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Tree Species Effects on Microclimate and Soil Chemical Properties in Indonesian Agroforestry Systems

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ABSTRACT

Deforestation is a challenge in Indonesia that exacerbates climate anomalies and decreases soil fertility. These impacts decrease crop production, so the approach that can be taken is a tree-based agricultural system, namely agroforestry. This study examines the characteristics and role of various types of trees in agroforestry systems regarding the microclimate and chemical properties of soil in Indonesia. The study was conducted in Karanganyar Regency, Central Java, Indonesia, on four types of trees: pine, mahogany, teak, and sengon. The type of tree stand plays a role in the microclimate and chemical properties of the soil. Sengon and teak stands with umbrella shapes and increasingly wide canopies cause a decrease in light intensity and temperature, and an increase in air humidity. Sengon stands provide an optimal microclimate for shade-tolerant understory crops by maintaining sufficient light transmission, as the canopy reduces incident radiation by only 49%. Tree litter plays a role in supporting soil chemical properties. Sengon litter contains 5.55% nitrogen, 0.26% phosphorus, 0.39% potassium, and 28.70% organic carbon, supporting higher total soil nitrogen, phosphorus, and potassium than other stands. Sengon demonstrated the potential to improve microclimatic conditions and soil chemical properties in agroforestry systems under the environmental conditions studied in Central Java.

1. INTRODUCTION

Indonesia has the ninth-largest forest area after Australia and Argentina, and experienced a relatively rapid decline in its forest area from 2014 to 2021. In 2021, Indonesia's forest area was 121,852,186.19 ha [1]. Based on data from the Central Statistics Agency in 2021, Indonesia's primary forests decreased by 270 thousand hectares. Indonesia's primary forest deforestation rate is ranked fourth in the world. This reflects the utilization of forests for various purposes (industry, plantations, agriculture), which is experiencing a relatively rapid rate, and often without considering the function of forests as providers of environmental services. The impacts include ecological damage and climate anomalies with longer than usual rainy and dry seasons (El Niño and La Niña). The increasing rate of deforestation also causes a decrease in the population of biodiversity and ecosystem services [2]. Based on the research of Pineda, deforestation causes a loss of 38-52% of national biodiversity in 2033, which will then lead to extinction [3]. In addition, deforestation directly reduces carbon absorption, endangering carbon neutrality targets and contributing to elevated air temperatures [4]. Forests and the forestry sector affect the concentration of carbon dioxide in the atmosphere through CO_2 absorption and carbon storage. This critical function is fundamentally supported by the trees' capacity for carbon absorption [5].

The approach that supports the transition between agriculture and forestry is a tree-based agricultural system, namely agroforestry, because it absorbs atmospheric carbon aboveground and contributes to carbon storage belowground. Soil carbon absorption in agroforestry systems is higher, namely 11.29 t C ha^{-1} $year^{-1}$, than monoculture systems of 4.38 t C ha^{-1} $year^{-1}$ [6]. This shows that forestry plants mixed with crops will increase the carbon absorption capacity of the atmosphere. The role of trees is influenced by trunk diameter, tree height, tree branches, leaf structure, and tree canopy space [7]. Trees that dominate forests in Indonesia are pine, teak, mahogany, rubber, and sengon. These trees have different characteristics. Trees with wide canopies can filter direct sunlight and reduce heat radiation that reaches the ground surface below, affecting air and soil temperatures [8]. Trees also play a role in regulating the movement of rainwater to support the hydrological cycle and become an optimal environmental carrying capacity [9]. Rainwater falls onto the tree canopy, which regulates and slows its movement toward the ground surface. Trees can reduce the kinetic energy of rainwater that falls to the ground surface [10]. Considerable kinetic energy can cause the release of soil aggregates, increasing the impact of erosion and reducing the fertile topsoil layer for plants [11]. Without vegetation to intercept rainfall, the impact of raindrops on the soil increases and leads to greater soil damage.

Tree species affect the quality of tree litter. Tree litter plays an essential role in driving the organic matter cycle and nutrient balance, maintaining soil fertility, and ensuring the availability of nutrients for plant growth. This is supported by the role of litter in forming soil organic matter, mineralization of organic nutrients, and carbon balance in the ecosystem. Soil is a litter carrier, so increasing the litter decomposition rate can increase the soil nutrient cycle and improve soil quality [12]. Litter quantity and quality are important in soil carbon storage and nutrient cycling. The quality and rate of litter decomposition influence soil nutrients and productivity [13]. In addition, leaf litter functions as a potential food source with stable and soluble compounds for soil microorganisms. Soil litter quality positively correlates with microbiological diversity and soil fauna communities [14]. Litter from the leaves of the leguminaceae family, such as sengon, can fix inorganic nitrogen and has a higher nitrogen concentration [15]. In addition, the leaves of this species undergo a rapid litter decomposition process and provide a higher concentration of soil nutrients than other litters [16]. Forest soil characteristics vary greatly depending on climate, tree species, and geological processes that have influenced soil formation [17]. However, forest soil generally has several distinctive characteristics strongly influenced by litter; namely, forest soil tends to have a thick layer of litter on the soil surface. When decomposed, this litter layer provides nutrients to the soil, helps maintain soil moisture, and isolates soil temperature from extreme fluctuations. Previous research has focused on microclimate, litter, or soil properties separately. Integrated studies on the influence of tree canopy characteristics on microclimate and soil chemistry in tropical agroforestry systems are still limited. Four tree species were selected because they have different canopy characteristics and litter quality. The novelty of this research lies in its integrated approach to analyzing the relationship between canopy characteristics, microclimate, and soil chemistry simultaneously across various tree species within agroforestry systems in Indonesia. This study aims to characterize the role of various tree species in the microclimate and soil chemical properties in agroforestry systems in Indonesia.

2. MATERIALS AND METHODS

2.1 Study site

The study was conducted on four types of tree stands, namely pine, mahogany, sengon, and teak. The population of pine and sengon trees was 40 on 360 m^2 of land, with a distance of 3 × 3 m each. The population of mahogany and teak trees was twenty trees on 480 m^2 of land, with a distance of 6 × 4 m each. The number of samples for each tree was ten. The pine and mahogany trees observed were 15-20 years old, while the sengon and teak trees were 10-15 years old. The research location for pine and mahogany trees was in the Special Purpose Forest Area of Mount Bromo, Karanganyar District, Karanganyar Regency, Central Java, Indonesia (07° 35' 20.2" E and 110° 59' 60.1" S) with an altitude of 254 meters above sea level (masl). Teak and sengon trees in the Community Forest Area of Sukosari Village, Jumantono District, Karanganyar Regency, Indonesia (07° 38 22.8" E and 110° 56 88.6" S) with an altitude of 158 masl. The research was conducted from April 2023 to December 2024. The average rainfall at the research location was 194.11 mm per month, with an air temperature of 29.02 °C, relative humidity of 80.03%, sunshine duration of 71.28%, and an average wind speed of 226.39 km·h^{-1}.

Sampling was conducted using purposive sampling on homogeneous stands. Ten sample trees from each species were selected based on uniform stand condition, canopy coverage, and tree health. Microclimate observations were conducted under each selected tree canopy. The control treatment consisted of open land without tree stands located adjacent to the study area under similar topographic conditions. Each treatment was replicated ten times.

2.2 Tree characteristics

Tree stand characteristics were analyzed using a hand-gun altimeter and a length-measuring tool to determine tree height and canopy area. Tree height measurement with a hand gun altimeter was done in 2 ways: using a meter and a scale board. Working time for height measurement was recorded with a stopwatch using a continuous method. Each work element in the height measurement process was timed while using the hand-gun altimeter. The working elements of tree height measurement with a hand gun altimeter are: finding the tree position (MP); finding the peak point (MTP); measuring the branch-free point (MTBC); and finding the base point (MTD). Tree height (T = AC), the formula for calculating the height was used:

If using a degree scale (degree-angle):

$$T = (tan\ \alpha - tan\beta)$$

If using a percent scale (% angle):

$$T = [\frac{\%MC - \%MA}{100}]$$

2.3 Characteristics of tree litter

The attributes of tree litter observed are nitrogen, phosphate, and potassium content. Nitrogen compounds were analyzed using either distillation or spectrophotometry. In the distillation method, the sample extract was treated with NaOH solution. The released NH_3 was captured by boric acid and titrated with a standard H_2SO_4 solution using a Conway indicator. The spectrophotometric method followed the indophenol blue method. Total nitrogen could also be measured using the Berthelot modification. After dialysis, ammonia was buffered and chlorinated into monochloramine. The addition of salicylic acid produced a 5-aminosalicylic compound. Through oxidation and oxidative coupling reactions, a green complex compound was produced. The absorption of the complex was measured at a wavelength of 660 nm. Phosphate analysis was carried out using a spectrophotometer. Sample preparation followed a modified method by Friel with wet ashing using HNO_3 and $HClO_4$ [18]. The ready solution was analyzed using a spectrophotometer with a wavelength of 400-470 nm. Potassium analysis was carried out using an atomic absorption spectrophotometer

(AAS); this method was chosen because it meets the ISO/IEC 17025 standard and is the easiest, simplest, most precise, and most accurate method [19].

2.4 Microclimate observation

The microclimate variables observed were temperature, environmental humidity, and light intensity under the tree stands, which were carried out at 07.00 am, 12.00 noon, and 05.00 pm. Temperature and air humidity observations using a thermohygrometer (Shanghai, China). Light intensity (lux) above and below the canopy using a lux meter (Mextech, China).

2.5 Soil analysis

Soil samples were collected beneath each tree stand at a depth of 0–20 cm under the canopy area of selected trees using ten replications for each tree species. Four subsamples were collected from different directions beneath each canopy and composited into one representative sample for laboratory analysis. The analyzed soil properties represented the current soil chemical conditions under different tree stands. Observations were made on soil conditions: pH, nitrogen content, phosphate, and total potassium, cation exchange capacity, base saturation, and organic carbon. Soil pH was measured to determine soil acidity or alkalinity. The pH value reflects the concentration of H^+ ions in the soil solution. The tool used to measure the pH value is a pH meter [20]. Total nitrogen was analyzed by distillation using the Kjeldahl method with slight modifications based on the technical instructions of the Soil Research Center. Total phosphate and potassium were analyzed by extracting soil samples through wet ashing using a mixture of concentrated acids, HNO_3 and $HCLO_4$. The extract was analyzed using a spectrophotometer to obtain total phosphate, and analyzed using atomic absorption spectrophotometry (AAS) to get total potassium.

Available nitrogen analysis was conducted by distillation using the Kjeldahl method and slight modifications according to the technical guidelines of the Soil Research Institute. The available phosphate analysis was done using a spectrophotometer with the Olsen and Bray method, and slight changes were made according to the technical guidelines of the Soil Research Institute. Available potassium analysis was conducted using the Morgan-Wolf method using an atomic absorption spectrophotometer (AAS) with a standard series as a comparison. Soil colloids (clay minerals and humus) were negatively charged to absorb cations. Exchange cations (such as Ca^{2+}, Mg^{2+}, K^+, and Na^+) in the soil adsorption complex will undergo a substitution reaction with the extractant (NH_4^+). Excess exchange cations were washed with 96% ethanol. Exchange cations K^+ and Na^+ were determined using a Flame photometer, while Ca^{2+} and Mg^{2+} were determined using AAS or titration with EDTA. Cation Exchange Capacity (NH^{4+}) was determined by Kjeldahl distillation. Organic carbon content using the Walkley & Black method. Organic carbon in the sample was oxidized by dichromate in acidic conditions. The chromium III formed is equivalent to the oxidized organic C and is measured spectrometrically. Tools: analytical balance, 100 ml volumetric flask, 10 ml scale dispenser/10 ml measuring pipette, 5 ml volumetric pipette, visible spectrophotometer. Reagents: H_2SO_4 pa. 98%, BJ 1.84, $K_2Cr_2O_7$ 2 N, namely by weighing 98.1 g $K_2Cr_2O_7$ + 100 ml H_2SO_4 pa, put it into a 1,000 ml measuring flask plus deionized water to the calibration limit, standard solution 5000 ppm C by weighing 12.5 g glucose in 1,000 ml deionized water. Tree characteristics and soil chemical properties were analyzed using ANOVA, followed by DMRT at the 5% significance level.

3. RESULTS AND DISCUSSION

3.1 Effect of stand type on microclimate

The study showed that stand types have different characteristics (Table 1). Stand characteristics influenced the microclimatic conditions beneath them (Table 2). Teak stands have the largest canopy area compared to other stands, causing the light intensity under the stand to be only 35,300 lux, 55.39% less than the light intensity outside the stand of 79,133 lux. The width and complexity of the tree canopy structure are the main factors that determine the light intensity under the canopy [21]. The canopy area of pine is higher than that of mahogany, so the light intensity under pine is lower than that under mahogany. The light intensity under mahogany stands is reduced by 57%, and under pine stands by 73%, compared to those without stands. Broader and more structurally complex canopies block more light, resulting in lower light intensity under the canopy. Leaves in the upper canopy layer receive more light, while the lower canopy layer experiences greater shade and lower light intensity [22]. Canopy characteristics such as leaf tilt angle, leaf rolling, and the ratio of projected leaf area to total leaf area can affect light interception efficiency.

Table 1. Characteristics of various stand types

Characteristics	Type of Stand			
	Mahogany	Pine	Teak	Sengon
Tree Height (m)	14.70a	15.30a	16.50b	20.00c
Trunk Height (m)	3.00a	5.80c	5.00b	6.50d
Canopy Height (m)	11,70b	9.40a	11.50b	13.50c
Canopy Area (m^2)	6.40b	6.80b	8.40c	5.50a
Trunk Diameter (cm)	24.70c	30.10d	22.40b	16.80a
Canopy Shape	Triangle	Cone	Umbrella	Umbrella

Means sharing the same letter in a column indicate no significant difference based on DMRT at $P \leq 0.05$.

Table 2. Microclimate in various types of stands

Climate Variables	Type of Stand				
	Open Area	Mahogany	Pine	Teak	Sengon
Light intensity (lux)					
07.00 am	58,398	23,713	15,767	28,240	31,920
12.00 noon	79,133	33,733	20,833	35,300	39,900
05.00 pm	61,658	28,620	16,647	25,077	29,925
Temperature (°C)					
07.00 am	26.8	24.2	22.0	26.2	26.7
12.00 noon	34.4	30.1	28.2	32.1	30.5
05.00 pm	31.5	27.8	25.8	30.2	28.2
Humidity (%)					
07.00 am	74.0	86.0	82.0	84.0	81.0
12.00 noon	62.0	76.7	71.7	73.0	70.0
05.00 pm	68.0	81.7	76.7	77.0	75.0

Sengon stands had a lower canopy area, so the decrease in light intensity is the lowest, at only 49%, compared to those without stands. Research shows that light availability under the sengon canopy generally benefits plant production. The open canopy of sengon trees facilitates light transmission, allowing plants to receive enough sunlight for photosynthesis [23]. The canopy shape affected the light intensity, temperature, and humidity under the canopy (Table 2). The umbrella canopy has a wide and spreading canopy resembling an inverted cone [24], while the cone-shaped canopy is narrower and tapers towards the top [25]. This causes the umbrella-shaped canopy to create a more closed microclimate underneath with higher humidity and lower temperatures than the cone-shaped canopy [26]. The results showed that teak and sengon stands with umbrella-shaped canopies maintained air temperatures of 26.2 and 26.7 ℃, respectively, and increased relative humidity to 84.0 and 81.0%, respectively, compared with the open area. A more expansive umbrella canopy can also provide more shade and reduce solar radiation reaching the ground [27]. Pine stands have a cone shape that can reduce light intensity by 73% and temperature by 18% compared to the conditions without stands. The results showed that pine stands caused a very high decrease in intensity (Table 2). Research shows that the presence of pine trees can cause a substantial reduction in the intensity of light reaching the ground. The findings of this study differ from those reported by Wei and Liang [28] that cone-shaped canopies can cause high airflow and light penetration compared to umbrella shapes. This can be caused by the density and spatial distribution of branches, leaves, and fruits in the canopy, which can cause differences in light intensity [29]. In addition, pine leaves are needle-shaped and arranged in high-density bundles so that the light intensity under the canopy is low.

A dense tree canopy can block more than 95% of visible light from reaching the bottom of the canopy [30]. The canopy shape with an open center can distribute a uniform microclimate with higher light intensity and temperature with decreased humidity [31]. Temperatures under the tree stands were reduced by as much as 9 ℃, compared with a reduction of up to 1 ℃ in the surrounding area. Greater temperature reduction tends to occur in trees with broader canopy areas. Taller trees also reduce more solar radiation. Canopy size and the amount of light that reaches the ground both contribute to lower air temperatures beneath the stand.

In addition, the taller the tree, the more it can reduce the amount of solar radiation. The area of the tree canopy and the light intensity under the canopy contribute to the decrease in air temperature. Trees have a blackout effect and can adjust the microclimate [32, 33]. Research [34] analyzed the shape of the canopy of each tree with horizontal images. It showed that the umbrella canopy shape had a higher temperature reduction effect than the triangular and conical shapes. The shape of the tree canopy is an essential characteristic for determining the shade structure. Trees can create microclimates through shade and transpiration. Larger and denser canopies can absorb more solar heat and provide more transpirational cooling [35]. Canopy shade and evapotranspiration are the main mechanisms used by trees to lower air temperatures below the canopy.

Dense tree canopies increase the relative humidity under the canopy [36]. The umbrella-shaped canopy can block solar radiation, creating a difference in relative humidity between the upper and lower canopies [37]. The structure and phenology of the canopy can also affect soil moisture and water flow [38]. Sengon trees with an umbrella canopy shape and a low area of 5.5 m^2 are essential in increasing humidity and lowering temperatures under the shade. The increase in moisture is caused by the reduced evaporation and transpiration rates from the soil surface due to the shading effect of the tree [39, 40]. The canopy acts as a wind barrier, reducing air movement and allowing water vapor accumulation [41]. The interaction between air humidity and temperature is significant in determining the overall health of plants in agroforestry systems.

3.2 Effect of stand type on soil chemical properties

The results of the study showed that mahogany tree litter contains the highest potassium compared to other stands, namely 0.43% (Table 3). The lowest nitrogen and phosphorus content was in teak litter, only 2.26 and 0.11%. Tree litter significantly affects soil chemical properties [42]. This can be caused by the decomposition of tree litter, which releases various nutrients into the soil, such as nitrogen, phosphorus, calcium, magnesium, and potassium. The rate and extent of nutrient release depend on the chemical composition and rate of litter decomposition, which can vary between tree species [43]. The soil under mahogany stands contains lower nitrogen and cation exchange capacity than others, namely 0.22% and 14.7 meq/100g. Land cover has a significant effect on soil quality, and the soil under mahogany stands has a low soil quality value, SQI 0.31 [44]. Mahogany trees are deciduous trees in the dry season, so the volume of litter is larger. A thicker litter layer can create a microenvironment that is less supportive of decomposition because the availability of light and humidity levels is needed for microbial metabolism [41]. A thicker litter layer can slow the decomposition rate by creating anaerobic conditions that inhibit microbial activity. A litter layer that is too thick can hinder the growth of specific microbial populations, thereby slowing down the decomposition process and affecting the availability of nutrients in the soil [43, 45]. In addition, based on research by Rachmawati et al. [46], mahogany litter contains nitrogen, 16.86% lignin, and 25.26% polyphenols, which are classified as high, which can slow decomposition, and nitrogen minerals are not available to plants [44].

Table 3. Characteristics of litter in various types of stands

Litter Characteristics	Type of Stand			
	Mahogany	Pine	Teak	Sengon
Total N (%)	2.11	3.09	2.26	5.55
Total P (%)	0.73	0.82	0.25	0.26
Total K (%)	0.43	0.12	0.11	0.39
Organic C (%)	18.40	17.30	24.10	28.70

Litter from different tree species can affect soil pH differently, with some species increasing soil pH by releasing alkaline compounds during decomposition. It can also decrease pH [47]. Based on the study's results, the soil under teak and sengon stands was classified as acidic soil with a pH of 5.67 and 5.26. The soil outside the stands is also classified as acidic, with an acidity level of 5.42. The results showed that teak litter can increase the soil's acidity level by 0.25. Litter from teak trees is characterized by a high carbon-nitrogen (C:N) ratio of 10.66, which can affect soil microbial activity and nutrient cycling. Decomposition of teak litter is slow due to the high lignin content, resulting in the gradual release of organic compounds that can change soil chemistry over time [48]. This slow release allows for a more sustained impact on soil pH because organic acids produced during decomposition may initially lower pH but may eventually increase base cations, particularly calcium, which can raise pH levels. The impact of litter on soil pH may also affect the availability and cycling of other soil nutrients [49].

The chemical properties of the soil under sengon stands contain the highest total nitrogen, phosphorus, and total potassium compared to the soil under other stands (Table 4). The soil under sengon stands contains 0.39% nitrogen, 19.40 mg/kg total phosphorus, and 15.10 mg/kg total potassium. The chemical properties of the soil are supported by the content of sengon litter, namely 5.55% total nitrogen, 0.26% total phosphorus, 0.39% total potassium, and 28.70% organic C (Table 3). Litter with a higher nitrogen content can increase soil nitrogen levels after decomposition, thereby increasing soil fertility [50]. The carbon-to-nitrogen ratio (C:N) of litter also plays a vital role in determining the rate of decomposition and nutrient release. Lower C:N ratios usually indicate higher nutrient release potential, which can lead to increased soil nitrogen levels [51]. Sengon is also a legume family that can fix atmospheric nitrogen. Legume litter such as *Mimosa caesalpiniifolia* Benth tree contains 20.55 g/kg of nitrogen and a carbon-nitrogen ratio of 21.79 [18]. Meanwhile, other studies with the legume *Pueraria lobata* contain 2.86% nitrogen, and non-legume pine trees contain 0.49% nitrogen [52]. Nitrogen fixation occurs through a symbiotic relationship with certain bacteria in the root nodules of legumes, which is an essential process for increasing nitrogen levels. Decomposition of Sengon litter releases nitrogen, phosphorus, and potassium nutrients back into the soil. Sengon is symbiotic with mycorrhiza, which facilitates phosphorus and potassium absorption from the soil [53].

Table 4. Soil chemical characteristics under different stands

Soil Characteristics	Type of Stand			
	Mahogany	**Pine**	**Teak**	**Sengon**
Acidity	6.93b	6.84b	5.67a	5.26a
Organic C (%)	2.94a	2.43a	2.34a	2.13a
Base saturation (%)	37.20d	27.30c	19.20b	16.80a
CEC (meq/100 g)	14.70a	21.32c	15.80b	24.30d
Total N (%)	0.22a	0.21a	0.33b	0.39b
Total P (mg/kg)	16.50b	14.90a	16.30b	19.40c
Total K (mg/kg)	12.70b	12.10b	11.50a	15.10c

Note: Means sharing the same letter in a column indicate no significant difference based on DMRT at $P \leq 0.05$.

The chemical properties of the soil under teak stands contain 0.33% total nitrogen, 16.3 mg/kg total phosphorus, and 11.5 mg/kg total potassium (Table 4). Phosphorus and potassium under teak stands are classified as low. This can be caused by high acidity. High leaching rates cause low nitrogen levels in acidic soils. In addition, soils with moderate to high organic carbon content can show low nitrogen status due to nitrate leaching, exacerbated under anaerobic conditions in the denitrification process, resulting in nitrogen loss [54]. Low pH in acidic soils can inhibit microbial processes essential for nitrogen fixation and mineralization, reducing nitrogen availability [55]. In addition, the slow rate of organic matter decomposition in acidic environments contributes to limited nitrogen supply because low pH levels often inhibit microbial activity. The results of this study are based on the research [56] that litter under teak stands has a lower nutrient status than other litter. The biochemical composition of teak litter with a higher carbon-nitrogen (C/N) ratio results in a slower decomposition rate, limiting the availability of nitrogen and other nutrients to the soil.

The phosphorus content under the pine stands is in the low category. Meanwhile, the phosphorus content under mahogany, teak, and sengon stands is included in the moderate category. Phosphorus availability is greatly influenced by soil acidity. Acidic soils have low exchangeable bases, which are crucial for increasing phosphate rock's dissolution [57]. Low pH can cause phosphorus precipitation as an insoluble compound, making it less available for plant absorption. Increased soil acidity can hurt nutrient dynamics [58]. High levels of aluminum and iron in acidic soils can also bind phosphorus, making it unavailable to plants [59]. In addition, low pH levels cause drainage of essential cations from the soil profile. This loss is exacerbated by the high aluminum content in acidic soils, which can inhibit potassium availability by competing for absorption sites on soil particles [56].

Pine litter contains 3.09% total nitrogen, 0.82% total phosphorus, 0.12% total potassium, and 17.30% organic C (Table 3). The content of pine litter affects the chemical properties of the soil under the pine stand. The soil under the pine stand contains 2.43% organic C, 0.21% total nitrogen, 14.90 mg/kg total phosphorus, and 12.10 mg/kg total potassium (Table 4). The high carbon content in pine litter contributes to organic matter in the soil, which is essential for maintaining soil structure and fertility. Litter releases nutrients into the soil and increases nitrogen [60]. In addition, the high C/N ratio of pine litter affects soil microbial activity and nutrient availability. This can cause nitrogen immobilization during decomposition because soil microbes utilize more carbon from litter, reducing soil nitrogen availability. The soil under pine stands has the same acidity level as the soil without stands, which is 6.84. The results of this study are inconsistent with the research [61], which suggests that pine litter contributes to a decrease in soil pH, which can then affect the soil microbial community and nutrient availability. The decomposition of light pine needles that can spread over a large area can cause soil acidification, thereby changing the chemical properties of the soil and affecting the dynamics of the ecosystem as a whole [62]. Based on the research [63], the activity of fauna such as earthworms under pine stands is lower than that of sengon and teak stands, thus slowing down the decomposition of organic matter.

4. CONCLUSIONS

Tree stand types play a crucial role in regulating the microclimate and soil chemical characteristics beneath the canopy. Trees with a broad, umbrella-like canopy architecture, such as sengon and teak, are highly effective at lowering surface temperatures and increasing air humidity. Sengon stands, in particular, create an optimal microclimate balance by reducing light intensity by 49%. This reduction ensures adequate light availability for the needs of the integrated crops beneath them. Tree litter is a key determinant in maintaining soil fertility. Sengon litter contains 5.55% nitrogen and 28.70% organic carbon. These nutrient contents have been shown to significantly increase the accumulation of total nitrogen, phosphorus, and potassium in the soil compared to stands of pine, mahogany, or teak. Sengon demonstrated the potential to improve microclimatic conditions and soil chemical properties in agroforestry systems under the environmental conditions studied in Central Java.

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