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Research article

Seasonal and management influences on yield of *Melientha suavis* Pierre in different alley agroforestry systems

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Abstract

Importance of the work: There is a recognized need to enhance productivity in agroforestry systems through the utilization of *Melientha suavis* Pierre, a native Thai tree valued for its significant economic and conservation benefits.
Objectives: To analyze the impact of environmental factors and management practices on the yield of *M. suavis* leaves across different seasons and to create yield prediction models to support sustainable management strategies for agroforestry systems.
Materials & Methods: The study was conducted using four alley farming plots in Saraburi province, Thailand based on measurements of plant growth and environmental variables: canopy gap, leaf area index (LAI), soil moisture, soil temperature and electrical conductivity of pore water. Data were collected seasonally and analyzed using Pearson's correlation coefficient and generalized linear mixed models, with Akaike information criterion (AIC) values utilized for model comparisons.
Results: Management practices and environmental conditions significantly influenced leaf yield, with distinct responses between dry and wet seasons. Canopy gap, LAI and soil moisture were particularly influential, with the lowest AIC value of 1509 indicating the best-fitting yield prediction model.
Main finding: LAI and soil moisture were critical in determining the seasonal yield of *M. suavis* leaves. Species selection and spatial arrangements in tree alley farming significantly affect productivity. The diameter over bark at ground level of *M. suavis* was the most influential factor regarding leaf yield, suggesting that management should focus on promoting radial growth to enhance yield efficiency and sustainability.

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Introduction

Agroforestry is the intentional integration of trees and shrubs with crops and livestock, constituting a dynamic and multifunctional agricultural practice that has garnered increasing attention within scientific and agricultural communities (Gold and Hanover, 1987). This integration is not merely a land-use strategy but a sophisticated approach to achieving sustainable intensification of agriculture (Wilson and Lovell, 2016). The incorporation of woody perennials into agricultural landscapes is increasingly recognized for its capacity to yield substantial economic and ecological benefits, a theme that has been extensively explored in the literature (Smith et al., 2012; Leakey, 2014; Geertsema et al., 2016). The multifaceted benefits of agroforestry systems have been well-documented, including enhanced agricultural productivity, carbon sequestration, biodiversity promotion, nutrient use efficiency, pest-resistance resilience and soil erosion mitigation (Jose and Holzmueller, 2009; Quinkenstein et al., 2009; Tsonkova et al., 2012; Lorenz and Lal, 2014; Torralba et al., 2016).

Despite these advantages, the adoption of agroforestry practices faces economic challenges, notably the substantial initial investment and the long maturation periods of trees and shrubs compared to annual crops (Williams and Gordon, 1992; Dyack et al., 1999). However, the strategic utilization of multispecies systems (Malézieux et al., 2009) and the integration of high-value tree crops (Molnar et al., 2013) have been proposed as viable solutions to overcome these economic barriers.

Alley farming has been practiced for commercial agroforestry purposes and emphasizes balancing productivity and using perennial plants interspersed with cash crops (Hodge et al., 1999; Wolz and DeLucia, 2018; Boinot et al., 2019). In Thailand, alley farming incorporates the cultivation of local economic plants within agroforestry systems, primarily to produce local foods but also for their conservation value (Samsantad and Phonoi, 2009). For example, *Melientha suavis* Pierre is a Thai native tree species that has been mostly planted for tree alley farming in combination with companion trees, such as *Pithecellobium dulce* (Roxb.) Benth. *Sesbania grandiflora* (L.) Pers. *and Azadirachta indica* A. Juss.; with the *M. suavis* leaves also being grown as an economic vegetable, mostly in Ban Mo district, Saraburi province, central Thailand (Julapak et al., 2016). This co-planting can potentially offer a range of productivity benefits, including improved soil fertility, reduced soil erosion and increased tree products.

The young leaf yield of *M. suavis* can be affected by several factors that can substantially affect plant growth, including topographic, climatic, edaphic, pyric, biotic and anthropogenic factors (Berglund, 1969). Tuaktatong et al. (2023) found that the management of *M. suavis*, with the companion trees varied depending on related factors.

Management varies within the microclimate of the modified tree alley farms. This microclimate is a key factor facilitating the growth of tree crops, with practices including managing the planting of trees at suitable spacings that allow for adequate sunlight and air circulation (Quinkenstein et al., 2009). In addition, it is important to control weeds and pests to prevent damage to the trees and crops (Piotto et al., 2024), while growth and yield can be promoted by applying fertilizer, coppicing the old stem and pruning the trees (Quinkenstein et al., 2009; Piotto et al., 2024).

M. suavis belongs to the family Opiliaceae and is a small tree with a hemi-parasitic root system (Pignone and Hammer, 2016). This species is classified as a monotypic genus with two subspecies: 1) *Melientha suavis* ssp. *suavis* and 2) *Melientha suavis* ssp. *macrocarpa* (Phuma and Sudee, 2014). These subspecies differ in fruit shape and distribution, with the suavis subspecies having fruits that are somewhat elliptical to ovoid; it is distributed in Thailand, Laos, Vietnam, Cambodia, Malaysia and the Philippines (Vongsenekeo et al., 2022). At present, the young-leaf yield of *M. suavis* is still insufficient to meet the market demands in Thailand (Julapak et al., 2016). Therefore, within this context, the current study focused on a detailed environmental analysis of *M. suavis*, a potentially high-value tree crop, examining how seasonal variations and management practices influence its yield in agroforestry systems and creating *M. suavis* yield prediction models in agroforestry system. In addition, this study aimed to bridge the gap in knowledge regarding the environmental and management factors affecting the productivity of *M. suavis*, to contribute to the broader discourse on sustainable agricultural practices and their implementation in diverse agroecological contexts. Furthermore, the modified management patterns were studied of tree alley farms involving *M. suavis*, along with the relationships among related factors, including management practices and soil properties, that can differentiate the shoot yield of *M. suavis* in the dry and wet seasons. The results should serve as a database to promote tree alley cropping patterns that affect higher productivity and support ecological co-benefits by growing suitable trees in *M. suavis* agroforest systems.

Materials and Methods

Study area and plot description

The study was conducted in Ban Mo district in Saraburi province, central Thailand (14˚N, 101˚E; total area of Ban Mo district 1,559.98 km^2; Saraburi Provincial Office, 2016), as shown in Fig. 1, where the topography consists of hills and plain, with a slight slope from the north to the south (Land Development Department, 2021). Department of Mineral Resources (2007) and Land Development Department (2021) provided some information on the general region where the study was undertaken. The Ban Mo district contains a rich mosaic of land uses that mirror its diverse geography and vibrant local economy. Predominantly an agricultural region, Ban Mo features extensive rice fields, plantations of sugarcane, maize, and cassava, and thriving fruit orchards, particularly mango and banana. The district also encompasses urban centers with residential neighborhoods, rural villages, commercial hubs, and industrial zones with factories and designated industrial estates. Natural and recreational areas, including parks and waterways, provide leisure opportunities and support agricultural irrigation. As depicted on the map, this dynamic blend of agricultural, residential, commercial, and industrial land uses highlights Ban Mo strategic planning and sustainable development (Fig. 1). The soil group type is mostly of moderate depth, extending to marl or calcareous layers, with good drainage and moderate to high fertility; it originates from river sediments on the marl layers of the limestone foothills, and features relatively flat to gently undulating terrain (Land Development Department, 2013).

Saraburi province is classified as having a tropical wet and dry climate according to the Köppen classification system (Climate data, 2022), with distinctly different wet and dry seasons. For example, the southwestern monsoon winds exert a major influence on the summer and rainy seasons, resulting in increased moisture and precipitation, whereas conversely, the winter season is predominantly shaped by the northeastern monsoon winds, which contribute to colder and drier conditions (Land Development Department, 2013). Saraburi province has temperatures and precipitation in the ranges 27–30°C and 1,200–1,400 mm/yr, respectively (Thai Meteorological Department, 2023). On average, there are 105 rainy days annually, with an average relative humidity throughout the year of 71.04% (Land Development Department, 2013). Most of the population is engaged in agriculture, representing 70% of all households, with reportedly more than 394 ha of *M. suavis* alley farms across the province (Julapak et al., 2016).

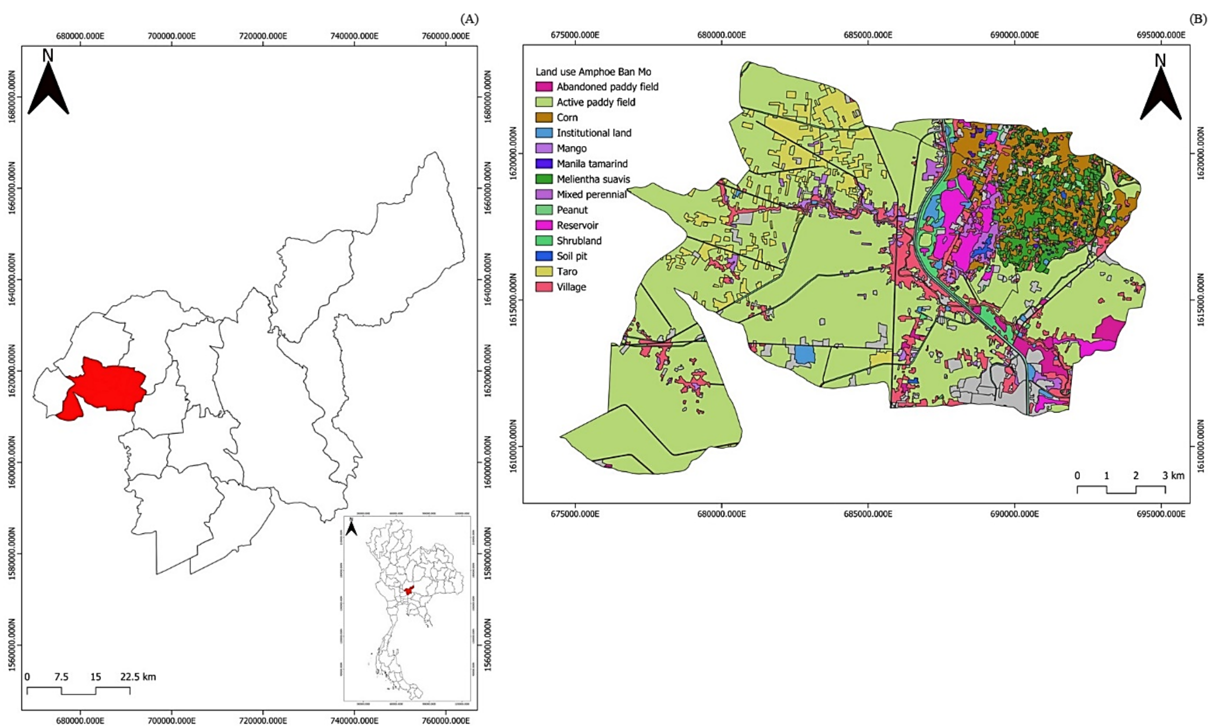

Fig. 1 Maps of: (A) Saraburi province, central Thailand; (B) Ban Mo study site

Four tree alley plots of *M. suavis* were selected using purposive criteria sampling to include a variety of species, stand ages (11–22 yr) and management practices to examine similarities and differences in agri-silvicultural techniques and factors relating to the yield of young leaves. In total, 354 individual *M. suavis* trees from the four alley farms were studied to evaluate the impact on yield harvesting of management practices, such as spacing, pruning, coppicing and watering systems. Measurements were made of microclimatic factors: canopy gap, leaf area index (LAI), soil temperature, soil moisture and the electrical conductivity of pore water (ECp).

Fig. 2 shows the current stand stages of the four tree alley farms (TAFs), with Table 2 providing the details of the various companion trees. The first managed stand (TAF1, Fig. 2A) contained *M. suavis* growing in a pure stand of a nitrogen-fixing tree species (*Pithecellobium dulce)*. The second managed stand (TAF2, Fig. 2B) contained *M. suavis* growing in between rows of mixed species of nitrogen-fixing trees, evergreen trees species and deciduous tree species. The third managed stand (TAF3, Fig. 2C) contained *M. suavis* growing in between rows of mixed semi-deciduous tree species and evergreen trees. The fourth managed stand (TAF4, Fig. 2D) contained *M. suavis* growing in between rows of mixed nitrogen-fixing tree species, deciduous tree species and evergreen trees.

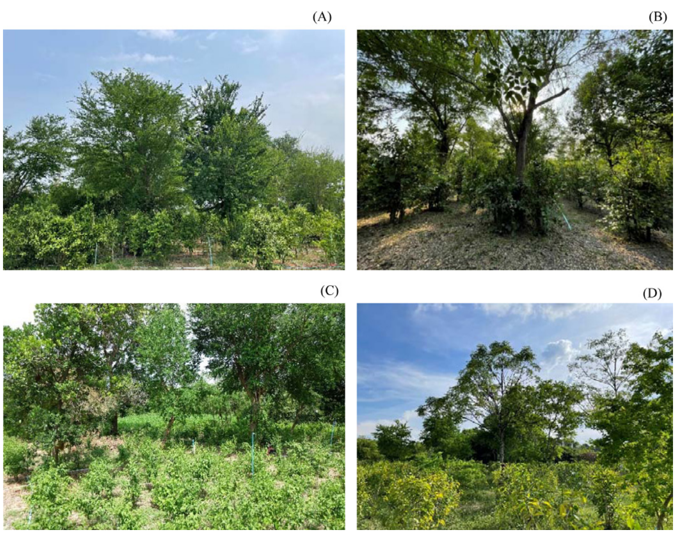

Fig. 2 Pattern variety in four studied tree alley farms (TAFs): (A) TAF1; (B) TAF2; (C) TAF3; (D) TAF4

Data collection

Vegetation in every other row was surveyed in the entire four plots using a systematic sampling method. All the tree crops (*M. suavis*) and companion tree species were identified and listed. The sampled tree crops were tagged. The young leaves were collected and weighed every 7 d after pruning of the targeted branches and mature leaves in each tree crop during the wet months of June and July and the dry months of March and April.

The tree crops were measured for diameter over bark (DOB) at ground level (D_0), DOB at height = 50 cm (D_{50}) and the total height. The companion trees were measured only for DOB at breast height (1.3 m) and total height. Canopy gaps were measured using an application of the FisheyeCam application Version 1.2.6 (2020) for smart phone (iPhone 12 Pro; Apple Inc.; China). For each tree, images were captured in the four cardinal directions (north, south, east and west) and analyzed using the Gap Light Analyzer program (Cary Institute of Ecosystem Studies, Simon Fraser University; Greater Vancouver, BC, Canada) on a personal computer.

Five variables (LAI, soil temperature, soil moisture, canopy gap and ECp) were collected three times per month. LAI data were collected using the LAI-2200C Plant Canopy Analyzer (LI-COR Biosciences UK Ltd.; Cambridge, UK) and averaged based on four dimensions (north, south, east and west). Data on soil temperature, soil moisture and the ECp were collected during both seasons (dry and wet) using a moister meter (model HH2+WET sensor; Delta-T Devices Ltd; Cambridge, UK).

Statistical analysis

The differences between factors and management TAFs were analyzed using one-way analysis of variance and the Kruskal-Wallis test. Pearson's correlation analysis was used for determining the relationship between each environmental variable and young leaf yield. Data were analyzed further based on generalized linear mixed models (GLMM) with Akaike information criterion (AIC) for the yield prediction model comparison, using the R software package, version 4.2.2 program (R Core Team, 2022). Measurements were presented as mean ± SD values.

Results and Discussion

Tree alley management patterns

TAF1 had been meticulously managed with a focus on the comprehensive integration of commercial activities, including the sale of seeds, seedlings and layered cuttings.

The *M. suavis* had been planted at 10,000 plants/ha, adhering to a closely monitored spacing of 1 m × 1 m. In addition, companion trees had been strategically planted using an 8 m × 10 m spacing, resulting in a density of 125 trees/ha. These trees had an average values for DOB at 1.3 m of 20.81 ± 9.96 cm at age 16 yr and for average height of 9.31 ± 2.60 m. To maintain optimal growth conditions, the height of the *M. suavis* trees had been carefully controlled to not exceed 2 m through regular trimming of the main stem and plucking the leaves. Consequently, the *M. suavis* trees had maintained an average total height of 1.73 ± 0.34 m. The average D_0 value was 4.51 ± 1.19 and D_{50} was 3.04 ± 0.98 cm, as detailed in Table 1. The farm had a small irrigation system to ensure an adequate water supply for both *M. suavis* and the companion trees, facilitating consistent growth and production.

TAF2 was established 22 yr prior to the study and had been managed as a *M. suavis* plantation. The cultivation process commenced with meticulous area preparation and sowing germinated seeds, adhering to the protocol of planting 4–5 seeds together. The plants were spaced at 1.5 m × 1 m intervals, achieving a density of 6,500 plants/ha. The *M. suavis* plants were cultivated with a variety of companion trees with a spacing interval of 6 m × 6 m, resulting in a density of 275 plants/ha. The companion trees exhibited notable growth, with an average DOB at 1.3 m of 18.11 ± 9.17 cm and an average height of 10.92 ± 3.79 m. To maintain optimal growth conditions for *M. suavis*, the owner had implemented a height restriction, ensuring that the tree crop did not exceed 3 m. Consequently, the *M. suavis* had an average height of 2.79 ± 0.50 m, with D_0 and D_{50} values of 6.79 ± 1.64 and 4.70 ± 0.93 cm, respectively, as shown in Table 1.

In TAF3, the *M. suavis* had been established 11 yr ago, using a planting spacing of 1.5 m × 1.5 m, corresponding to a density of 4,444 plants/ha. This cultivation method resulted in *M. suavis* achieving an average height of 1.21 ± 0.22 m. Additionally, the average D_0 and D_{50} values were 4.25 ± 1.27 cm and 2.00 ± 0.89 cm, respectively. In contrast, the companion trees that had been planted intermittently during 11 yr had been grown with a spacing of 8 m × 8 m, equating to a density of 156 trees/ha. These trees had an average DOB at 1.3 m of 19.44 ± 7.80 cm and an average height of 9.10 ± 1.90 m.

The TAF4 pattern was established as a *M. suavis* plantation 20 yr ago, with the cultivation spacing being 2 m × 1.5 m and a density of 3,331 plants/ha to allow a tractor to carry out weed control between the rows. The *M. suavis* had an average height of 1.28 ± 0.20 m and D_0 and D_{50} values of 12.07 ± 3.67 cm and 1.25 ± 0.40 cm, respectively. The companion trees had also been widely spaced at establishment, with a planting grid of 10 m × 10 m and a density of 100 plants/ha and DOB at 1.3 m of 14.58 ± 4.92 cm and an average height of 8.65 ± 1.16 m, respectively. (Table 1). The trees had been watered regularly using the farm-wide irrigation system.

In all four TFAs, the *M. suavis*, characterized by its medium-sized perennial growth and hemiparasite root system, had thrived particularly well when cultivated alongside nitrogen-fixing trees, forming a harmonious companion planting composition within the system due to the mutual benefits offered by such companion planting systems. The hemi-parasitic root system of *M. suavis* allows it to partially rely on the host plants for nutrients, while the nitrogen-fixing trees enrich the soil with essential nutrients, particularly nitrogen.

Table 1 Differences in tree alley farms (TAF1–4) of *Melientha suavis* Pierre components and management

Stand stage and growth	TAF1	TAF2	TAF3	TAF4	*p* Value
Melientha suavis Pierre					
Age of *M. suavis* (yr)	16	22	11	20	-
Spacing of *M. suavis* (m)	1×1	1.5×1	1.5×1.5	2×1.5	-
Density of *M. suavis* (trees/ha)	10,000	6,500	4,444	3,331	-
Average D_0 of *M. suavis* (cm)	4.51±1.19[c]	6.79±1.64[b]	4.25±1.27[c]	12.07±3.67[a]	$p < 0.01$
Average D_{50} of *M. suavis* (cm)	3.04±0.98[b]	4.70±0.93[a]	2.00±0.89[c]	1.25±0.40[d]	$p < 0.01$
Average total height of *M. suavis* (m)	1.73±0.34[b]	2.79±0.50[a]	1.21±0.22[c]	1.28±0.20[c]	$p < 0.01$
Companion trees					
Number of tree species	5	15	7	3	-
Spacing (m)	8×10	6×6	8×8	10×10	-
Density (trees/ha)	125	275	156	100	-
Average DOB at 1.3 m (cm)	20.81±9.96[a]	18.11±9.1[7]a	19.44±7.80[a]	14.58±4.92[a]	$p > 0.05$
Average height (m)	9.31±2.60[a]	10.92±3.79[a]	9.10±1.90[a]	8.65±1.16[a]	$p > 0.05$

DOB = diameter over bark; D_0 = DOB at ground level; D_{50} = DOB at height = 50 cm.

Mean ± SD in the same row superscripted with different lowercase letters are significantly ($p < 0.05$) different.

This symbiotic relationship enhances soil fertility, reduces the need for synthetic fertilizers, and promotes sustainable agricultural practices. Furthermore, the canopy structure of nitrogen-fixing trees provides shade and reduces water loss through evaporation, creating a more favorable microclimate for *M. suavis*. These factors collectively contributed to higher productivity and better resilience of the *M. suavis* plantations, making companion planting with nitrogen-fixing trees an effective strategy for optimizing growth and yield (Fig. 3).

Species composition

Farmers plant leguminous trees and small-leaf species as companion trees for nursing *M. suavis* because the leaves of these companion crops are decomposed easily which increases the organic matter and helps to improve soil quality. In addition, many trees in the Fabaceae family that have been selected as companion-trees have open canopies, facilitating photosynthesis for the *M. suavis*. Furthermore, legumes represent a valuable source of organic material and contribute nitrogen to the soil (Al-Falih, 2002) where there are bacteria from the Rhizobiaceae in the root nodes that fix nitrogen in the air into a form that plants can use (Chotechaungmanirat, 2010).

There were 10 families and 18 species of trees planted together with *M. suavis* (Table 2). The Fabaceae was the most common (43%), followed by the families of Moraceae, Meliaceae, Bignoniaceae, Lamiaceae and Anacardiaceae at 25%, 11%, 9%, 6% and 2%, respectively.

The most preferred species in all four TAFs was *Pithecellobium dulce* at 34% of the companion trees, followed by *Broussonetia papyrifera* and *Melia azedarac*, at 22% and 7%, respectively (Table 2).

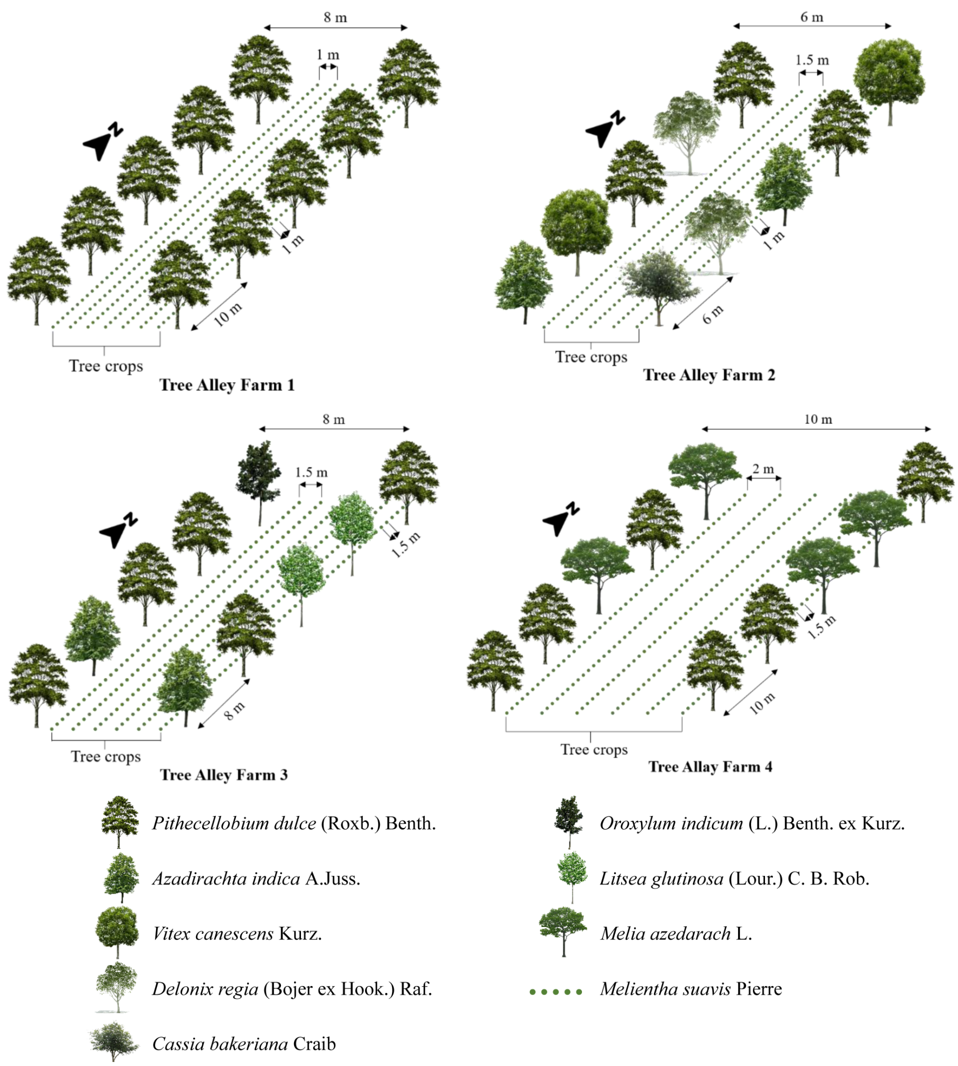

Fig. 3 Tree alley patterns in four sample plantings

Table 2 Diversity of cultivated companion trees species in the tree alley farms (TAFs) of *Melientha suavis* Pierre

Scientific name	Phenology	Family	TAF 1	TAF 2	TAF 3	TAF 4
Artocarpus heterophyllus Lam.	Evergreen tree	Moraceae	✓	×	✓	×
Azadirachta indica A.Juss.	Deciduous tree	Meliaceae	✓	✓	✓	✓
Broussonetia papyrifera (L.) L'Hér. Ex Vent.	Deciduous tree	Moraceae	✓	✓	×	×
Cassia bakeriana Craib	Deciduous tree	Fabaceae	×	✓	×	×
Cassia fistula L.	Deciduous tree	Fabaceae	×	✓	×	×
Cassia fistula L. x *Cassia javanica*	Deciduous tree	Fabaceae	×	✓	×	×
Delonix regia (Bojer ex Hook.) Raf.	Deciduous tree	Fabaceae	×	✓	×	×
Ficus sp.	Evergreen tree	Moraceae	×	✓	×	×
Litsea glutinosa (Lour.) C. B. Rob.	Deciduous tree	Lauraceae	×	×	✓	×
Mangifera indica L.	Evergreen tree	Anacardiaceae	×	✓	✓	×
Melia azedarach L.	Deciduous tree	Meliaceae	×	✓	×	✓
Moringa oleifera Lam.	Deciduous tree	Moringaceae	×	✓	×	×
Nyctanthes arbor-tristis L.	Evergreen tree	Oleaceae	×	✓	×	×
Oroxylum indicum (L.) Benth. ex Kurz.	Deciduous tree	Bignoniaceae	✓	×	✓	×
Pithecellobium dulce (Roxb.) Benth.	Evergreen tree	Fabaceae	✓	✓	✓	✓
Tecoma stans (L.) Kunth.	Evergreen tree	Bignoniaceae	×	✓	×	×
Tabernaemontana pandacaqui Poir.	Evergreen tree	Apocynaceae	×	✓	×	×
Vitex canescens Kurz.	Deciduous tree	Lamiaceae	×	✓	✓	×
Companion tree proportion (%)		100	27.78	83.33	38.88	16.67

In addition, the initial plantings included *Sesbania grandiflora* to allow light for the *M. suavis* seedlings. In addition, because *S. grandiflora* is a fast-growing tree in the bean family, it helps improve soil quality and increases nitrogen in the soil; however, it was not long-lived, dying within 5 yr of planting. Nonetheless, it still promoted the growth of *M. suavis* and other companion plants for 3–5 yr, before deteriorating and eventually dying. Then, other tree species were planted to replace the dead trees, specifically *P. dulce* in TAF1 as the only companion tree species. TFA2 was planted with various types of companion trees, including deciduous groups, such as *Delonix regia* and *M. azedarach*. TAF3 was planted with several fruit trees, including *Mangifera indica* and *Artocarpus heterophyllus*. TAF4 was planted with only three types of companion tree, with the main one being *P. dulce*, along with some *M. azedarach* and a few *Azadirachta indica*, (Table 2). The variations in planting density and species choice reflected the diverse strategies based on the phenological traits of the companion tree species and applied by the different owners to enhance productivity. Notably, Artru et al. (2017) indicated that the spatiotemporal shade dynamics of variety species impacted on wheat growth and yield. In the current study of tree alley farms, the leguminous trees, constituting 43% of the companion flora, were prevalent due to their nitrogen-fixing ability and soil improvement qualities. The selection of species such as *P. dulce* underscored the strategic integration of trees for both agronomic and ecological benefits.

Environmental factors and productivity

The environmental factors affecting the productivity of *M. suavis* focused on canopy gap, LAI, soil moisture, soil temperature, ECp and overall productivity. Each of these factors played a critical role in determining the growth and yield of plants in different alley farms as follows:

Canopy gap

The canopy gap, which refers to the fraction of plantation spacing that is not covered by foliage when observed from below the tree canopy, varied significantly across the different TAFs. TAF4 had the highest canopy gap (97.25 ± 4.23%), as shown in Table 3, which could indicate less shade and potentially more sunlight reaching the ground, possibly affecting the undergrowth and soil temperature and moisture. The significant differences in canopy gaps between the four alley farms suggested that light availability, influenced by canopy cover, was an important factor affecting plant growth and productivity. The interaction between the canopy gaps in the *M. suavis* plantations and the phenological patterns of the companion trees offered a clear insight into the complexity of forest ecosystems and plantations. The presence of deciduous trees, which lose their leaves seasonally, plays an important role in this dynamic. During the leaf-shedding period, these trees create openings in the plantation canopy, allowing more sunlight to penetrate to the forest floor (Casanova-Lugo et al., 2023). This increased light availability is crucial for the growth of *M. suavis*, particularly during its harvest season when the plant has greater light requirements (Tang et al., 2016). The yield of *M. suavis* is affected by optimal light conditions, which are modulated by the canopy gaps created by the deciduous trees (Piotto et al., 2024), highlighting the importance of understanding the ecological interactions within plantation environments and the need for careful management of both *M. suavis* and its companion trees. The canopy gaps not only affect light availability but also influence other microclimatic conditions, such as temperature and humidity, further impacting the growth of understory plants such as *M. suavis* (Durand et al., 2024).

Leaf area index

The LAI, a measure of leaf cover per unit ground area, varied between seasons, with lower values during the dry season and higher values in the wet season. During the dry season, the young leaves of *M. suavis* had a lower LAI, which increased in the wet season. For example, TAF2 had a lower LAI (2.82 ± 0.79 m^2/m^2) during the dry season than the wet season (3.26 ± 0.82 m^2/m^2), as shown in Table 3. The significant ($p < 0.01$) differences in the LAI values among the TAFs indicated that the farms had varying capacities for supporting resprouting shoot growth, which can directly influence the productivity of young leaves. At the same time, the statistical analysis confirmed significant ($p < 0.01$) differences between the dry and wet months, indicating a clear seasonal influence on the LAI. Since leaf development is strongly regulated by temperature (Gray and Brady, 2016), the seasonal variation was probably due to the plant life cycle or responses to environmental conditions, impacting photosynthesis and overall plant development.

Soil moisture content

Noticeably, the soil moisture content was higher during the dry season in most of the alley farms, likely due to increased irrigation efforts to compensate for the lack of rain. TAF3 had the highest soil moisture content during the dry season (44.68 ± 6.91%), whereas TAF1 had a lower soil moisture content during the wet season (31.05 ± 7.62%), as shown in Table 3. This counterintuitive finding highlighted the importance of human management practices in maintaining soil moisture and supporting plant growth, especially in dry conditions (Laidlaw, 2009).

Soil temperature

Soil temperature varied slightly between seasons but remained relatively stable across the alley farms. TAF1 recorded the highest average soil temperature during the dry season (31.31 ± 2.01°C), while TAF2 had the highest soil temperature during the wet season (31.55 ± 0.72°C), suggesting that this factor may not have as direct an impact on productivity as other factors considered in this study. However, extreme temperatures can affect root development and nutrient uptake, indirectly influencing plant health and yield (Laidlaw, 2009).

Table 3 Variety in tree alley farm (TAF) tree management based on factor and young leaf yield

Factor and yield	TAF1	TAF2	TAF3	TAF4	*p* Value
Factor					
Gap (%)	$54.35±29.72^{c}$	$44.36±15.23^{d}$	$66.69±29.55^{b}$	$97.25±4.23^{a}$	$p < 0.01$
Leaf area index (m^2/m^2)					
dry season	$2.07±1.04^{b}$	$2.82±0.79^{a}$	$1.58±0.53^{3}$c	$2.29±0.71^{b}$	$p < 0.01$
wet season	$2.24±0.99^{c}$	$3.26±0.82^{a}$	$2.75±0.80^{b}$	$2.47±0.72^{bc}$	$p < 0.01$
Soil moisture (%volume)					
dry season	$32.37±8.45^{b}$	$25.95±5.96^{c}$	$44.68±6.91^{a}$	$26.19±5.94^{c}$	$p < 0.01$
wet season	$31.05±7.62^{a}$	$27.03±5.58^{b}$	$27.94±5.16^{b}$	$20.10±3.65^{c}$	$p < 0.01$
Soil temperature (˚C)					
dry season	$31.31±2.01^{a}$	$31.17±1.69^{a}$	$28.70±3.08^{c}$	$29.53±2.28^{b}$	$p < 0.01$
wet season	$30.72±1.07^{b}$	$31.55±0.72^{a}$	$30.80±0.93^{b}$	$30.45±0.61^{b}$	$p < 0.01$
Electrical conductivity (dS/m)					
dry season	$1.99±0.25^{c}$	$2.08±0.24^{b}$	$2.34±0.16^{a}$	$1.72±0.22^{d}$	$p < 0.01$
wet season	$1.92±0.25^{b}$	$1.82±0.22^{c}$	$2.03±0.20^{a}$	$1.50±0.16^{d}$	$p < 0.01$
Young leaf yield (kg/tree)					
dry season	$0.009±0.005^{b}$	$0.020±0.011^{a}$	$0.005±0.003^{c}$	$0.019±0.013^{a}$	$p < 0.01$
wet season	$0.008±0.005^{b}$	$0.005±0.002^{b}$	$0.006±0.004^{b}$	$0.030±0.022^{a}$	$p < 0.01$

Mean ± SD superscripted with different lowercase letters are significantly ($p < 0.01$) different.

Electrical conductivity

TAF4 had the lowest ECp in both seasons, (1.72 ± 0.22 dS/m in the dry season and 1.50 ± 0.16 dS/m in the wet season), suggesting lower solute concentrations in its soil. Lower ECp values suggest fewer dissolved salts in the soil, which can be beneficial for plant growth if salinity levels are otherwise harmful. However, a very low ECp might also indicate insufficient nutrients, which could affect plant growth negatively.

Young leaf productivity

Productivity, measured as the mass of young leaves produced, varied between plots and seasons, with TAF2 having the highest yield of young leaves of *M. suavis* during the dry season (0.020 ± 0.011 kg/tree). TAF4 had the highest yield in the wet season (0.030 ± 0.022 kg/tree). These variations underlined the complex interplay between environmental factors and plant productivity. The differing productivity rates suggested that the farms had varying levels of efficiency in converting environmental resources into plant biomass.

Environmental factors influencing productivity across dry and wet seasons

Seasonal variations played a crucial role, with larger canopy gaps and optimal LAI associated with increased productivity. The study highlighted the importance of managing soil moisture and temperature to accommodate the plant seasonal growth demands. Table 3 shows significant seasonal variations in LAI, soil moisture, soil temperature, ECp and productivity of *M. suavis*. These findings suggested that the plant adapted its physiological processes in response to seasonal changes, influencing its growth and cultivation management. Further research is needed to explore the underlying mechanisms of these adaptations.

The productivity of *M. suavis* was significantly influenced by various environmental factors, with notable differences observed between dry and wet seasons. Canopy gap, LAI, soil moisture and temperature played crucial roles in determining yield outcomes. For example, during the dry season, a strong negative correlation between soil moisture and yield suggested that higher moisture levels reduced productivity, likely due to root oxygen stress or nutrient dilution. Conversely, positive correlations with DOB at breast height (1.3 m) and LAI indicated that larger leaf areas and robust stem bases enhanced productivity through increased photosynthesis. In the wet season, the electrical conductivity of the soil (ECp) had a strong negative correlation with yield, implying that a higher ionic content in soil adversely impacted productivity due to ionic concentration stress.

Additionally, excessive vegetative growth or wet conditions reduced yields, as indicated by negative correlations with soil moisture and D_{50}. However, robust stem bases and open canopies positively influenced productivity by improving light penetration and reducing disease incidence. The results presented in Table 3 highlight the importance of managing canopy gaps, LAI, soil moisture and ECp to optimize yields, with significant seasonal variations necessitating tailored management practices. This highlighted the complex interplay between environmental factors and the necessity for adaptive strategies to enhance *M. suavis* productivity across different seasons.

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The mixed-effects model scatter plot (Fig. 4A) shows the relationship between the log-transformed yield and the log-transformed DOB at D_0 for the four TAF systems. Positive slopes indicated higher yields with increased D_0 across all TAFs. TAF4 had the highest yield and strongest positive correlation, suggesting the application of effective management practices. TAF3 had lower yields and a weaker correlation, indicating potential limitations. Each model accounted for the random effects associated with each TAF system. For the relationship between log-transformed yield and log-transformed D_{50} for the four TAF systems, there was a positive slope, indicating a higher yield with increased D_{50}, across all TAFs. TAF4 had the highest yield and strongest positive correlation, suggesting the application of effective management practices. TAF3 had lower yields and a weaker correlation, indicating potential limitations. The models captured these relationships while accounting for random effects in each TAF system, as shown in Fig. 4B.

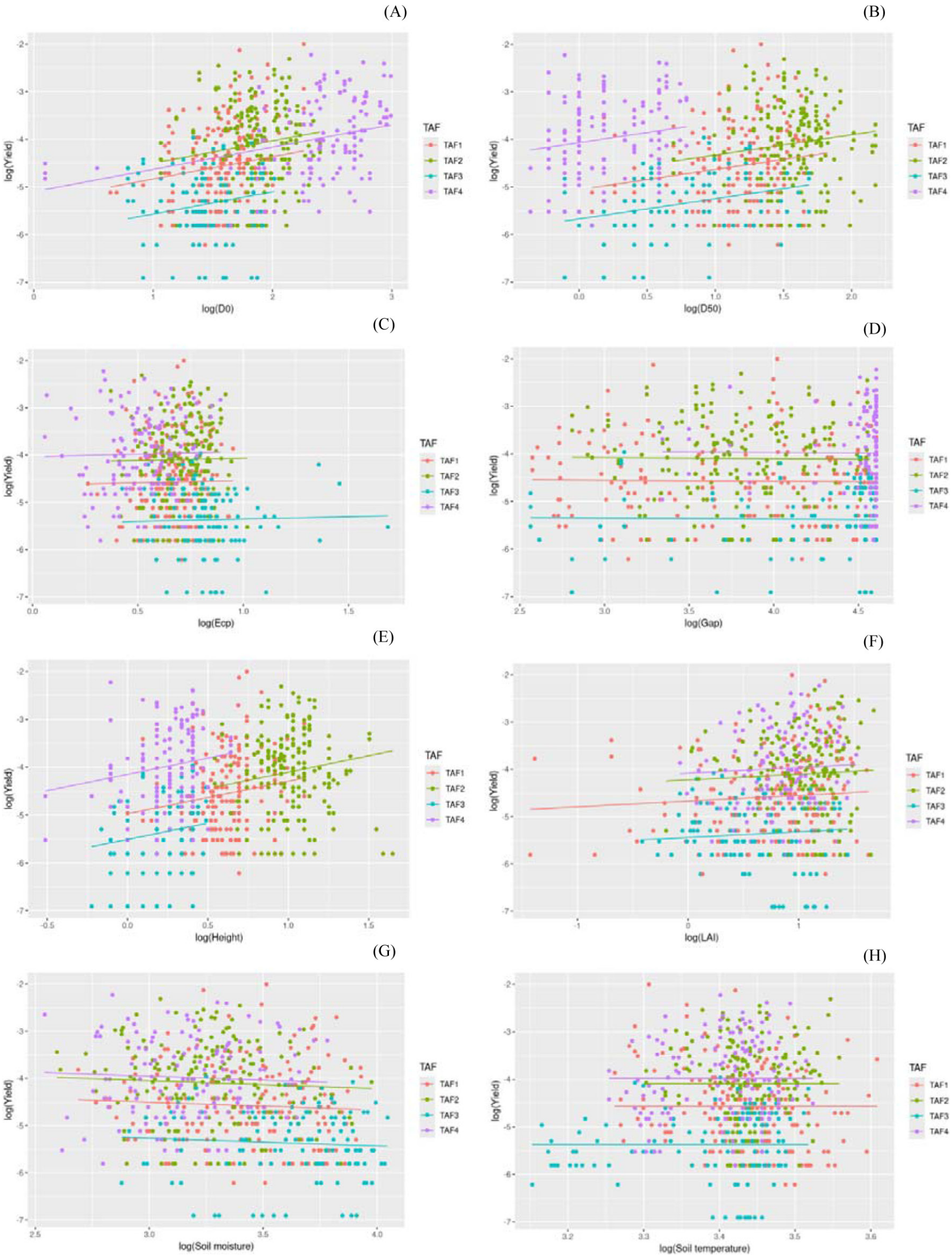

Fig. 4 Generalized linear mixed models analysis of young leaf yield of *Melientha suavis* in each tree alley farm (TAF) as influenced by: (A) log(D_0); (B) log(D_{50}); (C) log(Ecp); (D) log(gap); (E) log(height); (F) log(LAI); (G) log(soil moisture); (H) log(soil temperature), where D_0 = DOB at ground level; D_{50} = DOB at height 50 cm.; Ecp= electrical conductivity of pore water; Gap= canopy gap; Hight= total high; LAI = leaf area index

From the above results, it was evident that the environmental factors affecting the yield of *M. suavis* leaves varied across different seasons and management. Therefore, nine models were created based on GLMMs to finalize the most suitable model for *M. suavis* yield prediction. This approach evaluated the effectiveness of various predictors on the yield using the AIC values for model comparisons (Table 4). In total, nine models were tested, each incorporating different combinations of log-transformed predictor variables along with a random effect for each TAF. The AIC values indicate the relative quality of each model, with lower values suggesting a better model fit (Tesfamichael and Beech, 2016).

Model 1, which includes Log (D_0) as a predictor, achieved the lowest AIC value of 1509, indicating it was the best-fitting model among those tested. In comparison, other models, such as Model 4, which includes Log (Gap), and Model 5, which includes Log (LAI), had higher AIC values of 1533 and 1526, respectively, indicating poorer fits.

Table 4 Akaike information criteria (AIC) values for various yield prediction models

Model number	Model	AIC value
1	Log(Yield) ~ Log(D0) + (1|TAF)	1509
2	Log(Yield) ~ Log(D50) + (1|TAF)	1512
3	Log(Yield) ~ Log(Height) + (1|TAF)	1515
4	Log(Yield) ~ Log(Gap) + (1|TAF)	1533
5	Log(Yield) ~ Log(LAI) + (1|TAF)	1526
6	Log(Yield) ~ Log(Soil moisture) + (1|TAF)	1531
7	Log(Yield) ~ Log(Soil temperature) + (1|TAF)	1530
8	Log(Yield) ~ Log(Ecp) + (1|TAF)	1531
9	Log(Yield) ~ Log(D0) + Log(D50) + Log(Height) + Log(Gap) + Log(LAI) + Log(Soil moisture) + Log(Soil temperature) + Log(Ecp) + (1|TAF)	1511

AIC=akaike information criteria, lower values indicate a better model fit; Log(Yield)= natural log of *M. suavis* yield; Log(D0)= natural log of DOB at ground level; Log(D50)= natural log of DOB at height 50 cm.; Log(Height)= natural log of total height of *M. suavis*; Log(Gap)= natural log of canopy gaps; Log(LAI)= natural log of leaf area index; Log(Soil moisture)= natural log of soil moisture; Log(Soil temperature)= natural log of temperature; Log(Ecp)= natural log of electrical conductivity of pore water in soil; (1|TAF)=random effect for a grouping factor; DOB= diameter over bark.

The combined model (Model 9), which includes all predictors—Log(D0), Log(D50), Log (Height), Log (Gap), Log (LAI), Log (Soil moisture), Log (Soil temperature) and Log (Ecp) —also performed relatively well with an AIC value of 1511 but was not as good as the simpler form in Model 1. Based on the best model (Model 1) Log (D_0) was an important predictor of yield, with the relationship described by the equation where X was in the range from -6.037380 to -4.967811, as shown in Equation 1:

$$\text{Log (Yield)} = X + 0.468512 * \text{Log (D0)}, \quad X = -6.037380 \text{ to } -4.967811 \qquad (1)$$

This relationship indicates a positive association between Log (D_0) and yield, with higher values of Log (D_0) resulting in higher yield predictions.

In summary, the overall analysis provided a solid academic understanding for managing *M. suavis* in alley agroforestry systems. It was found that the productivity of *M. suavis* was significantly influenced by environmental factors such as LAI and soil moisture, which varied between dry and wet seasons. Additionally, strategic species selection and spatial arrangements, including the integration of nitrogen-fixing leguminous trees, played a crucial role in enhancing yield.

In conclusion, this research bridged the gap in knowledge regarding the environmental and management factors affecting *M. suavis*, providing a valuable foundation for future studies and sustainable agricultural practices. The findings highlighted the importance of focusing on practices that promote radial growth, as the diameter at ground level of *M. suavis* was a critical factor for improving the young leaf yield. By adopting these management strategies, farmers can enhance the efficiency and sustainability of their agroforestry practices, ultimately leading to better productivity and economic benefits.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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