kg, and K in very high quantity = 215.04-508.95 mg/kg (the standard value > 120 mg/kg; very high), are present in greater amounts in the mixed garden soil. This suggests that the coffee cultivation soil in the Ban Pang Khon area is fertile. The iron content is also high, ranging from 73.60-82.91 mg/kg, indicating good water drainage at the soil surface. The soil contains sufficient oxygen, substantial quantities of primary nutrients (N, P, K), secondary nutrients (Ca, Mg, S), and trace minerals required by coffee in smaller amounts but of significant importance, such as Mn, Zn, B, Fe, Cl, and Cu, as shown in **Table 2**.

In the analysis of residual chemical pesticides in the soil of the coffee plantation in Ban Pang Khon, it was found that no chemical residues from the four pesticide groups, namely organophosphates, carbamates, organochlorines, and pyrethroids, were detected in the soil samples from both the single-crop and mixed-crop coffee gardens. This is shown in **Table 3**.

Table 2 The chemical property analysis of soil from the coffee plantation in Ban Pang Khon, Huai Chom Phu Sub-district, Mueang District, Chiang Rai Province

Property analysis	Single-crop garden soil (Average for 3 replicates)	Mixed-crop garden soil (Average for 3 replicates)	Analysis method
Electrical Conductivity, EC)	27.61	25.79	EC meter (ดิน:น้ำ; 1:5)
Cation capacity (CEC, cmolc/kg) pH	18.53	20.22	NH_4OAc pH 7/distillation soil:water 1:2)
Organic Matter (%)	6.55	6.08	Walkly & Black
Cation Exchange Capacity (CEC, cmolc/kg)	18.53	20.22	NH_4OAc pH 7/distillation
Lime requirement, LR (Kg of lime/Rai)	516.00	516.00	Woodruff's buffer
Total Nitrogen, N (%)	**0.38**	**0.50**	Bray II Extraction
Extractable Nitrate (mg/kg)	34.72	37.52	KCl extraction
Extractable Ammonium (mg/kg)	17.46	18.78	KCl extraction
Available Phosphorus (mg/kg)	**14.43**	**10.37**	AAS
Exchangeable Potassium (mg/kg)	**215.04**	**508.95**	AAS
Exchangeable Calcium (mg/kg)	652.03	1187.95	AAS
Exchangeable Magnesium (mg/kg)	139.46	188.69	AAS
Exchangeable Sodium (mg/kg)	<2.20	<2.20	AAS
Available Iron (mg/kg)	73.60	82.91	AAS
Available Manganese (mg/kg)	7.06	5.22	AAS
Available Copper (mg/kg)	15.43	12.34	AAS
Available Zinc (mg/kg)	0.42	0.27	AAS
Extractable Boron (mg/kg)	0.03	0.03	Azomethine-H
Extractable Sulfur (mg/kg)	18.25	18.12	$BaCl_2$ method

Evaluation of the Arabica coffee beans quality under single-crop and mixed-crop cultivation systems

The results of testing the nutrient and key compound levels in Arabica coffee beans from two types of coffee gardens revealed that fresh cherries from the mixed-crop garden had a caffeine content of 1,082.56 mg/kg, a total phenolic compound content of 188.09 mg Gallic acid/g DW, and higher antioxidant properties , compared to fresh cherries from the single-crop garden, which had caffeine content of 783.43 mg/kg, total phenolic compound content of 135.54 mg Gallic acid/g DW, and 8.60 mg Vitamin C/g DW, respectively. Furthermore, the fresh cherries from the mixed-crop garden exhibited intermediate values of various nutrients, including fiber, protein, fat, and carbohydrates, which were higher than those of fresh cherries from the single-crop coffee garden, as indicated in **Table 4**.

Table 3 The analysis of residual chemical pesticides in the soil of the coffee plantation in Ban Pang Khon, Huai Chom Phu subdistrict, Muang District, Chiang Rai Province

List of analysis	Coffee garden soil		Analysis methods
	Single-crop	Mixed-crop	
Organophosphates			
Chlorfenvinphos			
Chlorpyrifos			
Diazinon	None was detected	None was detected	
Dichlorvos			
Dicrotophos			
Monocrotophos			
Profenofos			
Carbamates			
Bendiocarb	None was detected	None was detected	GPO-TM Kit
Carboryl			
Carbofuran			
Methomyl			
Organochlorines			
DDT	None was detected	None was detected	GPO-TM Kit
Endrin			
Endosulfan			
Pyrethroids			
Cypermethrin	None was detected	None was detected	GPO-TM Kit
Permethrin			
Deltamethrin			
Herbicides			
2,4-D			

Table 4 Key compound quantity in Arabica coffee beans from Ban Pang Khon, Huai Chom Phu Sub-district, Mueang District, Chiang Rai Province

List of analysis	Coffee garden soil		Unit	Analysis methods
	Single-crop	Mixed-crop		
Total Phenolic Content	135.54	188.09	mg Gallic acid/g DW	DPPH free radical scavenging activity assay method (Yingngam et al., 2014)
Antioxidant property (DPPH method)	4.75	8.60	mg Vitamin C/g DW	Folin-ciocalteu's phenol reagent method (Yingngam et al., 2014)
caffeine content	783.43	1,082.56	mg/kg	ISO 20481:2008 detected by HPLC
Moisture content	63.55	64.91	Percent	AOAC (2012), 934.06
Dry weight	36.64	35.08	Percent	AOAC (2012), 934.01
pH*	3.76	6.11	-	pH meter
Total sugar content	0.12	0.11	g/100 g	Phenol and sulfuric method (Dubois et al., 1956)
Ash	1.65	1.74	g/100 g	AOAC (2012), 940.26
Protein	3.67	3.80	g/100 g	AOAC (2012), 991.20
fat	1.60	1.63	g/100 g	AOAC (2012), 954.02
Carbohydrate	28.77	29.46	g/100 g	By difference

Note: 1. Limit of Detection (LOD) = 0.01 mg/Kg

2. The ratio of sample and water; 1:10 w/v

Results of fresh Arabica cherries from both single-crop and mixed-crop gardens, tested for residual levels of pesticides in the pyrethroid group, including Cyfluthrin, Cypermethrin, and other chemical compounds using the In-house method: T-005 based on AOAC Official Methods of Analysis 21st ed., 20198, method 2007.01, indicated that both fresh or dried Arabica coffee beans contained trace amounts of Cyfluthrin and Cypermethrin in the pyrethroid group, with levels below 0.05 mg/kg, which is considered safe. The values were within the range of Type II pyrethroids with a Rat oral LD50 value of 500 mg/kg, and no other types of pesticide chemicals were detected, as shown in **Table 5**.

Table 5 Test of residual levels of pesticides in Arabica coffee beans from Ban Pang Khon, Huai Chom Phu Sub-district, Mueang District, Chiang Rai Province

Test list	Soil type		Test list	Soil type	
	Single-crop	Mixed-crop		Single-crop	Mixed-crop
Organochlorines					
Aldrin	-	-	**Pyrethroids (contibued)**		
Chlordene	-	-	Cis-Rifenthin	-	-
Cicofol	-	-	Cyhalofop-Butyl	-	-
Dieldrin	-	-	Fennoxaprop-P-Ethyl	-	-
Endrin	-	-	Fenpropathrin	-	-
Endosulfan sulfate	-	-	Kresoxim-methyl	-	-
Endosuifan-Alpha	-	-	Metalaxyl	-	-
Endosuifan-Beta	-	-	Tetramethin	-	-
Gramma-HCH	-	-	Trifloxystrobin	-	-
Beta-HCH	-	-	**Carbamates**		
Alpha-HCH	-	-	Aldicarb	-	-
Heptachlor	-	-	Ametryn	-	-
Methoxychlor	-	-	Carbofuran	-	-
2,4'-DDD	-	-	Epoxiconazole	-	-
2,4'-DDE	-	-	Hexaconazole	-	-
2,4'-DDT	-	-	Methomyl	-	-
4,4'-DDD	-	-	Penconazole	-	-
4,4'-DDE	-	-	Prometrin	-	-
4,4'-DDT	-	-	Pacobutrazole	-	-
Organophosphates			Tebuconazole	-	-
Diazinon	-	-	Tetraconazole	-	-
Parathion-methyl	-	-	Triadimefon	-	-
Fenitrothion	-	-	Triadimenol	-	-
Malathion	-	-	Tricyclazole	-	-
Chlorpyrifos	-	-			
Pirimiphos-ethyl	-	-			
Profenofos	-	-			
Ethion	-	-			
Pyrethroids					
Lamda-cyhalothrin	-	-			
Permethrin	-	-			
Cyfluthrin	<0.05 mg/kg	<0.05 mg/kg			
Cypermethrin	<0.05 mg/kg	<0.05 mg/kg			
Fenvarelate	-	-			
Deltamethrin	-	-			
Benalaxyl	-	-			
Allethrin	-	-			

Discussion and Conclusion

Coffee cultivation in the Ban Pang Khon region under the agroforestry system, involving the intercropping of Arabica coffee with cold tolerate fruit trees, such as macadamia, apricot, peach and snow lotus in a rehabilitated natural forest (mixed-crop garden), aims to provide shade to the coffee plants. Shadiness is necessary because coffee plants require suitable light levels and shade to prevent adverse effects. While coffee cultivation in open areas (single-crop system) may initially result in better growth and production, long-term impacts from global warming and excessive sunlight exposure can lead to leaf damage and increased susceptibility to diseases such as coffee rust, eventually leading to plant mortality. The affected coffee plants do not yield for an extended period; they deteriorate rapidly, eventually leading to their desiccation and death. This is coupled with the necessity for intensive production factors such as high fertilizer or other agricultural chemicals use. There are limitations in terms of cultivation area as well. This is due to the nature of open-field coffee cultivation, which demands prior land preparation, involving tree clearing and burning to eliminate residual vegetation. This practice causes a continuous reduction in the natural forest area as part of the preparation, thus degrading soil and water resources, forests, and overall biodiversity in highland regions (Phatchani, 2008).

To ensure sustainable and high-quality coffee production, it is essential for farmers to cultivate coffee under shade conditions, allowing up to 70% shade cover. This practice helps lower temperatures, reduce light intensity, prevent soil erosion during rainy seasons, minimize weed growth, and regulate the chlorophyll content in coffee leaves. The shade also optimizes photosynthesis and fruit set as over-fruiting can cause the coffee to die-back easily (Van der Vossen, 1988), leading to an efficient assimilation of carbohydrate from photosynthesis and mineral nutrients for coffee growth. Interplanting coffee with fruit trees, banana, and pea, is recommended to prevent coffee rust disease and control the spread of pests. This is in line with the research of Prasert and Teeradej (2002), of which a study was conducted on the agroforestry system of Arabica coffee cultivation together with other plants that have an impact on natural resource conservation. Coffee was grown alongside various types of shade trees and fruit trees. The findings indicated that the agroforestry system of coffee cultivation with forest trees was highly suitable for natural resource conservation in highland areas. This is because various factors are utilized, including minimal use of chemical fertilizers and pesticides, as well as reduced watering during dry periods. Even during droughts, coffee plants can still thrive due to the moisture retention and shading provided by the other trees.

Soils in the mixed-crop garden and single-crop garden for Arabica coffee in Ban Pang Khon are characterized as moderately acidic, with a pH range of 5.42-5.35. This acidic nature is typical of tropical and developed soils, resulting in a process of leaching of various bases from the topsoil (Brady and Weil, 2017). The soil's electrical conductivity (EC) ranges from 25.79 to 27.61 µS/cm, indicating a non-saline level that is suitable for various crop cultivation (Standard criteria 0-0.2 mS/cm, salinity-nonsaline levels: Department of Land Development, 2010). The soils are nutrient-rich, with a high content of organic matter and organic carbon levels. The cation exchange capacity (CEC) is between 18.53 and 20.22 cmolc/kg, with the mixed-crop garden having higher CEC values and moisture content compared to the single-crop garden. The high nutrient content, particularly N, P, and K, is important for optimal coffee growth. These soils possess a net negative charge, enhancing the retention of positively charged nutrient ions like ammonium, potassium, calcium, and magnesium, resulting in better nutrient availability for coffee plants. Fresh coffee cherries from mixed-crop garden contain higher levels of caffeine, total phenolic compounds and antioxidants than those from monoculture. This is in accordance with research on the yield and growth of Arabica coffee, such as the study by Warapong (2001), indicating that intercropping has no impact on the growth of coffee plants and shade plants do not compete for nutrients or growing space with coffee plants. Bote and Struik (2011) found that growing coffee under shade trees generally resulted in higher specific leaf area (SLA), leaf area index (LAI), and leaf nitrogen content. The color of the leaves grown under shade trees tended to be darker compared to coffee plants grown in open conditions. Mixed agroforestry cultivation of coffee offers advantages and benefits in various aspects, as demonstrated by Moraris et al. (2006) that coffee grown under shade was found to be of higher quality due to its biochemical components, including caffeine, fats, and chlorogenic acids, in comparison to coffee grown in open-field systems. Additionally, it was discovered that mixed agroforestry coffee cultivation experienced a lower incidence of diseases caused by the *Colletotrichumkahowae* pathogen, with reduced chemical usage and production losses, as opposed to single-crop cultivation (Mouen Bedima et al., 2008).

Furthermore, growing Arabica coffee in agroforestry systems with cold-season fruit trees contributes to improving soil properties and fertility, ultimately promoting sustainable and quality coffee production on an organic agricultural basis. The benefits that farmers can gain from the knowledge obtained from this research are manifold. They can apply this knowledge to their own coffee cultivation and production practices, also utilize the insights on different coffee cultivation methods to foster new knowledge and share it with fellow farmers, thus contributing to community-based research that involves collaborative coffee production between government agencies and the public. Additionally, this information serves as a foundational resource for land use planning and soil management strategies tailored for efficient and appropriate coffee cultivation. This will help establish sustainable agricultural practices that enhance the quality and productivity of coffee yields, ultimately leading to increased income for farmers in the region in the future.

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