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Effect of *Acacia mangium* Canopy on Physicochemical Characteristics and Nutrient Concentrations of the Soil at Ayer Hitam Forest Reserve, Malaysia

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Abstract: The establishment of an *Acacia mangium* plantation often alters physicochemical characteristics and nutrient concentrations of soils. We aimed to evaluate the invasive potential of *A. mangium* forest on the soil in Ayer Hitam Forest Reserve, Peninsular, Malaysia. To achieve the mentioned target, four different regions, namely, the open ground region (OG), *Acacia mangium* region (AM), transition region (TZ), and native forest region (NF), were selected and each of the regions was divided into six plots. Composite samples were randomly taken from subplots at 0–15 cm depth (topsoil) and 15–30 cm depth (subsoil). Some physicochemical properties such as soil moisture and texture, textural classification, bulk density and particle density, pH, electric conductivity (EC), exchangeable bases (EB) (Ca, Mg and K), cation exchange capacity (CEC), organic matter (OM), total nitrogen (TN), and available phosphorous (Av. P) were analyzed. The results of our study showed that the soil of the AM region, which was clay loam, contained clay (51%), silt (32%), and sand (16%). The chemical analysis of topsoil showed significant differences in terms of OM%, exchangeable-Ca, Mg, K (molc kg^{-1}), N (%), gravitational water content (GWC), and Avail. P between all four regions. Additionally, the highest pH and OM of topsoil were seen in the AM region with 4.5% and 4.33%, respectively. In the subsoil, there were significant differences ($p \leq 0.01$) in terms of EC (ds/m), OM (%), Exchangeable- Ca, Mg and K (cmolc kg^{-1}), GWC, available phosphorus, and N (%) between all four regions. The highest GWC, N (%), and Ca (cmolc kg^{-1}) were observed in the AM region with 16.00, 0.14%, and 0.64 cmolc kg^{-1}, respectively. These results showed that *A. mangium* changed some soil characteristics due to its invasion potential. In summary, *A. mangium* showed high adaptability on degraded forest land and high ability to accumulate the soil physicochemical properties to enhance its growth.

Keywords: *Acacia mangium*; physicochemical characteristics; soil; degraded local forests; Peninsular Malaysia; Ayer Hitam Forest Reserve

1. Introduction

Tropical rainforests are known as the richest, most multi-functional, and complex natural ecosystem in the world [1]. These luxuriant forests have prevailed at an unprecedented level of detail and accuracy by anthropogenic activities such as commercial plantations, shifting cultivation, and timber extraction [2], leading to the degradation, fragmentation, and conversion of forestlands [3]. Degradation in the rainforest is defined as the reduction in the forestland capacity in terms of producing goods and services [4] due to the occurrence of different chemical reactions and physical processes [5]. Chemical degradation decreases the potential of soil fertility, while physical degradation increases the possibility of soil erosion and compaction [6]. To preserve the rainforest ecosystem, rehabilitation becomes an attractive task, avoiding or suppressing the degradation impact on vegetation stock, ecosystem structure, and soil nutrients [7]. Therefore, the cultivation of high-quality exotic species or indigenous trees has been considered as a successful rehabilitation strategy for degraded forestlands [8] (Figure 1).

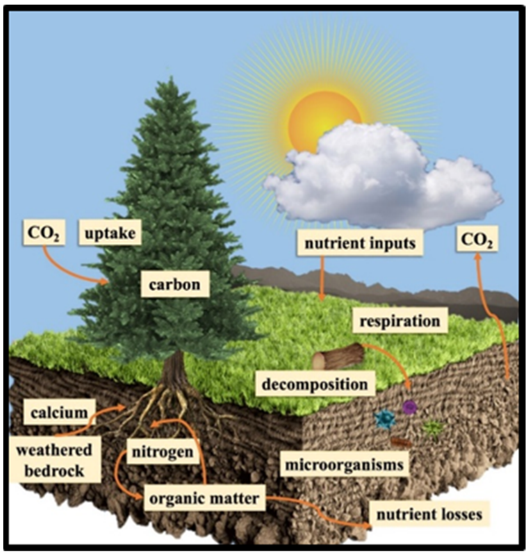

Figure 1. Rehabilitation plays a fundamental role in the host ecosystem. Beneficial factors to the ecosystem include providing oxygen, nutrients, water, and physicochemical support, adopted from Fisher et al. [9].

Over the past several decades, investigations have emphasized the negative impact of invasive alien plant species (IAPS) on the environmental quality, ecosystem services, local biodiversity, and human health [10]. It has been reported that more than one-fifth of the Earth's surface has been threatened by biotic invaders [11]. So far, different mechanisms, including empty niche (EN), novel weapon (NWH), and enemy release (ERH), have been proposed to describe the invasion of IAPS in the host ecosystem [10]. A growing amount of research has suggested that alien invasive plants increase nutrient pools and fluxes in the host ecosystems [12–15]. Additionally, soil properties such as pH, organic matter, and exchangeable bases have been changed when a plant species was replaced by introducing alien invasive trees in the host ecosystem [16].

The genus *Acacia* (family Fabaceae) comprises more than 1350 tree and shrub species and has been adapted in about one-third of land areas [17]. Cultivation of *Acacia* species has been recommended for different ecosystems due to the availability of enough nutrients in the environments, enhancement of nutrient cycling mechanisms, and boosting microbial activity [18,19]. However, *Acacia* species can change native climatic niches, affecting the storage and release of carbon and nitrogen [20]. Reportedly, invasion by *Acacia dealbata* changes microbial structure, nutrient pools, and the diversity of microorganisms in the soil [21]. Furthermore, it has been observed that the modification of soil properties by invasive *A. dealbata* promotes seedling of the native tree at the early stage of growth [22]. In addition, it has been reported that invasions by Australian *Acacias* influenced the structure and diversity of rhizobial communities in soil [23]. In addition to the above reports, a decrease in the plant diversity and an extensive development in the woodlands dominated by the invasion of *Acacia saligna* have been recorded in the host ecosystem [24].

Acacia mangium has been widely cultivated in many parts of the world. The importance of this species has been reported in agricultural, agroforestry, and forestry ecosystems [25,26]. For example, the cultivation of *A. mangium* in commercial monoculture plantations or mixed with other crops enhances soil fertility [27,28], stimulates productivity, promotes the growth of other crops [26,29,30], and interacts with microorganisms of the host ecosystem [31,32]. The ability of *A. mangium* to fix nitrogen may lead to soil acidification due to the accumulation of base cations in the biomass, which has been complemented by the exudation of H^+ from roots [30]. Therefore, the nitrate anions level is high in soils under nitrogen-fixing trees. Interestingly, in the presence of *A. mangium*, which has been known as an N-fixing species (NFS), forest productivity, crop yields, and soil N status rise on N-limited sites [33]. The diversity, distribution, and abundance of *A. mangium* have highly interacted with the physicochemical properties of the host soil [30,34,35]. The *A. mangium* tree associates with diazotrophic bacteria (Rhizobia), influencing the higher N availability in the soil [36]. Reportedly, *A. mangium* plantation increased pH, total N concentration, and available P in the soil [37]. It is worth noting that the influence of invasive species on soil properties as well as microorganism structure and function may not always remain constant or accumulate throughout the invasion [38].

The tropical rainforest of Malaysia is one of the most luxuriant and complex habitats in the world, which preserves the wealth of flora and fauna [39]. Notwithstanding the spectral features of forestland in Malaysia, many forest areas have been converted for urban and industrial settlement purposes and agricultural production [40,41]. Reportedly, the rehabilitation processes of degraded forests in the tropical regions of Malaysia, especially in Peninsular Malaysia, have been successfully applied with the plantation of *A. mangium* [35,42], *Azadirachta excelsa*, *Pinus caribaea*, and *Khaya ivorensis* [2]. Although the history of *Acacia* plantation in Malaysia goes back to 1932, when *Acacia auriculiformis* was introduced to the Forest Research Institute Malaysia (FRIM), the seeds of *A. mangium* were introduced to Sabah state in 1966 [43]. In 1976, *A. mangium*'s first commercial plantation was reported in Sabah. However, in 1978, due to the severe timber crisis caused by natural disasters, the authorities in Peninsular Malaysia selected *A. mangium* as the primary species for the Compensatory Plantation Programme in 1978 [44]. Interestingly, recent pattern analysis of *Acacia* plantation has confirmed the development of *A. mangium* plantation in Malaysia [45].

Notwithstanding the above literature regarding the interaction of soil with NFS trees and the importance of *Acacia* species in the rehabilitation programs, not very much is known about the impact of exotic *A. mangium* on soil properties. To this end, the present investigation was conducted to quantify and interpret the physicochemical adjustment of the soil under four different canopies in the *A. mangium* region, the native forest region, and the transition region between the *A. mangium* and the native forest. This study would lead to a better understanding of the effect of *A. mangium* canopy on the host ecosystem in Ayer Hitam Forest Reserve situated in Puchong, Selangor, which is one of the states in Peninsular Malaysia.

2. Materials and Methods

2.1. The Study Site Description

2.1.1. Geographical Distribution of the Study Site

The study site was in the Ayer Hitam Forest Reserve (longitude of 101°30′ E–101°46′ E and latitude of 2°56′ N–3°16′ N), Puchong experimental farm, Universiti Putra Malaysia (UPM), Serdang, Selangor (Figure 2). The Ayer Hitam Forest Reserve (AHFR) site lies in a lowland tropical rain forest. It comprises steep slopes, in which its highest peak reaches approximately 645 m above sea level [46–48]. The forest was logged over in 1906 with 4270.7 ha; however, the forest area has been decreased up to 72% (the current area is approximately 1176 ha) [48].

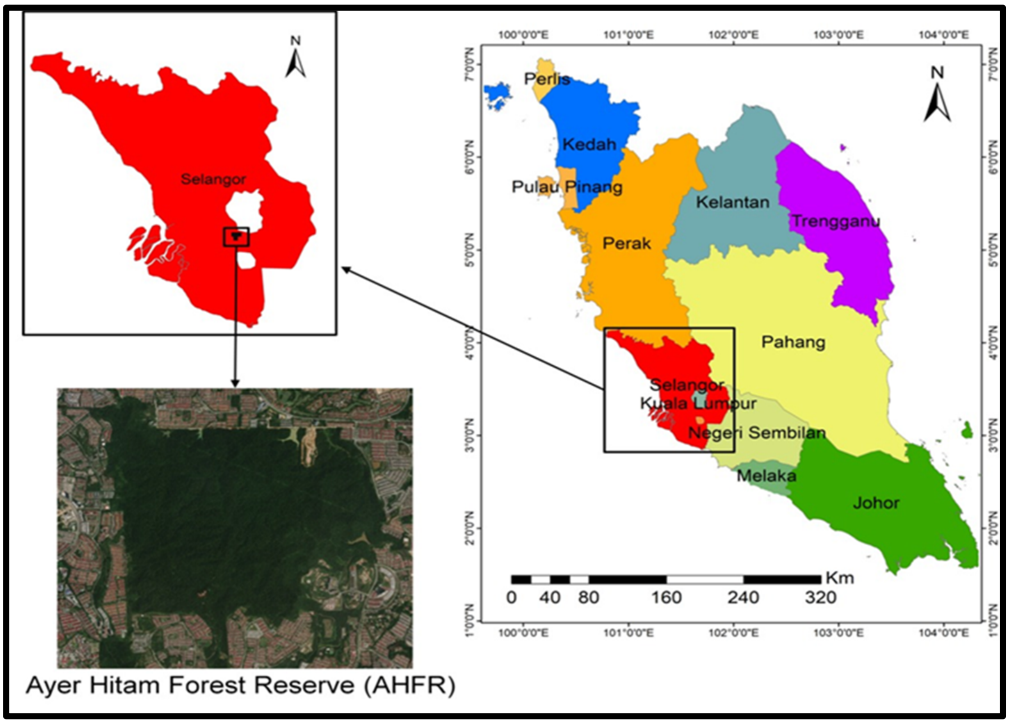

Figure 2. Location of Ayer Hitam Forest Reserve (AHFR), Puchong experimental farm, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia [49].

2.1.2. Climate Condition of the Study Site

Peninsular Malaysia has a tropical climate, influenced by the monsoon regime with an extensive seasonal reversal of the wind regime [50,51]. The major monsoon regimes are (1) the northeast monsoon (winter monsoon) and (2) the southwest monsoon (summer monsoon). The northeast monsoon usually occurs between November to March, while the Southwest monsoon occurs between late May and September. The transition from the southwest to the northeast monsoon season takes place in October [52,53]. Peninsular Malaysia has a constant mean annual temperature, light winds, and high humidity all year round. The study site, Puchong, Selangor, is characterized by a tropical climate with a mean annual temperature and precipitation of 38 °C and 2000 mm, respectively [54] (Figure 3). There is a slight variation of about 2 °C in the average monthly temperature of the study site. However, the daily variation in the temperature is about 10 °C [55].

2.1.3. Physiographical and Vegetation of the Study Site

The forest reserve has been severely degraded and encroached due to road construction, logging activities, and agriculture and housing projects [56,57]. AHFR is a secondary disturbed lowland dipterocarp forest with a history of logging activities. It has been placed under the purview of Universiti Putra Malaysia (UPM) [55]. AHFR lies within the Kenny Hill geological formation, which is located to the south of Kuala Lumpur [55]. This formation consists of a series of interceded mudstones, shales, and sandstones [58]. The site has an uneven landscape with an elevation between 15 and 200 m above sea level (ASL) and a mean slope of 10–20%. The AHFR site is a steep land, with an amalgamation of Durian, Serdang, and Kedah soil series, with metamorphic and sedimentary rocks as their parent material [58]. The forest is in the late stage of regeneration that is dominated by a high density of small and medium-size trees, with the forest floor densely covered by seedlings, saplings, herbs, climbers, creepers, palms, and ferns [59]. The forest contains one of the rarest species of small plants and herbs [46,60]. The *A. mangium* trees are located on the edge of native trees, most likely planted as windbreakers but diffused within the native trees.

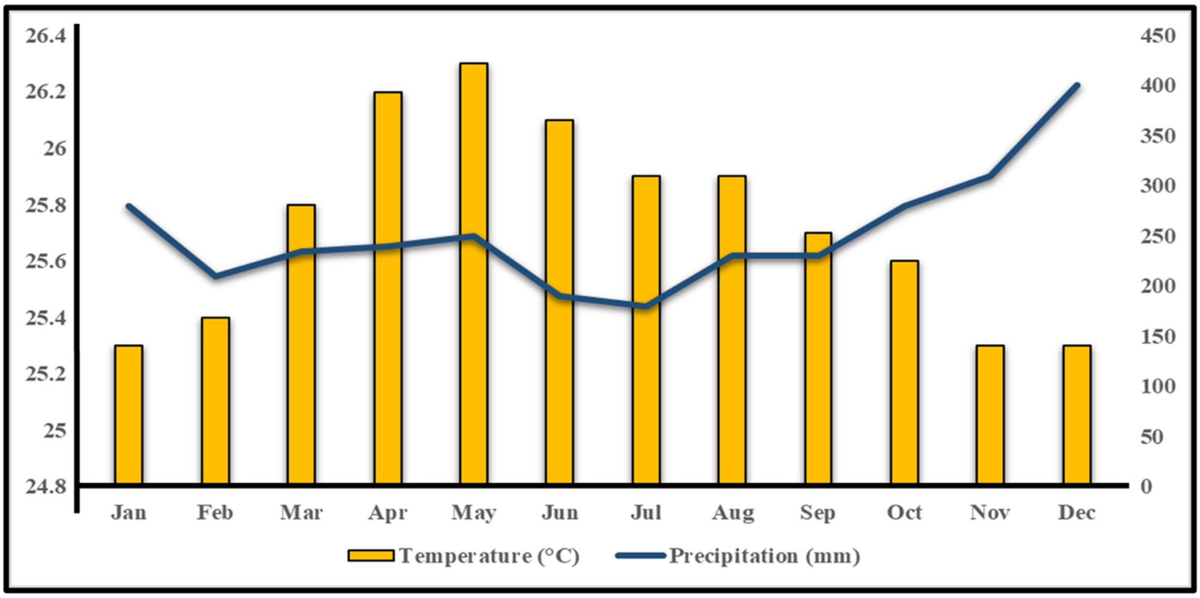

Figure 3. Climate average of the study site. (A) Average precipitation (mm) and mean temperature (°C) of the study site (Puchong) between 2010 and 2020 (Accessed on 23 April 2021, World Weather Online https://www.worldweatheronline.com/).

2.2. Data Collection

2.2.1. Soil Sampling, Preparation, and Analysis

In March 2018, soils were sampled from four places in the study area. A single transect line was established about 500 m apart, running in a north-south direction from the open ground region and passing through the *Acacia* trees region to the native tree area. A total of twelve pairs of 20 m × 20 m plots were set up along the line transects with plots 1–6 set up at the open ground region (OG), plots 7–12 at the *A. mangium* region (AM), plots 13–18 at the transition region (TZ) which lies between the *A. mangium* region and the native forest region, and plots 19–24 at the native forest region (NF) (Figure 4).

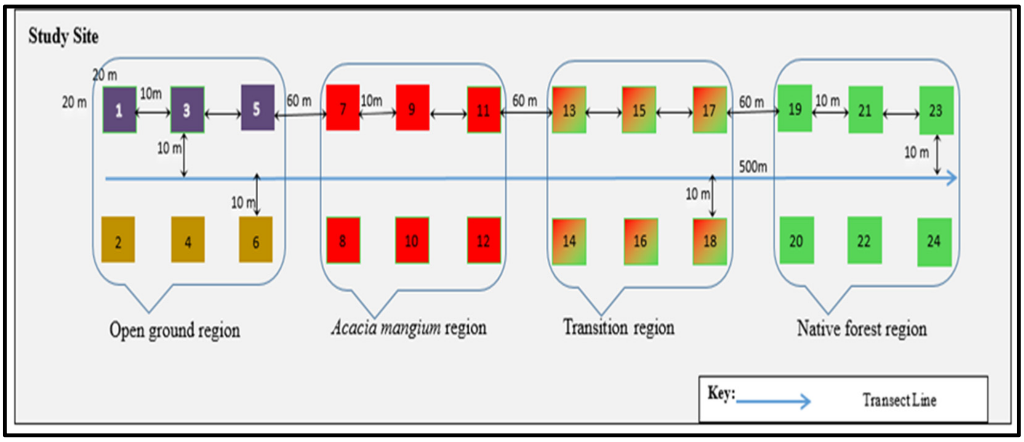

Figure 4. Schematic diagram of plot placement in this study.

Each plot (20 m × 20 m) was sub-divided into four 10 m × 10 m sub-plots (96 subplots in total). Composite samples were obtained by mixing well individual soil cores taken within each subplot, at 0–15 cm depth (topsoil) and 15–30 cm depth (subsoil) using a soil auger, and bulked together to form a homogeneous sample. A total of 48 representative soil samples were then used for analysis in the study of four regions as described in Table 1. The soil samples were kept in well-labelled sampling bags and transported to a laboratory for analysis. All analyses were performed in triplicate using calibrated equipment. The quality of the analysis and the analytical accuracy was considered through sampling, sample size, transportation methods, and the selection of a specialized and accredited laboratory for soil analysis.

Table 1. Description of plot placement.

Study Site Name	Region Code	Plots	Study Site Altitude
The *Acacia mangium* region	AM	7–12	3°00′18.2″ N, 101°38′51.2″ E, elevation 100 m
The native forest region	NF	19–24	3°00′22″ N, 101°38′49.1″ E, elevation 100 m
The open ground region	OG	1–6	3°00′19″ N, 101°38′54″ E, elevation 100 m
The transition region	TZ	13–18	3°00′20″ N, 101°38′ 50.3″ E, elevation 100 m

2.2.2. Physical Properties of Soil

Determination of soil moisture content was quantified using the oven-dry method by calculating the amount of mass lost by a 2-gm soil sample after it was dried at 105 °C for 24 h [40,61]. Soil texture was determined using the pipette method calculating for sand, silt, and clay properties using a textural triangle as described by The et al. [62]. The textural classification was based on the USDA soil texture triangle of size classes as: clay (<0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2.0 mm) [63]. Bulk density and particle density were determined according to the procedure described by Gupta et al. [64] for soil samples.

2.2.3. Chemical Properties of Soil

The soil samples were air-dried at room temperature (21–27 °C) for 1 week, ground and passed through a 2 mm sieve to remove gravel and debris, and analyzed at the Soil Laboratory of the Faculty of Agriculture, Universiti Putra Malaysia (UPM). The physico-chemical analyses of the soil samples were conducted at the Department Soil Laboratory of the Faculty of Agriculture following standard laboratory procedures. Soil chemical properties have been selected, taken (topsoil) and (subsoil) from the study regions for analysis of pH, electric conductivity (EC), exchangeable bases (EB) (Ca, Mg and K), cation exchange capacity (CEC), organic matter (OM), total nitrogen (TN), and available phosphorous (Av. P). pH was measured using a digital pH meter (Systronics 335) at a ratio of 1:2.5 soil-to-water suspension [65]. Electrical conductivity (EC) was measured using the EC meter (Systronics 335) in solution at a ratio of soil to water (1:5) [65]. Exchangeable cations were extracted using the leaching method by ammonium acetate (1 M) buffered at pH 7 [42]. The concentrations of Magnesium (Mg) and Calcium (Ca) in the solutions were determined by the atomic absorption spectrophotometer (AAS), and K was determined by a flame photometer [66]. Total nitrogen was determined using a LECO CR412 carbon analyzer (LECO, Corporation, St. Joseph, MI, USA) [67]. Available phosphorus was analyzed using an auto-analyzer by following the method described by Bray and Kurtz [42].

2.3. Statistical Analysis

All data collected were subjected to statistical analyses using SAS version 9.3 (SAS Institute, Inc., Cary, NC, USA). The difference in soil properties was determined using one-way ANOVA and comparison among the significant means was done using Duncan's multiple comparisons at $p \leq 0.01$.

3. Results and Discussion

As mentioned earlier, we implemented the experiment in four different regions, namely, OG, AM, TZ, and NF (Figure 4). Each specific region showed its unique characteristics, which could be taken into account for the qualitative observations. For example, the OG region was bare land without trees. In the NF region, there were 27 tree species from 25 genera and 17 families, where *Endospermum diadenum* dominated, followed by *Balakata baccata*, *Macaranga gigantean*, *Santiria tomentosa*, *Shorea macroptera*, *Xylopia fusca*, *Canarium pseudosumatranum*, *Knema hookeriana*, *Antidesma cuspidatum*, and *Adina polycephala*.

Furthermore, a total of 16 tree species from 13 genera and 11 families were reported in the TZ region, wherein the most dominant tree species were *Endospermum diadenum,* followed by *Acacia mangium, Macaranga gigantean*, and *Rinorea anguifera*. In the AM region, the most dominated tree species was *A. mangium,* followed by *Cinnamomum iners*, and *Endospermum diadenum*, while the least dominant was the *Rinorea anguifera*.

3.1. The Physicochemical Properties of Soils

3.1.1. Physical Properties of Soil

The results of ANOVA and Duncan's multiple comparison tests showed no significant differences in the soil texture among the four regions (Table 2). However, the results showed significant differences in the depth of the organic matter among the regions (Table 2). Clay soils are characteristic of an environment with a predominance of abundant rainfall and high temperature, which causes rapid weathering and degradation of soil material; this is the prevalent weather condition in the areas of the humid tropics such as Malaysia [68]. The clayey nature of the soil with a fair amount of loam makes it suitable for plantation activities, as the soil structure is not overly compact. This enables easy root penetration with a balanced ratio of air and water occurring within the soil [69]. Due to the clay nature of the soil and the high amount of sand in the soil, the site can be said to be dominated by coarse-grained rocks. These rocks include sandstone and/or clastic rocks, similar to the soils with well-drained structures. When the soil has more clay or a lesser amount of sand and loam, becomes tacky with a decreased water movement [70,71].

Table 2. Particle-size distribution of the soils in the regions under study.

Regions	Clay (%)	Silt (%)	Sand (%)	Textural Class	Depth of Organic Matter (cm)
AM	50.88 ^{a} ± 1.4	33.16 ^{a} ± 1.5	15.98 ^{a} ± 1.2	Clay Loam	3.47 ^{a}
NF	53.36 ^{a} ± 0.8	32.30 ^{a} ± 1.5	14.34 ^{b} ± 1.2	Clay Loam	7.03 ^{a}
OG	50.62 ^{a} ± 2.4	32.1 ^{a} ± 1.5	17.28 ^{a} ± 1.2	Clay Loam	1.5 ^{c}
TZ	52.53 ^{a} ± 1.1	33.1 ^{a} ± 1.5	17.53 ^{a} ± 1.2	Clay Loam	5.11 ^{b}

AM = *Acacia mangium* region, TZ = Transition region, OG = Open ground region, NF = Native Forest region. Different letters indicate significant differences between arsenic concentrations according to Duncan's multiple comparison test ($p \leq 0.01$).

3.1.2. The Chemical Properties of Topsoil (0–15 cm Depth)

The available phosphorus amount was significant at the level of $p \leq 0.05$ between all of the different regions. Furthermore, the highest exchangeable calcium, magnesium, and potassium were reported in OG, TZ, and TZ regions with 0.60, 0.42, and 0.26 cmolc kg^{-1}, respectively (Figure 5A). Additionally, the lowest exchangeable calcium, magnesium, and potassium were seen in the NF, NF, and AM regions with 0.54, 0.33, and 0.22 cmolc kg^{-1}, respectively (Figure 5A). The results of the electrical conductivity tests showed that the highest and lowest EC were observed in the NF and OG regions, with 0.14 and 0.10 ds/m, respectively. On the other hand, the highest and lowest organic matter were reported in the AM and OG regions, with 4.33% and 2.81%, respectively (Figure 5B). The highest and lowest soil pH were reported in the AM and OG regions, with 4.5% and 4.38%, respectively (Figure 5B). Reportedly, the highest total nitrogen, gravitational water content (GWC) and available phosphorus were observed in the AM (0.16%), OG (18.29), and NF (14.65 mg kg^{-1}) regions, respectively (Figure 5A,B). Finally, the lowest total nitrogen, GWC, and available phosphorus were observed in the OG (0.09%), TZ (17.49), and OG (12.72 mg kg^{-1}) regions, respectively (Figure 5A,B).

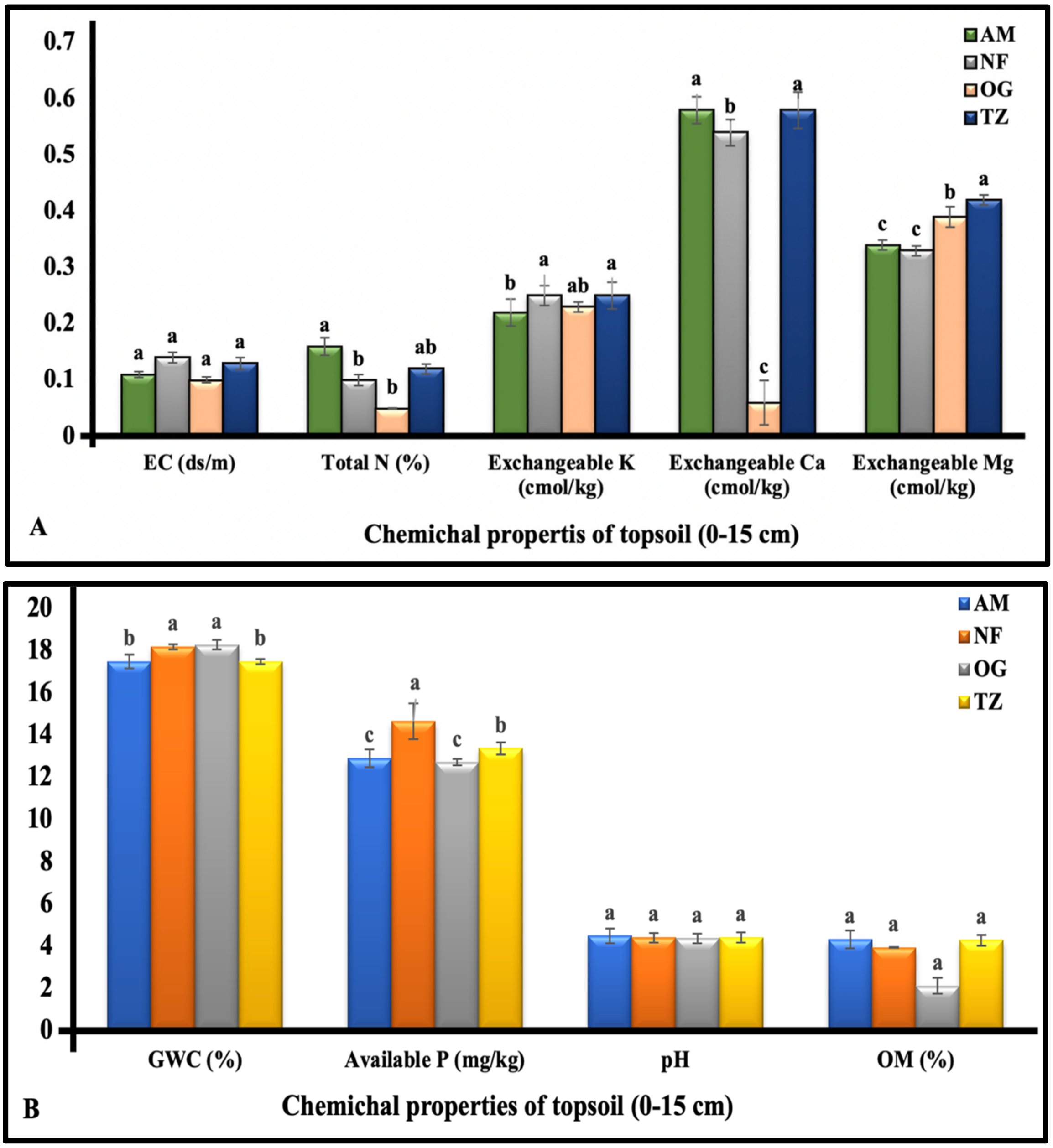

Figure 5. Measurements of (**A**) electrical conductivity (EC), total nitrogen (N), exchangeable calcium, exchangeable magnesium, and exchangeable potassium, and (**B**) gravitational water content, available phosphorus, pH, and organic matter of topsoil (0–15 cm depth) in Ayam Hiter forest of Malaysia across four different regions. Note: AM = *Acacia mangium* region, TZ = Transition region, OG = Open ground region, NF = Native Forest region. Distinct letters imply significant distinctions between arsenic concentrations following Duncan's multiple comparison test ($p \leq 0.01$).

The organic layer in the topsoil of the forest has been quite high, and this is mostly attributed to debris from dead plants and/or fallen leaves on the soil surface. The clayey soils tend to have more organic matter content than coarse soils [72]. A higher organic layer in the native forest region was thought to be due to a decrease in the decomposition rate of shrubs and leaves. This may happen as a result of low temperature and abundant moisture caused by shading in the native forest region. This finding was consistent with the observation of Matali et al. [73], who stated that the occurrence of shading in Heath Forest decreased the decomposition rate of herbs and shrubs, and increased organic layer depth in native regions. On the other hand, reducing the organic layer depth in the *Acacia* region was reported as a typical feature of soil under the canopy of invasive plants. The accelerated rate of decomposition, resulting from exposure of surrounding leaf litters to high temperatures, could be due to a reduction in trees and shrubs [74]. Also, *Acacia* has been known to decompose rapidly, and this could be due to its high foliar nitrogen, which increases the activities of microbial biomass responsible for decomposition in the soil [75,76]. Despite the relationship between the organic layer and the organic matter content, we could not establish differences in the organic matter content of the *Acacia* region, the native forest region, and the transition region. This may arise due to the thickness and fibrous nature of the leaf layers, which slows decomposition, hence the similarity in organic matter content of the plots [77,78].

3.1.3. The Chemical Properties of Subsoil (15–30 cm Depth)

The results of the electrical conductivity tests showed that the highest and lowest EC were observed in the OG and NF regions, with 0.11 and 0.09 ds/m, respectively (Figure 6A). Furthermore, the highest exchangeable calcium, magnesium, and potassium were reported in the AM, TZ, and NF regions, with 0.64, 0.43, and 0.30 cmolc kg^{-1}, respectively (Figure 6A). Additionally, the lowest exchangeable calcium, magnesium, and potassium were seen in the NF, AM, and AM regions, with 0.52, 0.30, and 0.21 cmolc kg^{-1}, respectively (Figure 6A). Besides, the highest and lowest organic matter were reported in the NZ and OG regions, with 4.22% and 2.14%, respectively (Figure 6B). The highest and lowest soil pH were reported in the TZ and AM regions, with 4.59% and 4.20%, respectively (Figure 6B). Reportedly, the highest total nitrogen, gravitational water content (GWC), and available phosphorus were observed in the AM (0.14%), NF (16.00), and NF (14.82 mg kg^{-1}) regions, respectively. Finally, the lowest total nitrogen, GWC, and available phosphorus were observed in the OG (0.09%), TZ (12.70), and AM (14.20 mg kg^{-1}) regions, respectively (Figure 6A,B). An acidic pH in the *A. mangium* plantation was probably due to high rates of nitrification from the *A. mangium* litter decomposition. It showed that the protons were released to exchange with nitrate uptake by the N-fixing legumes, thus causing soil acidification [79]. The high production of ammonium from plant material decomposition causes soil acid neutralization [12]. The reduction in microbial activities could increase the organic matter and cause soil acidity [80,81]. The higher mean concentration of nitrogen (N) in the *Acacia* region, unlike in the other regions, was probably due to a reduction in the organic matter decomposition of soil [82,83]. Also, the higher amount of N in the *Acacia* plantation region was due to the nitrogen-fixing capability of *Acacia* [84,85]. *A. mangium* can fix atmospheric N due to a symbiotic association with bacteria present in its root nodules; thus, it could produce N-rich leaves, compared to other tropical leguminous trees [85,86]. This phenomenon leads to extensive deposition of N rich litters, which increases the concentration of nitrogen in the soil under *A. mangium* canopy [15,85]. This claim was supported by Vijayanathan et al. [87], who found a higher level of total N in the soil during the second rotation of a 0–6-month-old *A. mangium* plantation in Peninsular, Malaysia, compared to a mixed dipterocarp forest.

3.1.4. Comparison of the Physicochemical Properties of Top- and Sub-Soil in the Four Regions

The ANOVA and Duncan's multiple comparison tests showed significant differences in the level of $p \leq 0.01$ for available phosphorus and organic matter, as well as $p \leq 0.05$ for cation exchange capacity between top- and sub-soil in the *A. mangium* region (Table 3A). Additionally, the ANOVA and Duncan's multiple comparison tests of the top- and sub-soil were significant ($p \leq 0.01$) in terms of gravimetric water content and cation exchange capacity in the native forest region (NF) (Table 3B). On the other hand, significant differences ($p \leq 0.01$) were observed in terms of cation exchange capacity as well as available phosphorus between top- and sub-soil in the open ground region (OG) (Table 3C). Finally, the ANOVA and Duncan's multiple comparison tests also showed significant differences in the level of $p \leq 0.01$ for available phosphorus and $p \leq 0.05$ for cation exchange capacity and total nitrogen between top- as well as sub-soil in the transition region (TZ) (Table 3D).

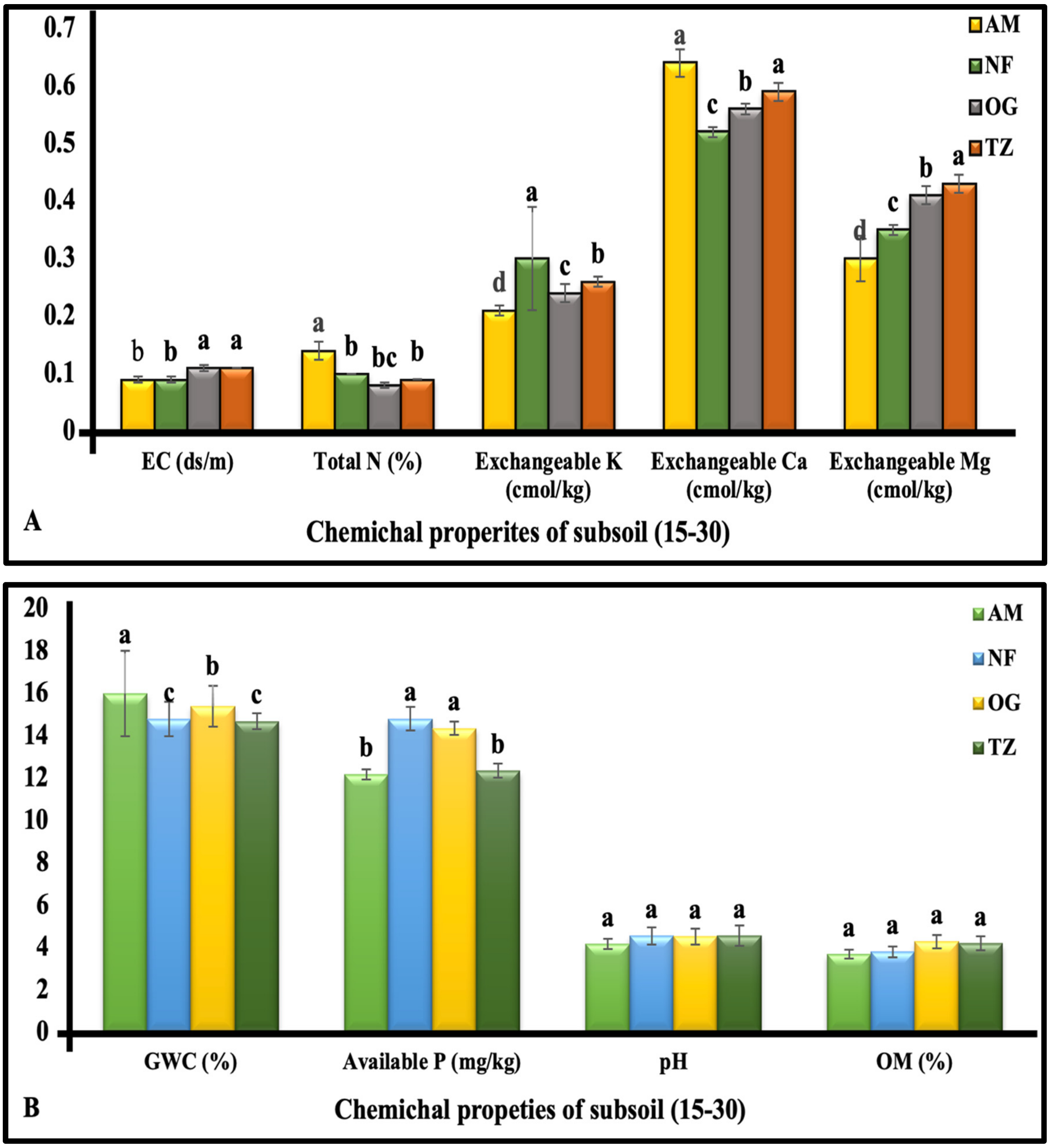

Figure 6. Measurements of (**A**) electrical conductivity (EC), total nitrogen (N), exchangeable calcium, exchangeable magnesium, and exchangeable potassium, and (**B**) gravitational water content, available phosphorus, pH, and organic matter of subsoil (15–30 cm depth) in Ayam Hiter forest of Malaysia across four different regions. Note: AM = *Acacia mangium* region, TZ = Transition region, OG = Open ground region, NF = Native Forest region. Distinct letters imply significant distinctions between arsenic concentrations following Duncan's multiple comparison test ($p \leq 0.01$).

Table 3. ANOVA results of physio-chemical characteristics of top- and sub-soil in the four regions of study.

		A *A. mangium* Region (AM)									**B Native Forest Region (NF)**							
S.O.V	df	GWC	pH	EC	OM	N	P	K	Ca	Mg	GWC	pH	EC	OM	N	P	K	Ca
Regions	1	3.5 ^{ns}	0.1 ^{ns}	0.0004 *	0.5 **	0.0006 ^{ns}	0.7 **	0.0001 ^{ns}	0.005 ^{ns}	0.002 ^{ns}	17.3 **	0.03 ^{ns}	0.003 **	0.02 ^{ns}	0.00001 ^{ns}	0.04 ^{ns}	0.003 ^{ns}	0.0006 ^{ns}
Replicate	2	7.9 ^{ns}	0.008 ^{ns}	0.00001 ^{ns}	0.0006 ^{ns}	0.0001 ^{ns}	0.12 ^{ns}	0.0006 ^{ns}	0.001 ^{ns}	0.005 ^{ns}	2.1 ^{ns}	0.11 ^{ns}	0.00006	0.002 ^{ns}	0.00002 ^{ns}	0.8 ^{ns}	0.006 ^{ns}	0.00015 ^{ns}
Error	2	1.5	0.01	0.00001	0.0005	0.00045	0.01	0.0002	0.0003	0.004	0.06	0.08	0.00006	0.001	0.0000001	0.45	0.004	0.0006
Total	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C.V.	-	7.4	2.9	4.01	0.56	14.1	0.97	6.57	3.06	21.07	1.5	6.5	6.9	1.06	0.8979	4.58	23.56	4.8

		C Open Ground Region (OG)									**D Transition Region (TZ)**							
S.O.V	df	GWC	pH	EC	OM	N	P	K	Ca	Mg	GWC	pH	EC	OM	N	P	K	Ca
Regions	1	12.5 ^{ns}	0.03 ^{ns}	0.0001 **	0.002 ^{ns}	0.00006 ^{ns}	4.08 **	0.0001 ^{ns}	0.002 ^{ns}	0.0006 ^{ns}	11.7 ^{ns}	0.043 ^{ns}	0.001 *	0.01 ^{ns}	0.001 *	1.53 **	0.000001 ^{ns}	0.0001 ^{ns}
Replicate	2	0.03 ^{ns}	0.006 ^{ns}	0.00006 ^{ns}	0.0002 ^{ns}	0.00001 ^{ns}	0.03 ^{ns}	0.0002 ^{ns}	0.004 ^{ns}	0.00005 ^{ns}	0.48 ^{ns}	0.006 ^{ns}	0.00006 ^{ns}	0.001 ^{ns}	0.00005 ^{ns}	0.001 ^{ns}	0.0006 ^{ns}	0.0009 ^{ns}
Error	2	1.7	0.002	0.000001	0.0008	0.00001	0.006	0.0002	0.006	0.0006	0.66	0.003	0.00006	0.003	0.00005	0.006	0.0002	0.0006
Total	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C.V.	-	7.8	1.1	0.754	1.3	4.7	0.58	6.01	13.4	6.3	5.06	1.28	6.9	1.34	6.73	0.63	5.43	4.35

S.O.V, source of variation. ** and *, significant at the 0.01 and 0.05 probability levels, respectively. ns, non-significant. GWC = gravimetric water content, pH = potential of hydrogen, EC = cation exchange capacity, OM = organic matter, N = total nitrogen, P = available phosphorus, K = exchangeable potassium, Ca = exchangeable calcium, and Mg = exchangeable magnesium subsoil and topsoil of four regions of *A. mangium* region (AM) and Native Forest Region (NF).

Compared to the subsoil, the EC level was higher in the topsoil of the AM, NF, and TZ regions, with 0.11, 0.14, and 0.13 ds/m, respectively. However, the EC level was higher in the topsoil of the OG region, with 0.11 ds/m, compared to topsoil with 0.1 ds/m (Figure 7A). The percentage of total N was higher in the topsoil of the AM and TZ regions and was lower in the topsoil of OG. Additionally, there were no significant differences between the N percentage in the top and subsoil of the NF area (Figure 7A). The soil of AM had the highest concentrations of total N at both topsoil and subsoil depths, with a mean between 0.16 and 0.14, respectively; the OG region had the lowest mean, between 0.09 and 0.08. The results of our observation showed significant differences between AM and other regions in terms of total N concentrations for both subsoil and topsoil (Figure 7A). Our data showed that the exchangeable K amount was higher in the topsoil of the AM region, compared to the subsoil. However, the exchangeable K rate was higher in the subsoil of the other three regions, compared to the topsoil (Figure 7A). Additionally, the exchangeable Ca rate was higher in the topsoil of the AM and OG regions (Figure 7A). Compared to the subsoil, the exchangeable Mg rate of topsoil was higher in the AM and TZ regions (Figure 7A). Our observations also showed that the mean of GWC was significantly higher in the topsoil of all four regions (between 17.50 and 18.29), compared to the subsoil (between 14.70 and 16.00) (Figure 7B). Reportedly, GWC could be influenced by some other soil characteristics such as depth of organic layer, soil structure, and texture. These physical characteristics of soil may lead to retaining water, preventing filtration, and surfacing runoff [88,89]. Thus, a higher level of organic layer depth may increase the soil pores and increases water infiltration. Our results in the open ground region also confirmed the correlation of GWC with organic layer depth and organic matter content. In addition to the above results, our observation showed that the level of pH was slightly different between soils (topsoil and subsoil) in all the studied regions (Figure 7B). The higher rate of exchangeable K could be due to the high mobility of K in the soil–plant system, which can leach to deeper soil layers [90,91]. Our results were in parallel with Yamashita et al. [33], who found that there was a non-significant difference in the exchangeable K of the soil between an *A. mangium* plantation, a secondary forest, and Imperata grassland. Similarly, Matali et al. [73] stated no significant difference in the amount of exchangeable K in the soil under the canopy of *Acacia* in Brunei.

The establishment of forests containing invasive plants such as *A. mangium* will reduce the availability of shrubs and tree layers, which will be expose the leaf litter layer to high temperatures [92]. For this reason, the leaf litters breakdown will be rapidly increased and the decomposition rate will be accelerated [93,94]. Reportedly, a high rate of decomposition has been observed in *Acacia* leaf litter and the high rate of foliar N may cause the high N accumulation [85] and the high microbial activity in the soil [95]. *Acacia* is considered to be an N_2 fixer plant that is able to increase the N or NH_4^+ pool in the soil. This could happen due to the higher production of litter by *Acacia*, which leads to returning of N into the soil and increasing the amount of inorganic N. For example, it has been reported that *A. longifolia* transfers large quantities of N to the soil and, simultaneously, uptakes a higher amount of P. This cycle creates an N/P imbalance in the ecosystem. Additionally, *Acacia* progressively and substantially changes C storage in invaded soils [96]. In parallel with the above literature, our results showed a higher accumulation of N and a lower amount of P in AM region (in both soil depths), compared to other regions. In addition, the leaf structures in other regions of our study were tougher and thicker than the leaves in the AM region. This may cause the high-speed uptake of N from soil to plant biomass due to the need for plants to protect their long-lived leaves [97].

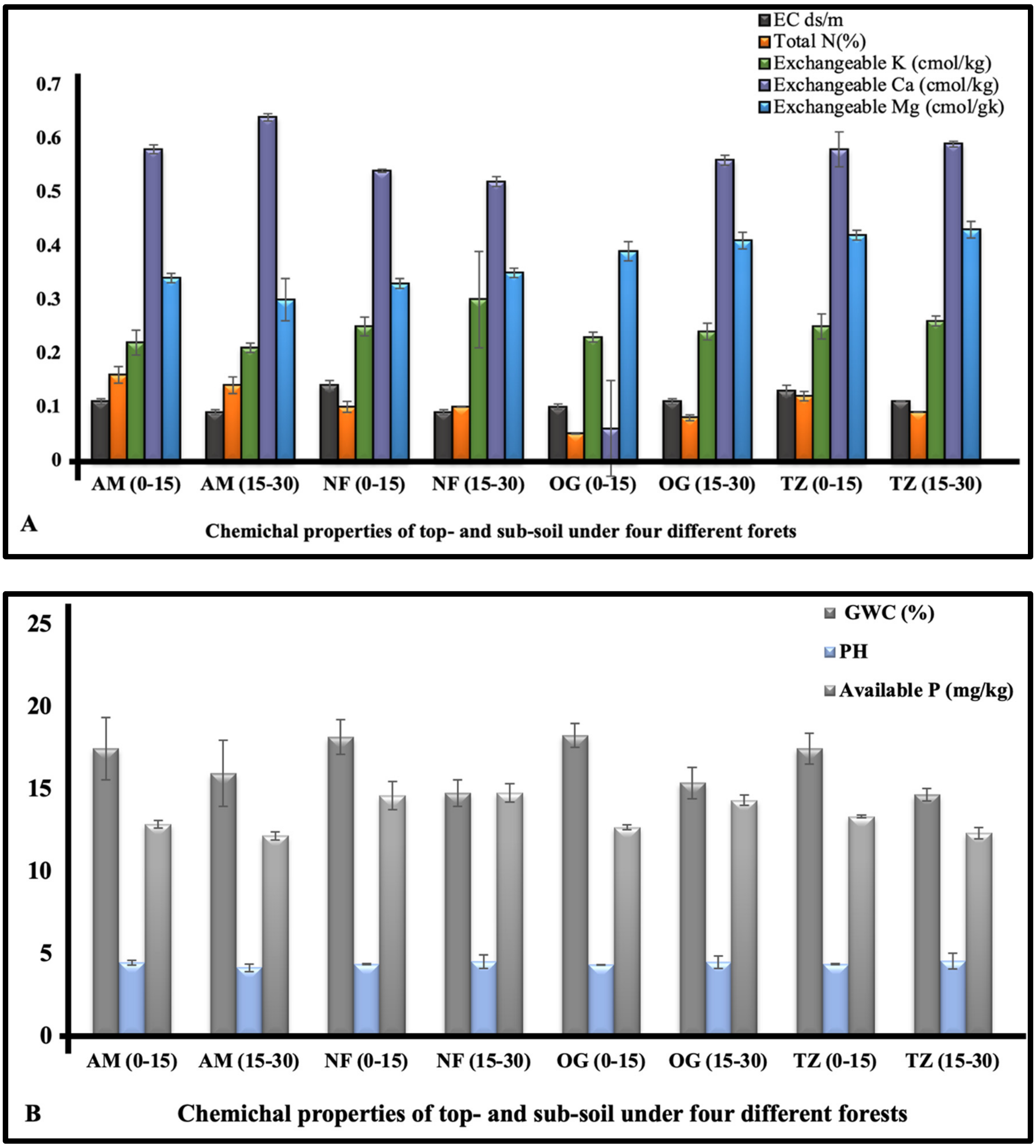

Figure 7. Measurements of (**A**) electrical conductivity (EC), total nitrogen (N), exchangeable calcium, exchangeable magnesium, and exchangeable potassium, and (**B**) gravitational water content, available phosphorus, pH, and organic matter of top and subsoil (15–30 cm depth) in Ayer Hitam FR across four different regions. Note: AM = *Acacia mangium* region, TZ = Transition region, OG = Open ground region, NF = Native Forest region. Distinct letters imply significant distinctions between arsenic concentrations following Duncan's multiple comparison test ($p \leq 0.01$).

At acidic pH soil, P ions react with iron (Fe) and Aluminum (Al) to form less soluble compounds (Fe-P and Al-P compound) [98]. Therefore, low available P in soils could be due to sequestration of P in the *Acacia* biomass [73] and could form the acidic pH soils under the canopy of *Acacia* in different ecosystems [99]. Nonetheless, Castro–Díez et al. [20] reported no significant differences in organic matter and pH after the invasion of *Acacia* in the host ecosystem. Additionally, Marchante et al. [100] and Rascger et al. [101] observed a significant increment in the litter, pH, C/N ratio, and amount of N and C in ecosystems that were invaded by *A. longifolia.* Katagiri et al. [102] reported that the soil acidification in the invaded region was due to a decrease in exchangeable bases or cation concentrations. The alteration in chemical ions could be due to the leaching of nutrients or translocation of base cations from soil to plant biomass. The results of our study also confirmed the lower level of exchangeable Mg and K in the AM region (in both top- and sub-soils) compared to other regions. However, the level of exchangeable Ca was higher in the AM region, compared to other regions. In contrast with our results, Moran et al. [82] reported that the concentration of Ca was lower in the *Acacia* region, compared to other regions, and suggested that this may happen due to the fast-growing potential of *Acacia* resulting in higher nutrients absorption. With regards to the above-mentioned observation and assumptions, we propose that a reduction in Ca level could be influenced by the high rate of nutrients leaching or returning nutrients in the soil of AM region. Generally speaking, the above results might show the drastic influence of the ecosystem condition and the importance of plant–soil interaction in the invaded regions.

Availability of water in the soil is another vital parameter influencing the growth and development of trees; thus, the lack of enough water may limit forest growth. *Acacia* is considered a high water-consuming tree, and their invasion may lead to a reduction in the water availability of the host ecosystem and an increase in the rate of evapotranspiration [103]. In our experiment, the level of GWCs was higher in the topsoil of NF and OG regions. This might be due to the root development of tree and weed plants into subsoil in the NF and OG regions. Additionally, it can be said that *Acacia* absorbed the available water in the top-soil easily. At the same time, GWC was higher in the subsoil of the AM region, compared to other regions. This may happen due to the high competition of different tree species in other regions, compared to the AM region. Our results might confirm that the water consumption could be alternatively observed as a community-level mechanism rather than an individual *Acacia* strategy in the ecosystem [104].

Acacia species has distinct advantages for improving the fertility of the soil in forestry, agroforestry and agriculture in regions with nutrient-deficient soils and for the restoration of degraded lands and ecosystems. Nevertheless, there is a dearth of research on the ecology of this species in regions whereby there is a lack of understanding pertaining to the range. Despite the several documented advantages of *A. mangium* in forestry, agroforestry, and agriculture, there is growing concern that owing to its invasive characteristics, *A. mangium* can have a profound adverse influence on human wellbeing, biodiversity, and soil. Commercial forestry plantations are usually set up in expansive open areas that are highly vulnerable to invasions by exotic trees [105,106]. *A. mangium* may find it easy to invade degraded and disturbed forests, particularly those which have experienced fire or drought and may threaten biodiversity [106]. Perhaps one of the reasons for invasion and the wide cultivation of the *Acacia* species outside their native range is their usage in large commercial plantations over decades without a prior consideration for associated risks of invasiveness [107]. *Acacia* species have become invasive with attendant adverse effects. Invasions and the presence effect usually manifest after many years following extensive cultivation. This phenomenon has been seen in some places in Asia, prominently in Vietnam and Malaysia [105,107]. As far as we know, invasions of *A. mangium* occurred recently, and no detailed evaluation has been conducted to study the influence of these invasions on biodiversity. *Acacia* causes variations in the functional diversity of microorganisms in the soils (fungi and root fungi) that hinder the growth of native tree species while restoring degraded lands [108]. As for the types of effects attributed to other invasive Australian *Acacias* in several regions across the globe, *Acacias* possess a wide range of effects on ecosystems which increase with time and disturbance, and often change the function of the ecosystem, subsequently reducing and altering the delivery of ecosystem services [13].

4. Conclusions

This study revealed that *Acacia mangium* can improve some physical and chemical properties of degraded secondary forest soils in Air Hitam Forest Reserve in Puchong, Malaysia. *A. mangium* has a very high nitrogen-fixing capacity because of its symbiotic connection with nodule-forming bacteria, resulting in seedlings with more nitrogen-rich leaves than native tropical trees. Hence, this phenomenon led to the extensive deposition of nitrogen-rich litters increasing the concentration of nitrogen in the soil under the *A. mangium* region. Therefore, *A. mangium*'s capacity to fix nitrogen may contribute to soil acidification because base cations accumulate in its biomass. Although the concentrations of exchangeable calcium (Ca), magnesium (Mg), and available phosphorus (P) in the soil of the *A. mangium* region were not significantly different from those measured in other regions, the pH was the most influential soil variable associated with the *Acacia*. In summary, this study presented a positive case for biological invasion, which may be utilised to better understand the ecological impact of *A. mangium* invasion in secondary forest degraded regions through *A. mangium*'s ability to improve the condition of the degraded soils and restore nutrient cycling in degraded systems to enhance its growth.

Author Contributions: H.A.-H. contributed to the design and implementation of the research and Y.H.-S. provided guidance during some aspect of soil and result analysis, J.M., A.-M.J. and H.R.N. assisted during the sample collection from the forest region, M.-N.S., R.A. and H.R.N. processed the experimental data, performed the analysis and drafted the manuscript. All the authors assisted in the development and editing of the manuscript. The soil analysis was conducted at the Soil Science Department Laboratory of the Faculty of Agriculture, UPM. The experimental study was conducted at the Ayer Hitam Forest Reserve in Puchong, Malaysia. All authors have read and agreed to the published version of the manuscript.

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