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Topography and phenological effects on soil-leaf interactions and durian productivity

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Abstract

Durian (*Durio zibethinus* Murr.), renowned for its distinctive aroma and flavor, is a key agricultural commodity in Malaysia and ASEAN countries, accounting for 42.6% of Malaysia's total fruit cultivation area. Despite its economic significance, the impact of topographical variations and phenological stages on durian growth and yield remains insufficiently studied. This research aims to bridge this gap by examining the influence of topography (flat vs. terraced land) and developmental stages on durian cultivation, focusing on soil and leaf properties and overall fruit yield. The study was conducted at Top Fruits Sdn. Bhd., Malaysia, from October 2022 to February 2023, using a randomized complete block design (RCBD). Results demonstrated significant interactions between topography and phenological stages under a two-factorial experimental design with ten replications. Weekly assessments of soil parameters (nitrogen, phosphorus, potassium, moisture, and pH) and leaf attributes (chlorophyll content, nitrogen concentration, moisture, and temperature) confirmed notable variations influenced by both factors, indicating their combined effect on durian growth performance. Trees cultivated on terraced slopes exhibited higher chlorophyll and nitrogen levels, likely due to improved water drainage, nutrient distribution, and reduced soil erosion, fostering better photosynthetic activity. In contrast, durians grown on flat terrain demonstrated stable root development and higher soil moisture retention, contributing to sustained growth. Significant correlations ($p < 0.05$) were observed between phenological stages, leaf moisture, and soil properties across different topographical conditions. These findings highlight the crucial role of site-specific nutrient and water management in optimizing durian cultivation. Understanding the interactions between environmental factors and durian physiology offers valuable insights for precision agriculture, ensuring sustainable yield improvement and long-term orchard productivity.

Keywords Durian, Topography, Phenological stages, Leaf attributes, Soil properties, Yield

1 Introduction

Durian (*Durio zibethinus* Murr.) belongs to the Bombaceae family and is a climacteric and popular fruit renowned for its distinctive aroma and unique taste. It holds a prominent status as one of the most important fruits in Malaysia, Thailand, Indonesia,



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Vietnam, and other ASEAN countries [1]. Durian stands as Malaysia's primary fruit crop of utmost importance. In 2022, durian cultivation accounted for approximately 42.6% of Malaysia's total fruit cultivation area, which amounted to 85,366 hectares [2]. During that timeframe, durian production constituted 27% of the total local fruit production, amounting to 459,747 tonnes [2]. According to the Ministry of Agriculture and Food Security [3], the per capita consumption of durian is 12.8 kg per year, the highest among other fruits. Durian plays a crucial role in Malaysia's agricultural economy, with both small-scale farmers and large commercial durian plantations bolstering the nation's thriving durian industry.

The favourable tropical climate of Malaysia with continual warmth and humidity creates an ideal environment conducive to the flourishing growth of durian trees. Topography is one of the main factors that profoundly influences the soil properties, tree growth, and fruit production in a planting area. It encompasses studying Earth's surface features [4] which involves observing and recording landscape features like terrain characteristics, hill and mountain relief, slope angles, and drainage patterns for a specific area [5]. According to Kumhálová et al. [6], topographic data are useful in elucidating the variation in soil and yield of a planting field. Additionally, it is widely recognized that topography plays a crucial role in shaping local microclimates, resulting in changes in temperature patterns, relative humidity, and rainfall, and consequently influencing the soil properties in the plantation [7].

The phenological stages of encompasses flowering, fruiting, and dormancy, intricately regulating the physiological process that dictates the growth and development of the durian tree. At the onset of the growth cycle, the durian tree focuses on vegetative growth. This stage involves the emergence of new shoots, leaves, and branches, as the tree establishes its canopy structure and increases in size. Durian flowering is triggered by 18 days of drought, with rainfall less than 1 mm of rainfall per day [8]. Flower buds begin to open in the evening, reaching their peak at midnight. The flowering stage is crucial in durian's phenological cycle. In the morning, pollen viability diminishes, while the stigma, most receptive at night, retains limited receptivity in the morning before dropping in the afternoon. Following the successful pollination, all flower components except the ovary and filament shed and the ovary develops into fruit while the filament dries. This stage marks the beginning of fruit development, as the fertilized ovaries start to grow and form the initial structure of the durian fruit. As the fruits continue to grow, they undergo several developmental changes. Initially, durian fruits are small and green, resembling marbles. As they mature, these marble-sized fruits undergo significant growth, increasing in size, changing color, and developing a distinct texture. In the final stage of the durian's phenological cycle, known as the maturation stage, the durian fruits develop their distinctive flavor, aroma, and texture, indicating the readiness for harvest. After durian fruits are harvested, the durian tree enters a period of dormancy and the growth activity slows down, and the durian tree conserves energy in preparation for the next growth cycle.

While both topography and phenological stages are known to influence crop growth dynamics, their combined effects on durian cultivation remain poorly understood. Most existing studies have examined these factors independently, without considering how their interaction affects soil properties, nutrient dynamics, leaf characteristics, and yield performance. As durian cultivation expands into diverse landscapes from flat lowlands

to sloped terrains, such interactions become increasingly important for optimizing site-specific management. Furthermore, with the global demand for durian rising rapidly and the need for more sustainable, high-yield cultivation practices, it is crucial to understand how environmental variation and growth stages collectively shape durian productivity. Therefore, this study aims to investigate the influence of different topographic patterns and phenological stages on soil properties, leaf characteristics, and yield performance. By addressing this gap, the research provides valuable scientific insights to guide precision cultivation, enhance resource-use efficiency, and improve the overall productivity and sustainability of durian plantations.

2 Materials and methods

2.1 Plant materials

“Musang King” durian trees were selected from a local durian plantation of Top Fruits Sdn. Bhd., located in Parit Sulong, Batu Pahat, Johor, Malaysia, during the fruiting season from October 2022 to February 2023 (Fig. 1). The phenological stages observed included flowering, fruit set, fruit development, and maturation. Flowering generally occurred in October, followed by fruit set in November, fruit enlargement through December to January, and maturation in February. These stages represent the typical reproductive cycle of durian under tropical climatic conditions.

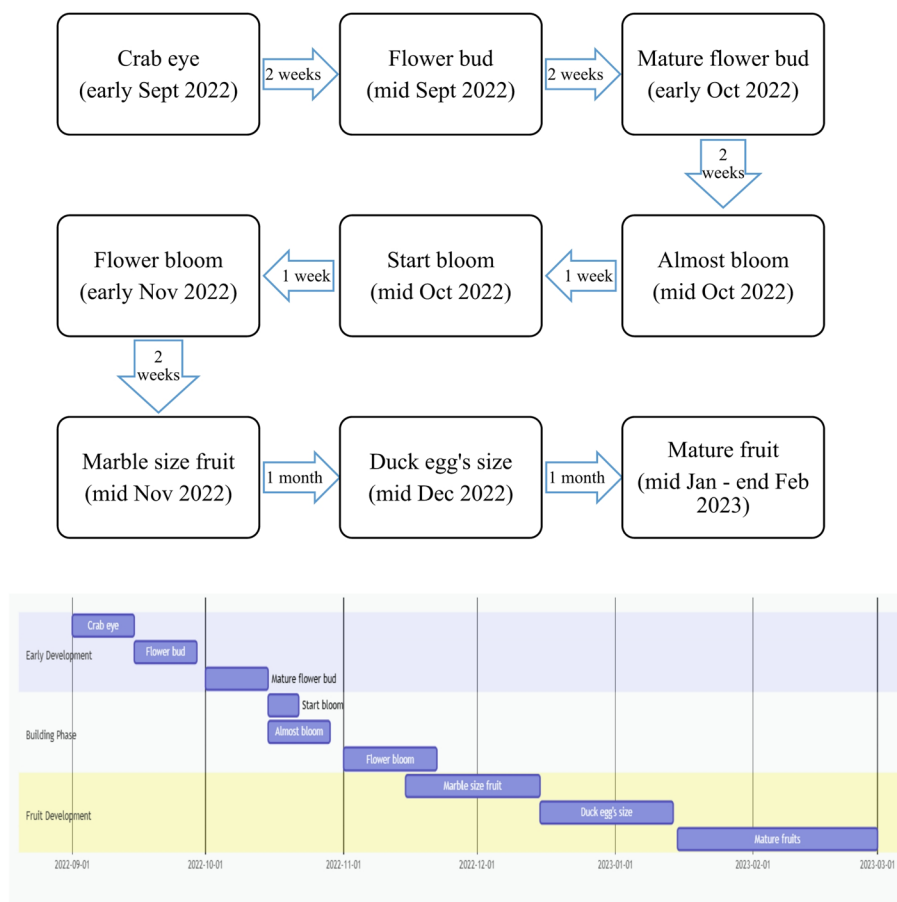


Fig. 1 (a) and (b): Musang King Durian Phenological Stages from Crab Eye to Mature Fruit (Harvesting) Stages (18 weeks in total) from 2022 to 2023

Top Fruits's durian plantation encompasses flat and terrace areas (Fig. 2 (b) and (c)), each presenting distinct topographical features. To ensure comprehensive coverage, four plots were selected from each type of terrain. A total of 10 durian trees were chosen for this study. The chosen durian trees ranged from 15 to 20 years of age and were carefully inspected to ensure they were disease-free. Comprehensive data, encompassing soil composition, leaf characteristics, and durian yield, were systematically gathered every week and subjected to statistical analysis. The soil composition data consists of soil nitrogen, soil phosphorus, soil potassium, soil moisture, soil temperature, and soil pH, while leaf characteristics include leaf chlorophyll, leaf nitrogen, leaf moisture, and leaf temperature.

2.2 Leaf characteristics

2.2.1 SPAD value, nitrogen content, moisture, and temperature of the leaf

A chlorophyll meter (SPAD-502, Minolta, Japan) was used to obtain readings of estimating non-destructive measurement of leaf chlorophyll concentration (SPAD value), nitrogen content, moisture, and temperature of the leaf. SPAD-502 m was calibrated using the reading checker supplied by the manufacturer before measurements [9]. Five fully matured dark green leaves were randomly selected from each direction (East, South, West, and North) at both the upper and lower parts of each tree. Leaves that could not be reached by hand were collected using a ladder. SPAD values, nitrogen content, moisture, and temperature of the leaves were recorded and analyzed throughout the growth stages, from crab eye development to mature fruit harvesting.

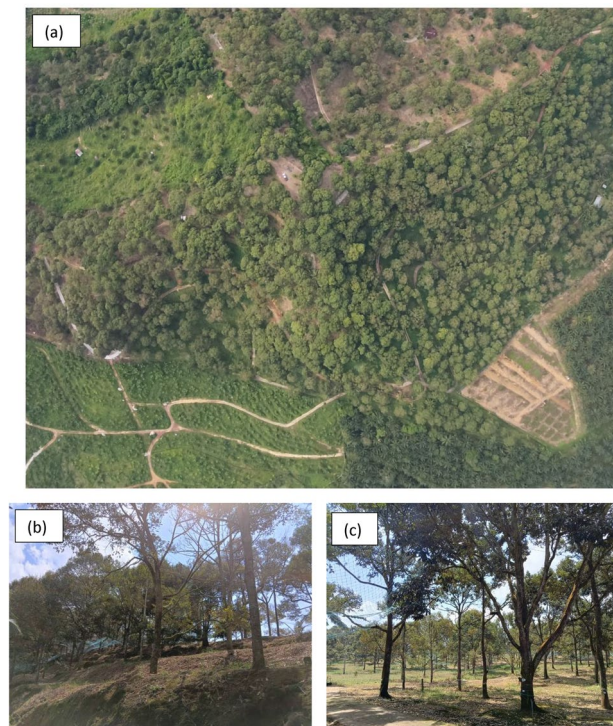


Fig. 2 Location map of the Top Fruits durian plantation illustrating (a) the overall plantation layout, (b) terrace topography, and (c) flat land topography

2.3 Soil properties

A real-time all-in-one sensor (JXBS-3001-SCY-PT, China) was used to measure soil nitrogen (N), soil phosphorus (P), soil potassium (K), soil moisture, soil temperature, and soil pH. The sensor includes a stainless-steel rust-proof, electrolytic-resistant, and salt-alkali-resistant probe. Before using the soil sensor, it was calibrated according to the manufacturer's instructions. Five points on the soil were selected for each tree, ensuring they were located at the canopy edge with 3 m distant from the durian tree and within the area reachable by micro-sprinklers for irrigation. A hoe was used to dig the soil to a depth of approximately 15 cm at each selected point. Subsequently, the device's probes were inserted into each soil point at the chosen durian trees, ensuring proper contact and stability during the measurement. Finally, the readings for soil N, P, K, moisture, temperature, and pH for each sampling site were recorded.

2.4 Yield

All the durian fruits collected from the chosen durian trees in this study were collected manually by using a basket in the farm and subsequently transported to the collection centre for weighing. The durian fruits were quantified both by counting the number of pieces and by measuring their weight in kilograms daily throughout the season. Additionally, the total yields were calculated by summing up the total number of pieces and kilograms for each month. Lastly, the collected data was tabulated and further analyzed statistically.

2.5 Statistical analysis

The study used a randomized complete block design (RCBD) with a two-factorial arrangement of treatments, consisting of topography patterns and durian phenological stages, each with ten replications. Statistical analysis was performed using Analysis of Variance (ANOVA) conducted in SAS version 9.4 (SAS Institute, Cary, NC). Mean comparisons were compared using the Tukey Honestly Significant Differences (Tukey's HSD) test at a significant level of $p = 0.05$. Pearson's correlation (r) analysis was conducted at $p = 0.05$ to investigate the relationships between all the measured variables in this study.

3 Results and discussion

3.1 Leaf characteristics

Leaf characteristics such as chlorophyll content (SPAD value), leaf nitrogen, moisture and temperature are important for the health and productivity of durian trees, and the phenological stages and topography of the durian trees significantly influence these factors (Table 1). Plants need optimal sunlight for higher chlorophyll and nitrogen levels to promote photosynthesis and growth, but these needs vary across different phenological stages of the plants. For instance, trees on well-drained slopes with optimal sunlight typically exhibit higher chlorophyll and nitrogen levels, essential for photosynthesis and growth [10]. However, during different growth stages, such as vegetative, flowering, and fruiting, the tree's demand for nutrients and its ability to regulate moisture and temperature vary [11]. Proper management of these leaf characteristics according to the tree's developmental stage and terrain ensures robust growth and high fruit yield.

There was a significant relationship ($P < 0.05$) between durian phenological stages and leaf chlorophyll (SPAD value) for durian trees planted on flat and terrace areas (Table

Table 1 Leaf and soil characteristics with sample Size, Range, Mean, and Std Dev

Parameter	Range	Maximum	Mean	Minimum	Std Dev
SPAD	35.200	57.800	44.638	22.600	7.641
Leaf N	61.500	71.300	18.083	9.800	9.001
Leaf moisture	67.300	84.000	65.444	16.700	12.847
Leaf temperature	10.280	31.250	28.251	9.500	2.692
Soil N	13.500	23.000	14.900	13.250	3.225
Soil P	21.250	34.500	20.664	33.250	5.278
Soil K	59.750	93.000	55.260	20.100	13.564
Soil moisture	25.700	45.800	30.772	20.100	6.757
Soil temperature	16.000	35.300	24.222	19.300	3.770
Soil EC	209.600	339.500	200.561	130.00	45.228
Soil pH	2.850	6.400	5.280	3.550	0.899
Yield (pcs)	4616.000	4627.000	757.725	11.000	995.357
Yield (kg)	6925.000	6942.000	1129.000	17.000	1488.000

2; Fig. 3). A high leaf SPAD value was recorded in the flat land at 52.15 in during the mature fruit stage and the highest chlorophyll level on the terrace was recorded during the flower bloom stage at 48.1. Leaf chlorophyll is related to soil nitrogen content [12]. In this study, as nitrogen increases, leaf chlorophyll also increases, except during the flower bloom to duck egg stage in both topographies (Table 2; Fig. 3). The chlorophyll content of the leaves is connected to the photosynthetic rate of the trees. According to Kondo et al. [13], low chlorophyll content corresponds to low photosynthesis ability, and this is influenced by light conditions. Strong light conditions lead to a low photosynthesis rate in durian [13]. There is a positive correlation between chlorophyll fluorescence and photosynthesis, which also extends to the yield of fruit [14]. According to Lechaudel et al. [15], chlorophyll levels decrease as the fruit ripens. Similarly, in the present study, leaf chlorophyll content showed a decrease toward fruit maturity compared to the levels recorded during the mature flower bud and flower bloom stages across both topographies (Fig. 3). Although leaf chlorophyll levels decreased during fruit maturation, such a trend was not clear, suggesting that chlorophyll variation in durian leaves may depend more on site-specific and environmental factors than solely on fruit maturity [14].

Leaf moisture is the moisture level inside the leaf where wet cells exchange gases with large airspace and leaf moisture is important for the photosynthesis process [16]. Table 2; Fig. 4 shows there was a significant difference between the durian phenological stages and leaf moisture in flat and terrace areas. Like leaf chlorophyll (SPAD), leaf moisture was highest during the mature fruit stage in flat areas, whereas it peaked during the mature flower bud to flower bloom stage in terrace areas. Leaf moisture varied, increasing drastically at the beginning in flat areas but decreasing slightly in terrace areas. The disparity in leaf moisture between flat and terrace areas arises from distinct microclimatic conditions. Flat terrain, characterized by restricted air circulation and drainage, tends to harbour higher surface moisture levels, fostering an environment conducive to elevated leaf moisture [17]. Conversely, terraced environments facilitate improved air movement, which mitigates moisture accumulation around foliage. This differential microclimatic influence plays a pivotal role in shaping plant physiological responses, including growth patterns and disease susceptibility [17].

Leaf nitrogen is crucial for durian trees as it supports photosynthesis, growth, fruit production and disease resistance; meanwhile, leaf temperature affects physiological processes like transpiration and photosynthesis, with optimal temperatures between 25

Table 2 Factors and the parameters measured in this study

Factor	Leaf chloro	Leaf N	Leaf humidity	Leaf temp.	Soil N.	Soil P.	Soil K.	Soil moisture	Soil temp.	Soil EC	Soil pH	Yield (pcs)	Yield (kg)
Topography (Topo)													
Flat	47.46 ^a	20.39 ^a	67.76 ^a	28.28 ^a	13.93 ^b	15.59 ^b	51.09 ^b	29.86 ^a	24.02 ^a	187.68 ^b	5.17 ^b	620.7 ^a	928.8 ^a
Terrace	41.78 ^b	15.78 ^a	68.12 ^a	28.23 ^a	15.87 ^a	22.74 ^a	59.43 ^a	31.69 ^a	24.43 ^a	213.44 ^a	5.39 ^a	894.8 ^a	1329.1 ^a
Phenological stages (PS)													
Mature flower bud & flower bloom	47.06 ^a	24.21 ^a	63.29 ^a	29.37 ^a	16.25 ^a	22.38 ^{ab}	64.5 ^a	36.51 ^a	26.33 ^a	218.63 ^a	6.11 ^a	729.6 ^b	1082.8 ^b
Flower bloom & marble-sized fruit	46.70 ^a	17.44 ^a	69.61 ^a	29.37 ^a	15.88 ^a	20.92 ^{ab}	50.08 ^{ab}	36.68 ^a	26.73 ^a	206.71 ^a	5.98 ^a	614.6 ^b	930.3 ^b
Duck-egg size & mature	46.83 ^a	17.49 ^a	69.89 ^a	28.28 ^a	11.97 ^b	16.69 ^b	44.94 ^b	28.65 ^b	20.28 ^b	153.41 ^b	4.31 ^b	98.9 ^b	149.3 ^b
Mature & harvest	43.25 ^a	16.49 ^a	65.46 ^a	29.74 ^a	14.38 ^{ab}	19.5 ^{ab}	54.38 ^{ab}	28.00 ^b	27.91 ^a	199.88 ^{ab}	5.81 ^a	2185.4 ^a	3279.6 ^a
Recovery & Vegetative growth	39.35 ^a	14.79 ^a	58.97 ^a	24.49 ^b	16.03 ^a	23.84 ^a	62.41 ^a	24.02 ^b	19.87 ^b	224.19 ^a	4.18 ^b	160.1 ^b	202.8 ^b
Topo*PS	*	ns	*	ns	ns	*	*	ns	ns	ns	ns	ns	ns

Means within the factor and column followed by different letters are significantly different at $p=0.05$, as determined by Tukey's HSD test, * = significant different and ns = no significant different

°C and 35 °C, and extreme temperatures potentially harming fruit quality. In this study, there was no significant relationship ($P < 0.05$) between durian phenological stages and leaf nitrogen contents and leaf temperature for durian trees planted on flat and terrace areas (Table 2; Figs. 5 and 6). The leaf nitrogen content shows a rapid decrease during the marble size stage for the flat area while maintaining relatively steady levels at the terrace area. Table 2; Fig. 6 shows that the leaf temperature is relatively consistent in both flat and terrace areas, but there was a sharp reduction in leaf temperature from the mature fruit stage to the recovery and vegetative stage in both areas. During the recovery and vegetative stages of plants or fruit trees, leaf temperature tends to be lower due to increased transpiration rates supporting new growth and reduced metabolic activity, which decreases heat production. Leaf nitrogen content may also decrease initially as plants redistribute nutrients from fruiting to support new leaf and shoot growth, while soil nutrient depletion from intense fruiting periods further contributes to lower nitrogen levels until replenished. These adjustments reflect plants' adaptive strategies to optimize growth and resource utilization throughout their developmental stages [18].

3.2 Soil properties

The successful growth of durian trees is intricately tied to soil properties such as Nitrogen, Phosphorus, Potassium, moisture content, temperature, electrical conductivity (EC), and pH levels. These soil characteristics play critical roles in supporting optimal growth and fruit production. Topographical features significantly influence soil properties, with factors like slope, aspect, and drainage patterns affecting nutrient availability and soil moisture retention. Moreover, the phenological stages of durian trees, including crab eyes, flowering, fruit development, and recovery, exhibit distinct soil property requirements [19]. There was no significant two-way interaction ($P < 0.05$) was observed between durian phenological stages and topographical conditions (flat and terraced areas) on soil nitrogen content (Table 2; Fig. 7). Nevertheless, both phenological stage and topography exhibited significant main effects on soil nitrogen contents. Throughout the durian growing season, soil nitrogen levels fluctuate significantly across different phenological stages and topographical conditions. This study indicates that nitrogen availability in terraced areas typically decreases from the mature flower bud stage to the duck egg size stage, followed by a subsequent increase leading into the vegetative phase. In contrast, nitrogen content in flat terrain exhibits varying patterns across all phenological stages, reflecting complex interactions influenced by soil type, drainage, and nutrient management practices. These dynamics underscore the critical role of both phenology and topography in shaping soil nitrogen availability, thereby influencing durian tree growth, flowering, and fruit development.

Based on recent studies, nitrogen dynamics in durian cultivation exhibit distinct patterns compared to other crops. Unlike observations in strawberries where nitrogen uptake is typically low in the early stages and increases towards harvesting, our study reveals a different scenario for durian trees across varying topographies [20]. Specifically, we found elevated soil nitrogen levels during both early and harvesting stages in terraced and flat areas alike, with notable decreases observed between the marble-size fruit and duck egg-size stages. Moreover, higher elevations consistently recorded higher soil nitrogen content compared to lower elevations, a trend supported by previous findings correlating total nitrogen levels with topographical variations [21]. Notably, soil

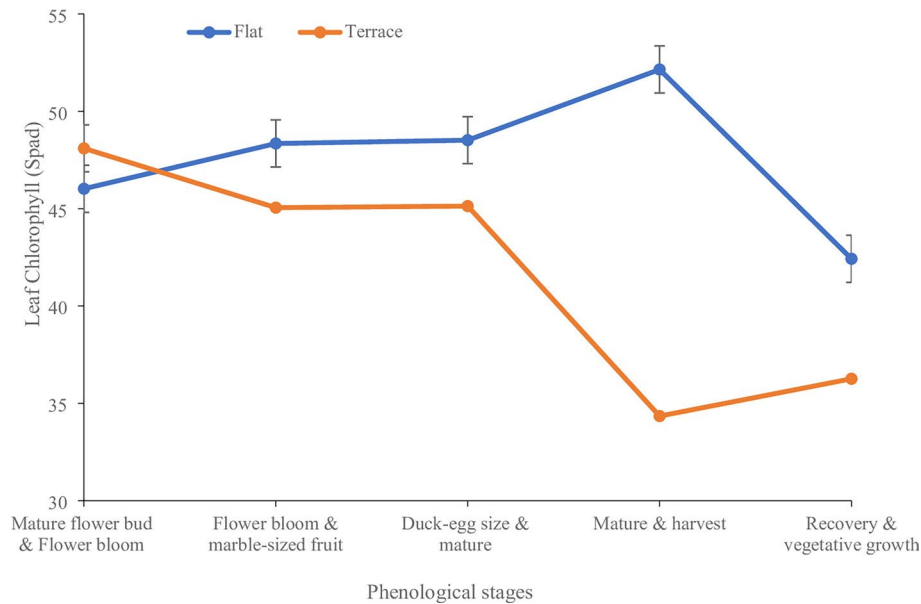


Fig. 3 Relationship between phenological stages of durian and leaf chlorophyll (SPAD) at flat and terrace areas

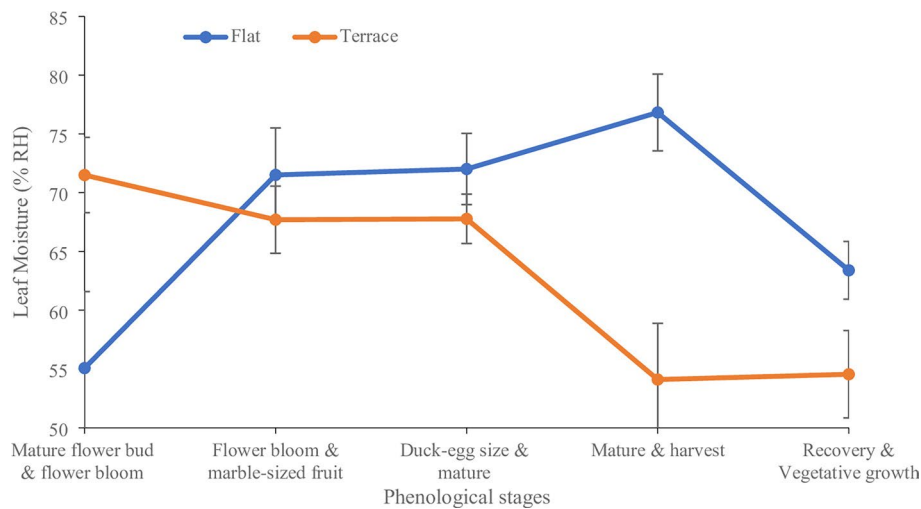


Fig. 4 Relationship between phenological stages of durian and leaf moisture at flat and terrace areas

nitrogen accrual was not solely attributed to applied fertilizers but also to microbial contributions [21], underscoring the multifaceted sources influencing nitrogen availability in durian cultivation. This aligns with findings associating soil nitrogen levels with vegetative growth phases [22], where our study confirms elevated nitrogen levels during the recovery and vegetative stages across different topographies. Moreover, our findings are consistent with the positive correlation observed between nitrogen content and reproductive development in durian plants as noted by Suarta et al. [23]. These insights highlight the nuanced interplay of soil nitrogen dynamics, topographical influences, and their implications for optimizing durian cultivation practices to enhance yield and quality.

Table 2; Fig. 8 shows there was no two-way interaction relationship ($P < 0.05$) between durian phenological stages and soil phosphorus contents for durian trees planted on flat and terrace areas. However, notable distinctions were evident in the relationship

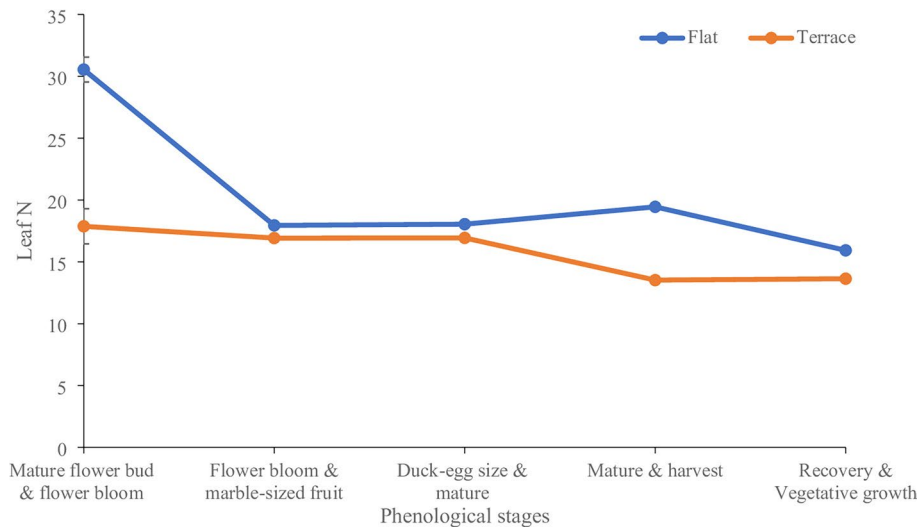


Fig. 5 Relationship between phenological stages of durian and leaf nitrogen at flat and terrace areas

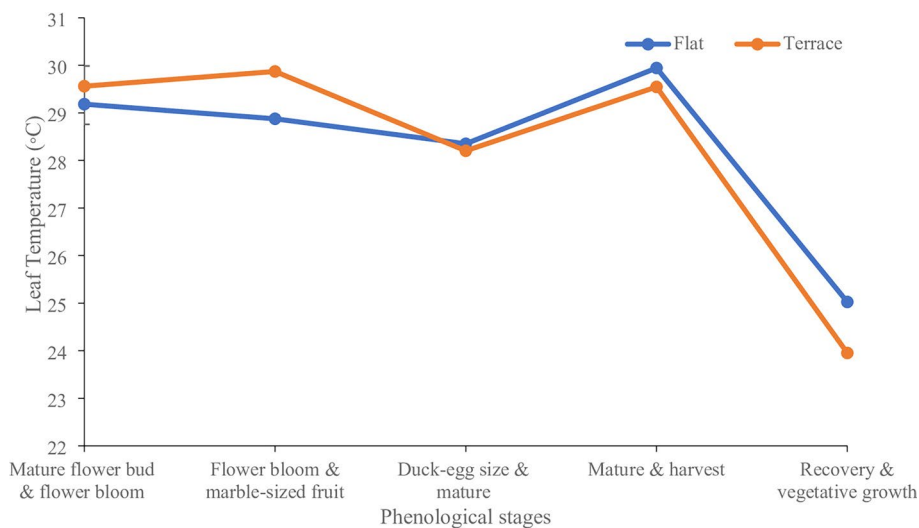


Fig. 6 Relationship between phenological stages of durian and leaf temperature at flat and terrace areas

between topography and soil phosphorus content for durian trees. Additionally, significant variations were observed among different phenological stages of durian trees concerning soil phosphorus levels in this study. These findings underscore the independent impacts of topography and phenology on soil nutrient dynamics, particularly highlighting the nuanced influence of soil phosphorus content throughout durian growth stages across varied planting terrains. This contrasts with previous findings by Amran et al. [21] and Bayram and Elmacı [24], where phosphorus levels showed minimal variation across different topographies, ranging from 1.624 to 8 mg/kg. In contrast, our study documented higher available phosphorus levels ranging from 15.34 mg/kg to 29.38 mg/kg, emphasizing the variability in phosphorus availability influenced by local soil conditions and management practices. Terrace areas showed higher soil phosphorus content compared to flat areas, attributed to enhanced water drainage and nutrient retention in terraced landscapes. Conversely, flat areas typically experienced greater nutrient leaching and runoff, leading to potentially lower soil phosphorus levels. These findings highlight

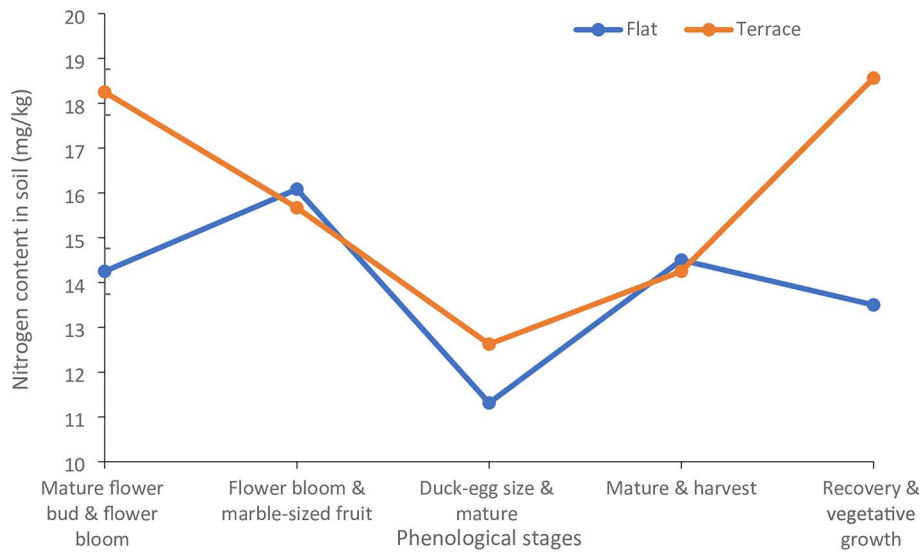


Fig. 7 Relationship between phenological stages of durian and soil nitrogen content at flat and terrace areas

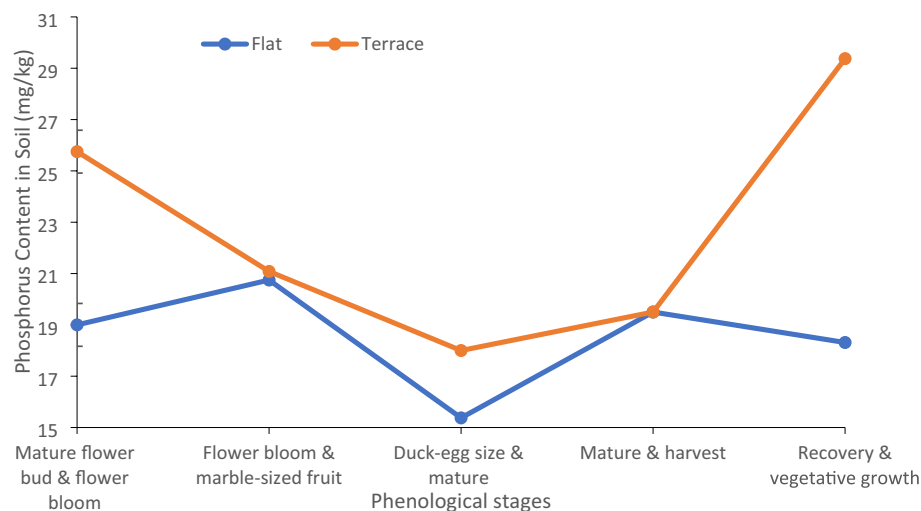


Fig. 8 Relationship between phenological stages of durian and soil phosphorus contents at flat and terrace areas

the critical role of topographical factors in shaping soil phosphorus contents to optimize durian growth and productivity.

The relationship between soil phosphorus and different phenological stages of durian trees reveals nuanced dynamics crucial for effective nutrient management. Early vegetative stages typically exhibit lower phosphorus uptake as resources focus on establishing plant structure. As durian trees progress to flowering and fruiting stages, there’s an increased demand for phosphorus to support reproductive growth and fruit development, potentially influencing soil phosphorus levels. Our study observed fluctuations in phosphorus availability during fruit development, particularly noting a decrease from marble-sized to mature fruit stages. Towards maturation and recovery, phosphorus requirements may decrease again as metabolic activity slows.

Soil potassium content is crucial for supporting essential plant functions such as water regulation, nutrient transport, enzyme activation, and stress tolerance in durian

cultivation. Adequate potassium levels promote healthy growth, flowering, and fruit development, enhancing durian tree resilience to environmental stresses and optimizing overall yield and fruit quality [18]. There was a statistically significant interaction ($P < 0.05$) observed between durian phenological stages and soil potassium contents across both flat and terrace planting areas (Table 2; Fig. 9). Initially, soil potassium contents showed a gradual decrease during the early stages from mature flower bud to flower bloom, reflecting the uptake for initial plant establishment in this study. As durian trees transitioned into fruit development, soil potassium levels tended to stabilize or increase, notably during the transition from the duck egg stage to fruit maturity. This observation suggests an increased demand for potassium in the soil to support fruit growth and maturation. During the fruit maturation and recovery phases, soil potassium levels continued to increase in terrace areas but decreased in flat areas, possibly due to differences in nutrient uptake efficiency by the trees and soil nutrient redistribution associated with topographical conditions.

According to Amran et al. [21], significant differences in soil potassium levels were observed based on topography. Unlike olive trees, which typically experience maximum potassium depletion from fruit development to maturity [18], while our study on durian trees revealed an initial decrease in soil potassium levels followed by an increase during the transition from the duck egg stage to maturity. This finding aligns with Boulal et al. [25], who recommend potassium application during later stages of crop growth and fruit ripening when potassium demand is highest. This pattern observed not only in olives but also in durians, correlates with higher yields observed in January. Soil nitrogen, phosphorus, and potassium levels exhibited consistent trends across all phenological stages of durian, irrespective of topography. Regarding topographical influences, terrace areas generally exhibited more stable and potentially higher soil nitrogen, phosphorus, and potassium levels compared to flat areas. This difference can be attributed to better nutrient retention and reduced leaching in terraced areas, which promote more consistent nutrient availability throughout the growing season.

Soil moisture of durian trees plays a critical role in their growth and development, influencing various physiological processes and overall health. Optimal soil moisture

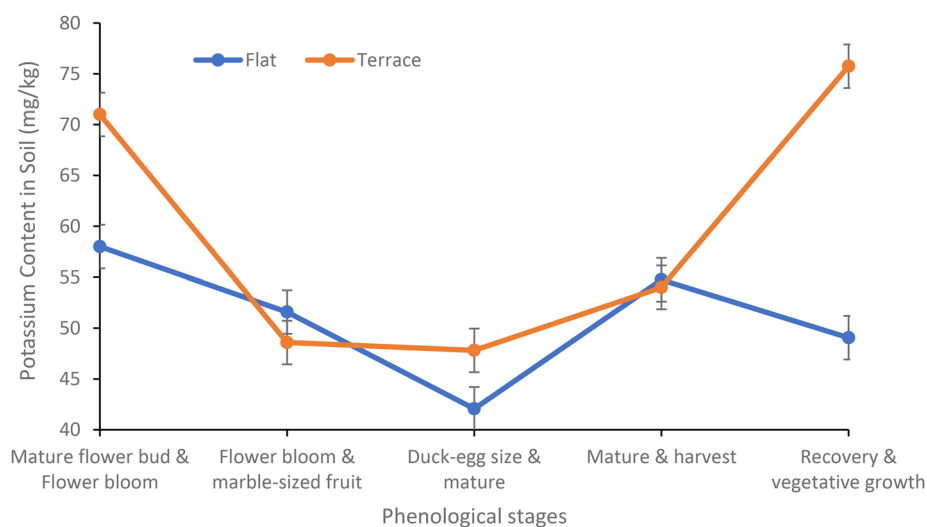


Fig. 9 Relationship between phenological stages of durian and soil potassium contents at flat and terrace areas

levels are essential throughout the durian growing season, from immature to fruiting stages. Adequate soil moisture facilitates nutrient uptake, root development, and photosynthesis, crucial for vigorous vegetative growth and optimal fruit production. Conversely, both excessive moisture and drought stress can adversely affect durian trees, leading to reduced nutrient absorption, root rot, and ultimately, diminished yield and quality [26]. There were no significant interaction effects ($P < 0.05$) between durian phenological stages and soil moisture for durian trees planted on flat and terrace areas. Nevertheless, significant effects were evident in the relationship between phenological stages and soil moisture for durian trees (Table 2; Fig. 10). In this study, soil moisture levels declined in terrace and flat areas. During the fruit maturation stage, terrace areas experienced an increase in soil moisture, whereas the recovery and vegetative stages showed the lowest soil moisture levels. The decrease in soil moisture from the flower bud to marble-sized stages is crucial, as excessive water can cause flower buds to develop into new leaves rather than progressing into marble-sized fruits. This highlights the critical importance of carefully managing water levels during the pivotal growth phases of durian trees. According to botanical principles, excessive soil moisture during the transition from durian flower buds to marble-sized fruits may divert plant resources toward vegetative growth rather than supporting optimal fruit development [27].

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Additionally, this study showed that terrace areas have higher soil moisture compared to flat areas for durian planting. This finding is consistent with Amran et al. [21], who reported that terrace areas exhibit higher soil moisture levels compared to flat lands, with elevated terrain generally showing increased soil moisture percentages. This factor is crucial as soil moisture plays an important role in various stages of durian tree development. Specifically, soil moisture levels influence flower induction, as noted by Masri [26] and Ketsa et al. [28]. A moderate level of drought stress can promote flower initiation in durian trees, highlighting the nuanced relationship between water availability and reproductive processes. However, sustained development from flowering to fruiting stages necessitates appropriate irrigation management. Additionally, soil moisture conditions impact fruitlet retention, with Masri [26] indicating that restricted soil moisture can lead to higher rates of premature fruitlet drop. These findings underscore

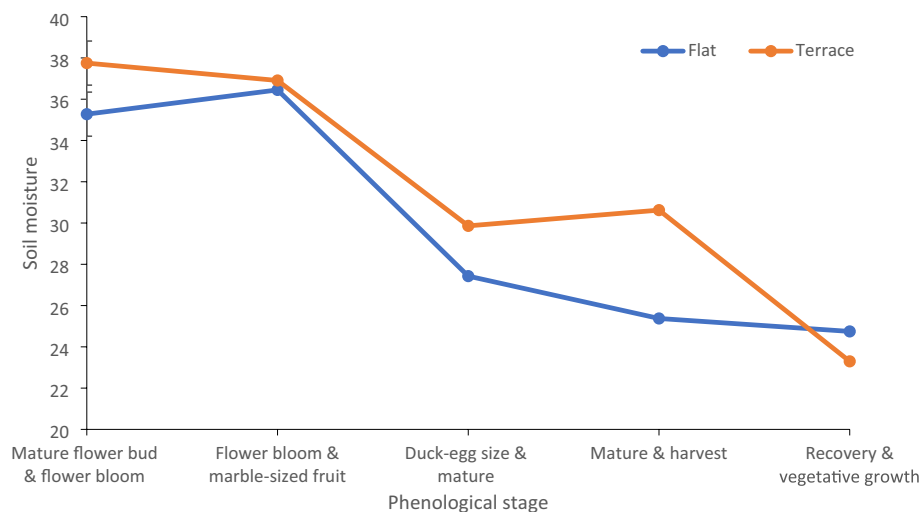


Fig. 10 Relationship between phenological stages of durian and soil moisture at flat and terrace areas

the intricate balance required in managing soil moisture to optimize both flower induction and fruit development in durian cultivation.

Additionally, soil temperature also important for the growth and development of durian trees. Excessively high or low soil temperatures during these critical stages can negatively impact fruit quality and yield. Figure 11 shows there was no significant interaction between the phenological stages of durian and soil temperature on flat and terrace areas. However, there was a significant difference in soil temperature at different phenological stages of durian. During the flower bud to flowering stages, the soil temperature remained between 26 and 27 °C. There was a rapid drop in temperature during the young fruit stage, followed by a drastic increase during the mature fruit stage. This study also showed that the recovery and vegetative stages of durian exhibited the lowest soil temperatures across all the phenological stages. The observed decrease in soil temperature from the flowering to marble fruit stage in durian trees may be attributed not only to increased transpiration rates and the shading effect of the expanding canopy but also to prevailing climate conditions during this period, such as reduced ambient temperature and increased rainfall. The average temperatures recorded across the phenological stages ranged from 27 to 32 °C during daytime. As the fruits mature, transpiration decreases, and microbial activity in the soil increases, leading to a rise in soil temperature. Additionally, reduced shading allows more sunlight to warm the soil. During the recovery and vegetative stages, soil temperature drops again due to post-harvest cooling and renewed vigorous growth, which increases transpiration and cools the soil. These fluctuations reflect the dynamic interplay between the physiological processes of the durian tree and environmental factors at different phenological stages.

Soil pH can significantly vary with different topographies and phenological stages of durian trees, influencing nutrient availability and overall tree health. According to the Asia-Pacific Association of Agricultural Research Institutions – APAARI [29], the optimum pH range for durian growth is 5.5 to 6.5, which aligns with the findings of this study, except for December and February for both flat and terrace land. Table 2; Fig. 12 illustrate that there were no significant interaction effects between durian phenological

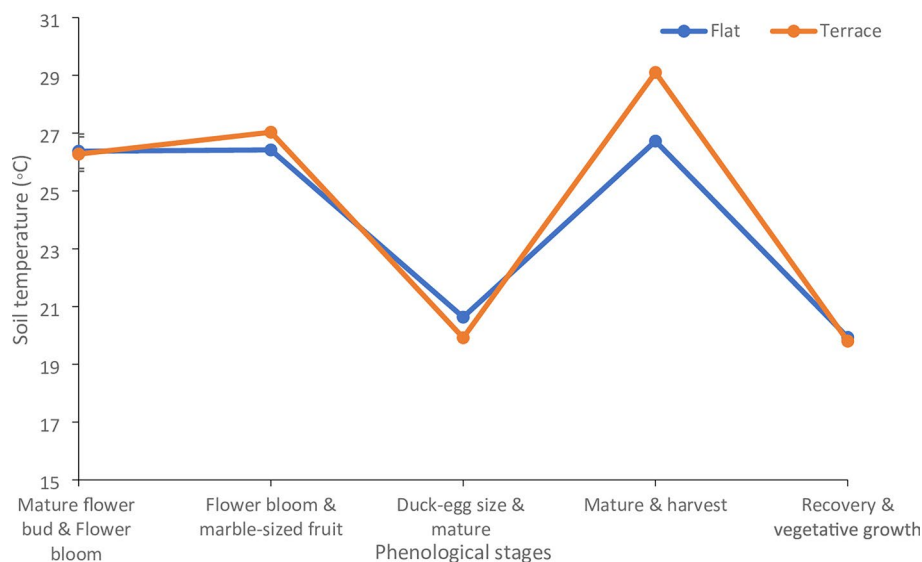


Fig. 11 Relationship between phenological stages of durian and soil temperature at flat and terrace areas

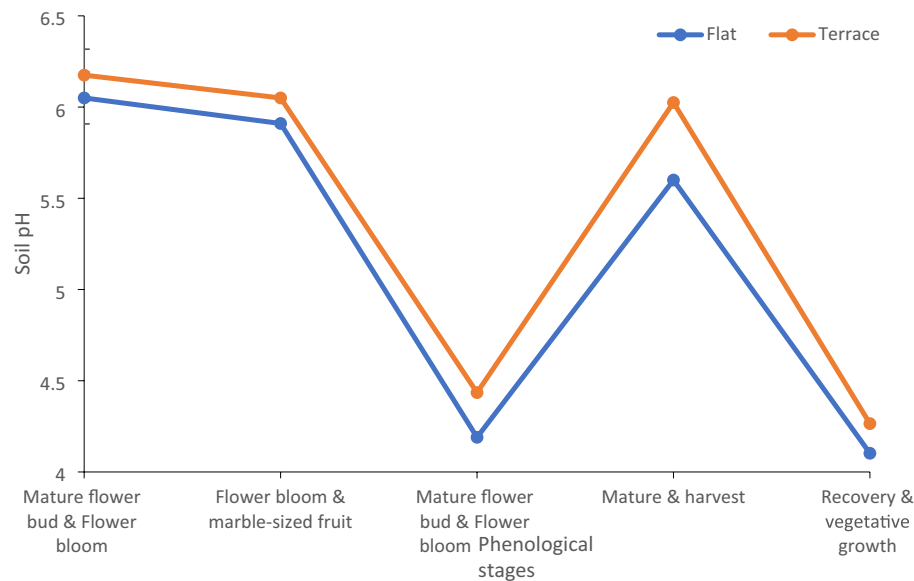


Fig. 12 Relationship between phenological stages of durian and soil pH at flat and terrace areas

stages and soil pH across flat and terrace areas. Instead, the analysis revealed distinct single-factor effects of both durian phenological stages and topography on soil pH. This finding suggests that while both factors independently influence soil pH, their combined effect did not show a statistically significant interaction in this study. Soil pH can significantly vary with different topographies, influencing nutrient availability and the overall health of durian trees. In terrace areas, soils generally have better drainage and are less prone to waterlogging, leading to more stable pH levels, often slightly acidic to neutral, which is favourable for durian trees. The terracing practice helps prevent erosion and leaching, maintaining more consistent soil properties. In contrast, soils in flat areas might have poorer drainage and be more susceptible to waterlogging and leaching, potentially resulting in more acidic or variable pH levels. In such areas, pH levels can sometimes drop below the optimal range due to the accumulation of organic acids or improper nutrient cycling [30].

Based on findings in this study, during the transition from flower bud formation to flowering, it is crucial to maintain soil pH within the optimal range of 5.5 to 6.5. This range is essential for ensuring adequate nutrient availability, particularly for phosphorus, which plays a critical role in promoting flowering. If the pH is too low or too high, it can affect nutrient uptake and flowering success. During the young fruit stage, soil pH can slightly decrease due to increased root activity and nutrient uptake. As the fruits mature, soil pH might stabilize or slightly increase as nutrient uptake balances. Maintaining optimal pH is crucial for fruit development and quality. During the recovery and vegetative stages, the emphasis is on promoting regrowth and replenishing nutrients. Therefore, it is essential to monitor soil pH and adjust it if necessary to ensure availability of essential nutrients for vegetative growth. However, the findings of this study indicated that the soil pH was quite acidic, ranging between 4.1 and 4.2.

3.3 Durian yield

Healthy leaves contribute to overall tree vigour and fruit quality. In this study, topography, particularly the slope of the land, was found to significantly influence the yield

of durian, as shown in Table 2; Fig. 13. The slope can affect various factors crucial for durian production, such as water drainage, soil erosion control, and sunlight exposure. Terraced or gently sloping lands often facilitate better water management and nutrient distribution, promoting healthier root systems and overall tree vigour. Additionally, the orientation of slopes can influence microclimatic conditions, potentially mitigating risks from extreme weather events and optimizing conditions for fruit development. These findings underscore the importance of considering topographical factors in durian cultivation practices to enhance yield and ensure sustainable production. However, contrasting findings were observed in studies by Farooque et al. [31], where higher yields of blueberries were reported in mild slope areas, while high slope areas yielded less. This discrepancy was attributed to nutrient washout in higher-elevation lands. Similar trends were noted in Farooq [32] study on wheat production. This difference in findings may be attributed to the fact that different fruits have specific topographical preferences that optimize their growth and yield potential. Factors such as water drainage, nutrient retention, and microclimatic conditions vary across different types of terrain. While some fruits like blueberries thrive on mild slopes where water retention is optimal, others like durians may benefit from terraced or gently sloping lands that provide balanced water management and nutrient distribution. Understanding these specific requirements is crucial for tailoring cultivation practices to maximize yield in different fruit crops.

3.4 Correlation analysis

Correlation analysis was performed to determine the relationship between leaf characteristics, soil properties, and durian yield at different phenological stages of durian trees planted in flat and terrace areas (Table 3). This analysis provides insights into how these variables interact with one another and identifies which factors have a direct influence on durian yield. A significant, positive, and strong correlation ($r = 0.83$) was found between durian leaf chlorophyll content and leaf moisture, indicating that higher chlorophyll levels are associated with increased leaf moisture. This is supported by studies showing that chlorophyll content is a good indicator of leaf health and photosynthetic activity, which can influence leaf water retention [33]. Additionally, there was a significant, positive,

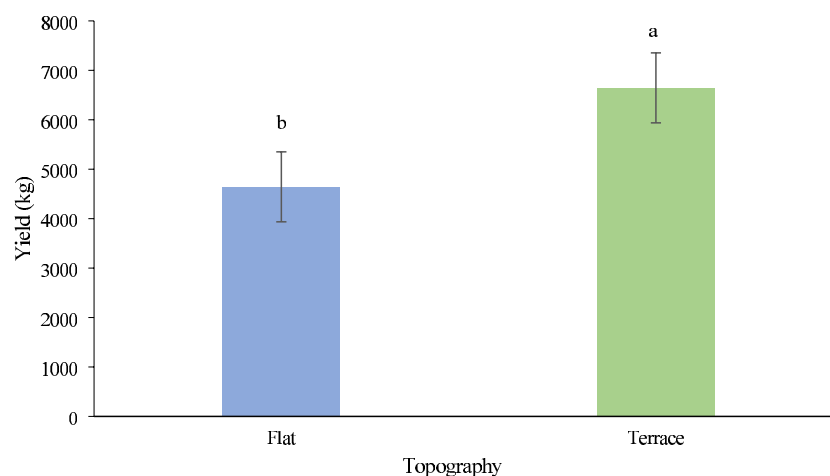


Fig. 13 The durian yield at flat and terrace areas. Means for yield followed by different letters are significantly different at $p = 0.05$, as determined by Tukey's HSD test

Table 3 Correlation coefficients (*r*) between leaf characteristics, soil properties, and Durian yield at different phenological stages of Durian trees planted in flat and terrace areas

	Leaf chloro	Leaf N	Leaf moisture	Leaf Temp	Soil N	Soil P	Soil K	Soil moisture	Soil Temp	Soil pH	Yield
Leaf Chloro	1.00	0.36*	0.83**	0.42*	-0.09 ^{ns}	-0.08 ^{ns}	-0.15 ^{ns}	0.19 ^{ns}	0.15 ^{ns}	0.16 ^{ns}	-0.22 ^{ns}
Leaf N		1.00	-0.37*	0.30 ^{ns}	0.07 ^{ns}	0.04 ^{ns}	-0.02 ^{ns}	0.31*	0.15 ^{ns}	0.26 ^{ns}	-0.06 ^{ns}
Leaf Moisture			1.00	0.25 ^{ns}	0.16 ^{ns}	0.12 ^{ns}	-0.14 ^{ns}	-0.03 ^{ns}	0.06 ^{ns}	0.02 ^{ns}	-0.14 ^{ns}
Leaf Temp				1.00	0.05 ^{ns}	0.03 ^{ns}	-0.07 ^{ns}	0.42*	0.54*	0.59**	0.37*
Soil N					1.00	0.89**	0.80**	0.24 ^{ns}	0.17 ^{ns}	0.23 ^{ns}	0.05 ^{ns}
Soil P						1.00	0.91**	0.12 ^{ns}	0.01 ^{ns}	0.08 ^{ns}	0.02 ^{ns}
Soil K							1.00	0.01 ^{ns}	0.01 ^{ns}	0.13 ^{ns}	0.10 ^{ns}
Soil Moisture								1.00	0.51*	0.62**	0.09 ^{ns}
Soil Temp									1.00	0.85**	0.60*
Soil pH										1.00	0.56*

Correlation coefficients (*r*) with four replications. ^{ns} = non-significant, *, ** = significant at $p=0.05$ or 0.01 , respectively

and strong correlation between soil nitrogen, phosphorus, and potassium contents for durian trees, suggesting that an increase in these soil nutrients enhances nutrient uptake by the trees, promoting healthier growth and potentially higher yields [34]. Furthermore, the study revealed a significant, positive, and strong correlation ($r = 0.85$) between soil pH and soil temperature, consistent with findings that soil temperature can influence soil pH levels. Soil pH also showed significant, positive, and moderate correlations with leaf temperature ($r = 0.59$) and soil moisture ($r = 0.62$). In terms of durian yield, the analysis indicated significant, positive, and moderate correlations with soil temperature ($r = 0.60$), suggesting that optimal soil temperature and pH are important for maximizing durian yield [35].

4 Conclusion

This study highlights the intricate interplay between topography and phenological stages in influencing soil and leaf properties, ultimately affecting durian yield. The findings reveal significant variations in soil nitrogen, phosphorus, potassium, moisture, and pH levels across different topographies and phenological stages, underscoring the importance of site-specific nutrient management. Leaf characteristics such as chlorophyll content, moisture, and nitrogen levels also exhibited notable changes throughout the durian growth cycle, further emphasizing the dynamic nature of durian cultivation. The positive correlation between leaf chlorophyll content and moisture, alongside soil nutrient fluctuations, indicates the necessity for tailored agricultural practices to optimize durian production. This research provides valuable insights into durian cultivation by addressing the gap in understanding environmental influences on growth and yield. However, future studies should incorporate a broader range of topographical conditions,

long-term monitoring, and additional physiological parameters such as stomatal conductance and photosynthetic efficiency to further refine best practices. Additionally, integrating precision agriculture technologies, such as remote sensing and IoT-based monitoring, could enhance data accuracy and decision-making for sustainable durian production. These findings reinforce the need for adaptive agricultural strategies that consider both the developmental stage of trees and their planting terrain to maximize durian tree health, fruit yield, and overall productivity.

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Author contributions

- **Tan Xue Yi** : Conceived and designed the study, served as the corresponding author, and was primarily responsible for writing and editing the manuscript.- **Vinailosni Amirthalingam** : Conducted data analysis, interpretation, and manuscript writing.- **Tan Sue Sian** : Provided funding and critically edited and reviewed the manuscript.- **Crystale Lim Siew Ying** : Editing and reviewing the manuscript.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The authors confirm that formal permission to conduct experimental work within the study area was obtained from Top Fruits Plantation, the legal owner and managing authority of the site. All research activities were undertaken in accordance with the plantation's regulations and with the full knowledge and approval of its management.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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