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Influence of plant morphology on microclimate dynamics and resource optimization in multitier agroforestry systems

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ABSTRACT: *Agroforestry systems offer a sustainable approach to enhance microclimate regulation, yet the role of plant morphology in this process remains inadequately explored. The present study aimed to assess the influence of tree morphology on microclimatic modifications under a multitier agroforestry system (AFS) comprising Teak (Tectona grandis) and Karanj (Pongamia pinnata) with intercrops like Pigeon pea and Chickpea. Significant variations were observed in tree height, canopy spread, and basal girth across different treatments, which directly influenced microclimatic parameters such as Photosynthetically Active Radiation (PAR), temperature, and relative humidity (RH). A positive correlation was recorded between tree height and PAR, similarly between canopy spread and PAR. Maximum RH improvement (10.90%) was observed under Karanj in the Teak+Karanj system, highlighting the role of canopy structure in moisture retention. However, there were significant decreases (maximum by 9.68%) in air temperature under multitier AFS over control. The findings emphasize that appropriate tree selection and spatial arrangement can optimize light availability, air temperature moderation, and humidity regulation, thereby improving the overall microclimatic conditions. It is recommended to promote agroforestry models with species exhibiting suitable morphological traits to maximize ecological and production benefits, particularly in regions prone to climatic stress.*

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1. INTRODUCTION

Agroforestry systems represent one of the most ancient and ecologically sustainable land management practices, wherein trees, crops, and sometimes livestock are integrated within the same unit of land to derive ecological and socio-economic benefits (Brookfield and Padoch 1994; Bene and Obirih-Opareh 2009). Archaeological pollen records reveal that such integrated systems have been in use for nearly 1300 years, with domestication of tree species beginning even earlier (Simmonds 1985). Over the last few decades, agroforestry has gained significant attention in agricultural research due to its ability to combine the productivity of farmland with the resilience and ecological services of forest systems (Garrity 2004; Nair *et al.* 2010; Nair 2011).

The increasing challenges posed by global climate change, evident through rising temperatures, erratic rainfall, and land degradation, have further underlined the importance of agroforestry as a climate-resilient, sustainable land use strategy (Hansen 2002; IPCC 2007; Buchman, 2008). Trees in agroforestry systems have been shown to significantly alter microclimatic conditions by reducing air temperature, moderating soil moisture, reducing wind speed, and improving atmospheric humidity, thereby enhancing crop growth and yield (Davis and Norman 1988; Monteith *et al.* 1991; Brandle *et al.* 2004; Steffan-Dewenter *et al.* 2007).

Despite such recognized benefits, the degree of microclimate modification in agroforestry systems is highly dependent on the morphological characteristics of the plant species involved, particularly in complex multitier systems where interactions between species create varying microenvironments. The morphological features such as canopy structure, leaf orientation, foliage density, and photosynthetic pathways (C3 vs. C4) directly influence parameters like light interception, soil temperature, air humidity, and wind speed (Boardman 1977; Anderson and Sinclair 1993; Lin 2007). However, comprehensive studies focusing

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on how plant morphology contributes to microclimate regulation under existing multitier agroforestry systems remain scarce, especially in tropical regions like India where such systems have significant livelihood implications.

In the face of escalating climate variability and unsustainable agricultural practices, agroforestry has emerged as a viable option to improve microclimatic conditions and enhance system resilience. However, inadequate scientific understanding of the role of plant morphological traits in influencing microclimate under multitier systems limits the ability to optimize such systems for maximum ecological and economic benefits.

It is hypothesized that variations in plant morphology including canopy structure significantly influence microclimate parameters such as light intensity, air temperature and relative humidity under four existing multitier-based agroforestry systems. Keeping in view, an experiment was conducted to investigate the effect of plant morphology on microclimate modification under existing multitier-based agroforestry systems.

2. MATERIALS AND METHODS

Experimental area

`The present study was conducted at the experimental farm and laboratory of the ICAR Research Complex for Eastern Region (ICAR RCER), Farming System Research Centre for Hill and Plateau Region (FSRCHPR), Plandu, Ranchi, Jharkhand. The experimental site, located at the 2^{nd} farm of the centre (Churu) at coordinates 23°16'26.6" N latitude and 85°22'29.3" E longitude with an elevation of 657.76 meters above mean sea level, lies approximately 7 km from the institute's main campus (Fig. 1). This region, part of the Chotanagpur plateau, is characterized by undulating terrain with large patches of forest and agricultural land, though urban expansion is rapidly altering the landscape.

The site experiences a subtropical climate comprising three distinct seasons: summer (March to June), monsoon (July to September), and winter (November to February). The average annual rainfall ranges between 1500–1600 mm, with about 80% of the precipitation received during the southwest monsoon. The area is marked by lateritic, sandy-loam textured Alfisols, which are acidic (pH 4.5–5.5) and generally low in fertility, particularly nitrogen, phosphorus, and potash.

Experimental Details

The models were developed during the year 2016 and validated the experimental result after completion of five years when economic harvesting was measured out of those systems during 2021. The microclimatic data as well as it's correspondent plant growth attributes were measured in a 5-year-old existing multitier agroforestry system comprising Teak (*Tectona grandis*) as the upper storey and Karanj (*Pongamia pinnata*) as the middle storey, planted in alternate lines at a spacing of 5 m × 10 m. The lower storey consisted of seasonal intercrops such as Pigeon pea (*Cajanus cajan*) and Chickpea (*Cicer arietinum*) generally cultivated during July–December of each year after implementation of the agroforestry models.

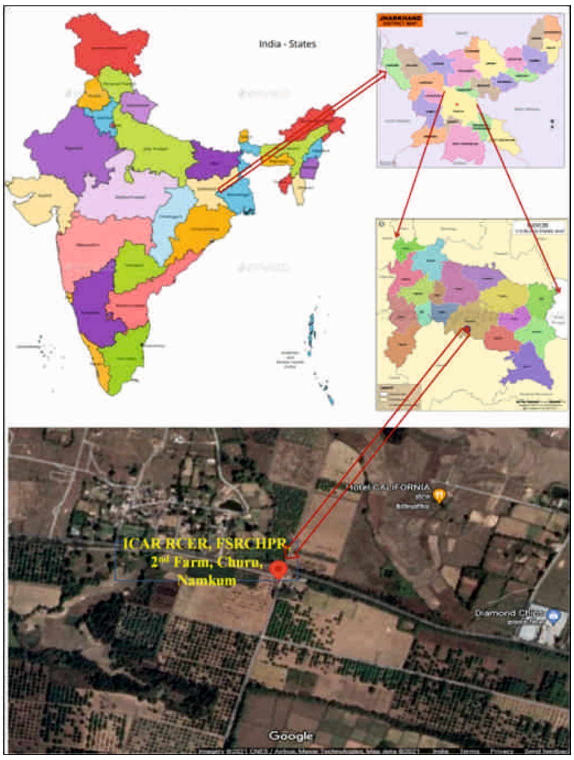

Fig. 1. Geographical map of the experimental location

A Randomized Block Design (RBD) with five treatment combinations and four replications was adopted for the experiment to minimize variability and ensure statistical validity (Table 1).

Data Collection Techniques

Data were collected systematically to examine the effect of plant morphology on microclimate modification across all treatments. Observations were recorded at 15-day intervals from March to June, three times a day (9:00–10:00 AM, 12:00–1:00 PM, and 3:00–4:00 PM) in four cardinal directions (North, South, East, West). For, morphological observations, tree height, canopy height, basal girth, number of branches and canopy spread, etc. were measured using the standard protocol and the scientific instruments. While in case of microclimatic observations, parameters like light intensity, air temperature and relative humidity were measured.

Statistical Analysis

The collected data were compiled and analyzed with Systat 12 statistical software (Wilkinson & Coward 2007) to assess the significance of treatment effects.

3. RESULTS

Effect of plant morphology on microclimate modification under existing multitier agroforestry system

Tree morphological characteristics

The growth performance of Teak (*Tectona grandis*) and Karanj (*Pongamia pinnata*) trees under different multitier agroforestry treatments revealed notable morphological variations (Table 2). The height of Teak trees varied significantly across treatments, ranging from 4.85±0.64 m to 7.17±1.59 m, with the tallest trees recorded under the Teak + Karanj system, while the shortest were observed under the Teak + Karanj + Chickpea system. Karanj trees followed a similar trend, with heights ranging between 2.18 ± 0.21 m and 3.17±0.80 m, the maximum being observed in the Teak+Karanj system. The canopy height of Teak trees ranged from 1.00±0.38 m to 1.57±0.07 m, with maximum values under the Teak+Karanj treatment. Karanj trees exhibited canopy heights between 0.72±0.27 m and 1.00±0.38 m, highest under the Teak + Karanj + Pigeon pea (5 lines) system. The basal girth of Teak trees ranged from 36.83±4.44 to 45.00±2.52 cm, while for Karanj, it varied between 29.17±3.09 cm and 35.00±3.79 cm, with maximum girth observed in systems with fewer intercrops. The number of branches per Teak tree ranged from 3.33±0.33 to 8.33±1.86, maximum in the Teak + Karanj system, while Karanj trees had between 3.67±0.33 and 5.00±0.58 branches, with more branches observed under Chickpea-based systems.

Canopy Spread

The canopy spread of Teak trees ranged between 3.20±0.03 m and 3.85±0.66 m, with the widest canopies in the Teak+Karanj+Pigeon pea (5 lines) system. Karanj trees showed a canopy spread from 2.47±0.42 m to 3.67±0.78 m, the maximum recorded under the Teak+Karanj system (Table 3).

These results indicate that tree morphology is strongly influenced by the system composition and crop combination, with relatively better growth observed under Teak+Karanj based systems compared to those with additional intercrops.

Effect of tree morphology on microclimatic modifications

The interaction between tree morphology and microclimate parameters was assessed within a 1 m radial zone of tree trunks and at the centre between trees under different agroforestry systems (Figs. 2 - 15).

Table 1 Details of the treatments and its related components

S.No.	Treatment symbol	Treatment description	Components and spacing
1.	T1	Control	No trees, No Crops
2.	T2	Teak+Karanj	Teak and Karanj at 5 m × 10 m spacing; no intercrops
3.	T3	Teak+Karanj+Pigeon Pea	Teak and Karanj at 5 m × 10 m; Pigeon pea at 20 cm × 75 cm
4.	T4	Teak +Karanj+Pigeon	Teak and Karanj at 5 m × 10 m; Pigeon pea at 20 cm × 60 cm
5.	T5	Teak +Karanj+Chickpea	Teak and Karanj at 5 m × 10 m; Chickpea at 10 cm × 30 cm

Table 2 Physiological growth parameters of 5 years old Teak and Karanj trees under different agroforestry systems.

Trt.	SP	PH (m)	CH (m)	BA (m)	BG (cm)	NB
Teak+Karanj	Teak	7.17 ± 1.59^{a}	1.57 ± 0.07^{a}	0.55 ± 0.08^{a}	45.00 ± 2.52^{b}	8.33 ± 1.86^{a}
	Karanj	3.17 ± 0.80^{bc}	0.55 ± 0.15^{bc}	0.92 ± 0.36^{a}	35.00 ± 3.79^{b}	3.67 ± 0.33^{bc}
Teak+Karanj+Pigeon pea (PP: 4 Lines)	Teak	5.17 ± 0.58^{ab}	1.00 ± 0.14^{abc}	0.67 ± 0.08^{a}	43.00 ± 8.08^{b}	6.67 ± 1.20^{ab}
	Karanj	2.18 ± 0.50^{c}	0.33 ± 0.08^{c}	0.92 ± 0.08^{a}	29.17 ± 3.09^{b}	4.67 ± 0.33^{bc}
Teak+Karanj+Pigeon pea (PP: 5 Lines)	Teak	5.00 ± 0.10^{abc}	1.00 ± 0.38^{abc}	1.47 ± 0.27^{a}	43.17 ± 4.23^{b}	3.33 ± 0.33^{c}
	Karanj	2.33 ± 0.67^{bc}	0.72 ± 0.27^{bc}	0.92 ± 0.33^{a}	32.33 ± 4.26^{b}	4.00 ± 1.00^{bc}
Teak+Karanj+Chickpea	Teak	4.85 ± 0.64^{abc}	1.22 ± 0.28^{ab}	0.23 ± 0.13^{a}	36.83 ± 4.44^{b}	5.00 ± 0.58^{bc}
	Karanj	2.58 ± 0.51^{bc}	0.50 ± 0.14^{bc}	0.67 ± 0.22^{a}	29.67 ± 4.41^{b}	5.00 ± 0.58^{bc}
P value		<0.01	<0.05	0.074	0.152	<0.05
F value		4.361	3.58	2.44	1.86	3.14

Trt= treatment; SP= species; PH= plant height; CH= canopy height; BA= basal area; BG= basal girth; NB= number of branch. Data is shown as mean values of variables ± SE. Means in a column followed by different superscript letters are significantly different using DMR test.

Table 3 Canopy spread of 5 years old Teak and Karanj trees under different agroforestry systems.

Treatment	Species	Canopy spread	
		N-S	E-W
Teak+Karanj	Teak	3.80±0.65	3.333±0.50
	Karanj	3.67±0.78	4.067±0.69
Teak+Karanj+Pigeon pea (PP: 4 Lines	Teak	3.23±0.38	3.260±0.15
	Karanj	2.47±0.42	2.647±0.58
Teak+Karanj+Pigeon pea (PP: 5 Lines	Teak	3.80±0.66	4.133±0.56
	Karanj	3.33±0.47	3.867±0.67
Teak+Karanj+Chickpea	Teak	3.20±0.03	3.233±0.78
	Karanj	3.35±0.07	3.690±0.95
P value		0.570	0.346
F value		0.844	1.329

Data is shown as mean values of variables ± SE

Photosynthetically Active Radiation (PAR)

There was significant variation in PAR availability across treatments (Figs. 2 - 6). The differences and variations were recorded in the percent of PAR available (Fig. 2) at direction-wise radial distance from tree base upto 5 m when compared with control (i.e., Cropping field with no trees/any crops). The highest PAR value (48.51%) was recorded under Teak in the Teak+Karanj system, while the lowest value (30.65%) was found in Karanj in the Teak + Karanj + Pigeon pea (5 lines) system (Fig. 2). A positive relationship between tree height and PAR was observed, indicating that taller trees allow higher light penetration at lower levels (Fig. 3). Among them Teak tree height showed a positive and weak co-relation with PAR (R^2=0.520), while the moderate level of co-relation was observed under Karanj trre height with PAR (R^2=0.688). Besides these, the highest PAR value was recorded under Teak (48.51%) in the Teak+Karanj system, while the lowest value of PAR was recorded in Karanj (30.56%) in the Teak+Karanj+Pigeon pea (5 lines) system (Fig. 3).

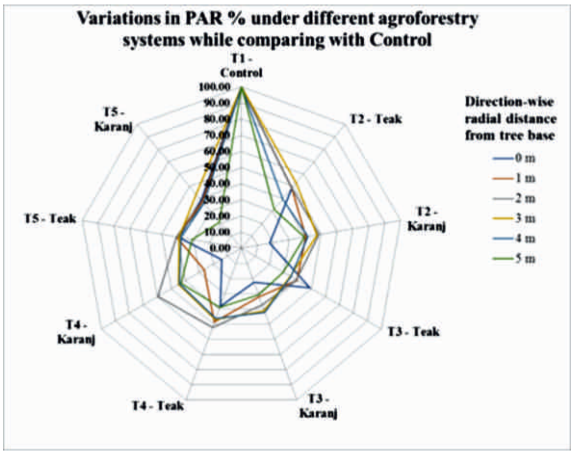

Fig. 2 Direction-wise variations in PAR under different agroforestry systems

When PAR was measured at the centre between two trees, values were higher than those recorded directly under tree canopies. The maximum PAR at the centre (49.53%) occurred in the Teak+Karanj+Pigeon pea (5 lines) system (Fig. 4). A positive but weak relationship (R^2=0.082-0.133) between tree height and PAR was observed, indicating that the influence of tree spacing and canopy gaps on light distribution (Fig. 4).

Systems with broader canopies, particularly Karanj in Teak+Karanj+Pigeon pea (4 lines), recorded lower PAR under the canopy (Fig. 5). On the other hand canopy spread of Teak tree showed a strong and positive co-relation (R^2=0.726) with PAR compared than Karanj. Similar patterns were observed for PAR at the centre between trees, where wider canopies generally reduced light penetration, though the central zones still exhibited higher PAR than the immediate periphery (Fig. 6).

Relative Humidity (RH)

Relative humidity around tree trunks varied substantially among systems (Fig. 7 & 8). There is significant differences and variations recorded in the percent of RH in different agroforestry system (Fig. 7) at direction-wise radial distance from tree base upto 5 m when compared with control. The maximum RH value (22.29%) was recorded under Karanj tree in the

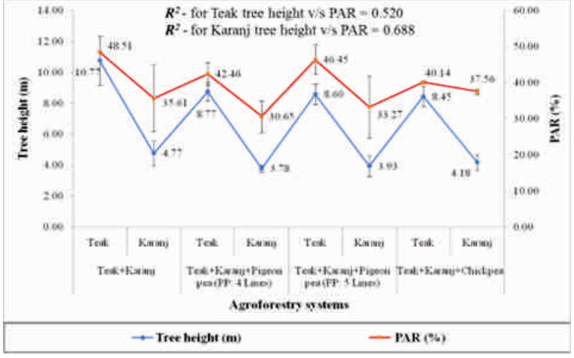

Fig. 3 Effect of tree height on per cent PAR (Photosynthetically Active Radiation) under 1 m radial periphery of the tree species.

Teak+Karanj system (5 m lines), while the minimum value (20.00%) was found in the control system (Fig. 7). The maximum increase in RH (10.90%) occurred under Karanj in the Teak+Karanj system, while the minimum (3.57%) was recorded under Karanj in the Teak+Pigeon+Chickpea system (Fig. 8). Here, the karanj tree showed a strong and positive correlation (R^2=0.824) with RH compared to Teak.

Interestingly, the relationship between tree height and RH was complex. In systems like Teak + Karanj and Teak + Karanj + Pigeon pea (4 lines), taller trees were associated with lower RH under their canopies, whereas in Teak + Karanj + Chickpea, a positive correlation was evident (Fig. 9). It was also observed that Karanj tree showed a strong and positive co-relation (R^2=0.730) with relative humidity change.

In another case, a positive but weak association was observed between canopy spread and RH (Fig. 10). Wider canopies contributed to higher humidity levels, likely due to increased shading and reduced evapotranspiration losses.

Air Temperature

Air temperature around tree trunks varied substantially among systems (Fig. 11-14). There is significant differences and variations recorded in the percent of air temperature in different agroforestry system (Fig. 11) at direction-wise radial distance from tree base upto 5 m when compared with control. The maximum air temperature value (42.56°C) was recorded under control system (5 m lines), while the minimum air temperature value (38.44°C) was found under Karanj in the Teak+Karanj system (Fig. 11).

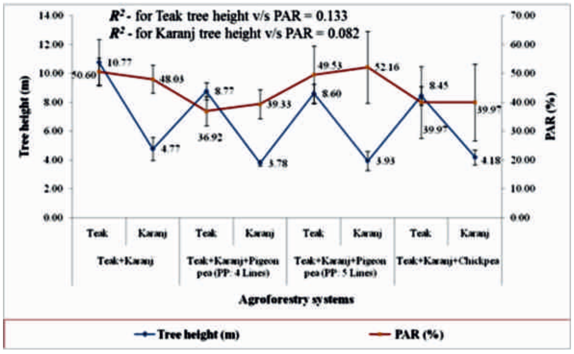

Fig. 4 Effect of tree height on per cent PAR (Photosynthetically Active Radiation) at the centre between two trees.

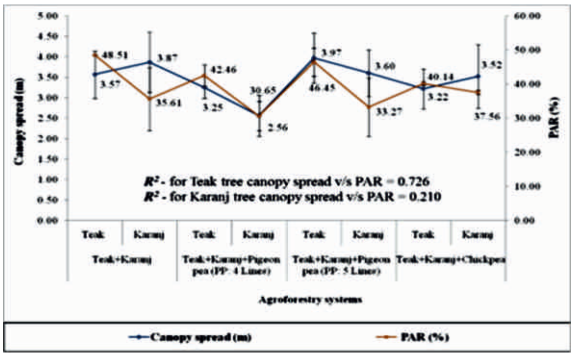

Fig. 5 Effect of canopy spread on per cent PAR (Photosynthetically Active Radiation) under 1 m radial periphery of the tree species

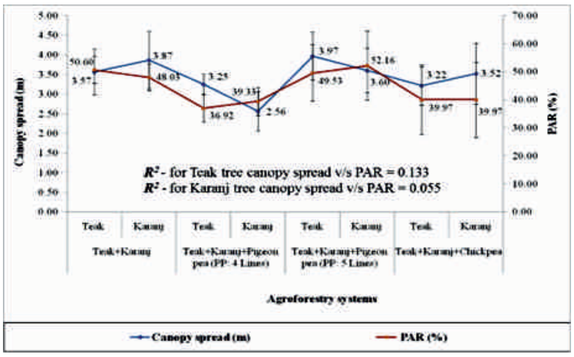

Fig. 6 Effect of canopy spread on per cent PAR (Photosynthetically Active Radiation) at the centre between two trees

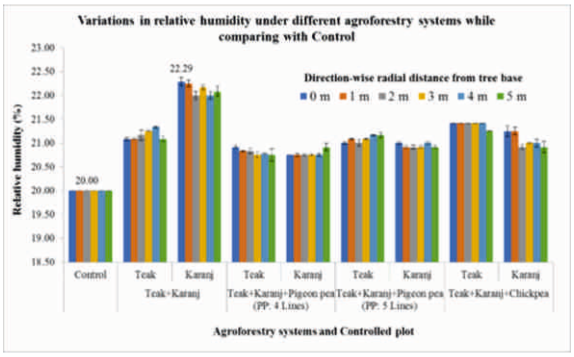

Fig. 7 Direction-wise variations in relative humidity under different agroforestry systems.

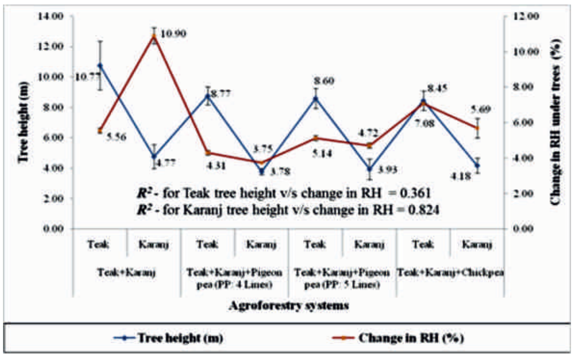

Fig. 8 Effect of tree height on per cent changes in relative humidity under 1 m radial periphery of the tree species.

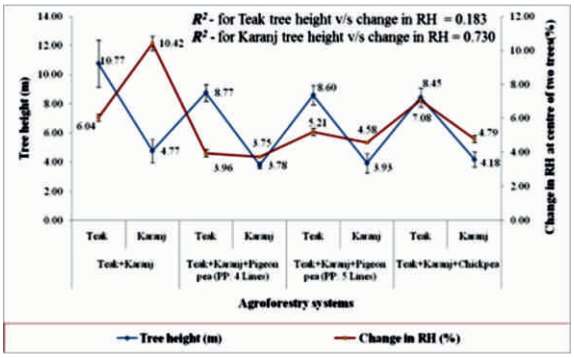

Fig. 9 Effect of tree height on per cent changes in relative humidity at the centre between two trees.

Air temperature showed considerable variability influenced by tree morphology. The highest temperatures (39.03°C) were recorded under Teak trees in the Teak+Karanj+Pigeon pea (4 lines) system, while the lowest (35.85°C) occurred under Karanj in the Teak + Karanj system (Fig. 12). The Karanj tree height showed a positive and strong co-relation with atmospheric temperature (R^2=0.921), while the weak level of relationship was recorded in Teak trre height with atmospheric temperature (R^2=0.433).

Generally, a positive relationship was observed between tree height and air temperature under certain treatments, particularly Teak + Karanj and Teak + Karanj + Pigeon pea (4 lines). However, at the centre, there was high correlation between Karanj tree height and atmospheric temoperature was observed (R^2 = 0.859*)* compared than Teak tree height and atmospheric temoperature (R^2= 0.433) (Fig. 13).

Similarly, the canopy spread influenced air temperature patterns, though the relationship was not static. Broader canopies tended to moderate temperatures by reducing heat accumulation beneath them, but in certain configurations, overlapping morphological factors such as canopy gaps and branching modified these trends (Figs. 14 & 15). In both the situations, canopy spread in Karanj tree showed a strong and positive co-relation (R^2 = 0.732 - 0.823) with air temoperature.

4. DISCUSSION

Tree Physiology and Microclimate Interactions

The present investigation clearly demonstrated that plant morphological attributes, such as tree height, canopy spread, basal girth, and branching pattern, play a decisive role in regulating microclimatic conditions under multitier agroforestry systems. The findings corroborate the growing body of evidence highlighting agroforestry's potential to moderate environmental parameters, including light availability, air temperature, and relative humidity (Huxley 1983; Brunig and Sander 1983). These modifications are crucial not only for improving crop performance but also for enhancing the overall ecological sustainability of agroforestry models.

Light Interception and Distribution

The study revealed considerable variation in Photosynthetically Active Radiation (PAR) across different agroforestry treatments, primarily influenced by tree height and canopy spread. A positive correlation was observed between tree height and PAR, with taller trees, especially Teak under the Teak+Karanj system, permitting greater light penetration near their bases. This aligns with earlier findings where taller tree species facilitated better light interception in agroforestry setups (Chundawat and Gautam 1993).

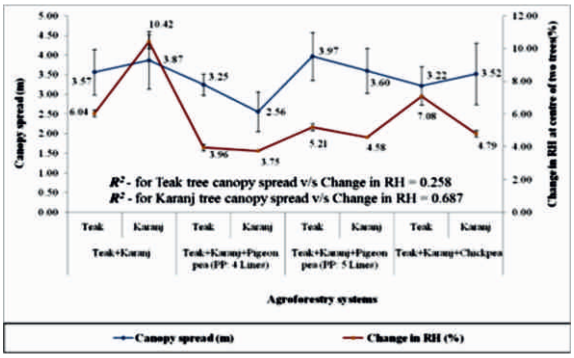

Fig. 10 Effect of canopy spread on per cent changes in relative humidity at the centre between two trees.

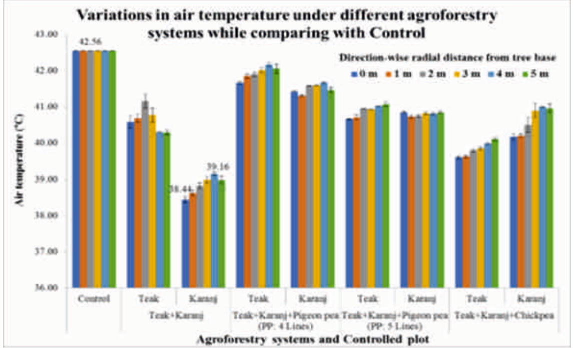

Fig. 11 Direction-wise variations in air temperature under different agroforestry systems.

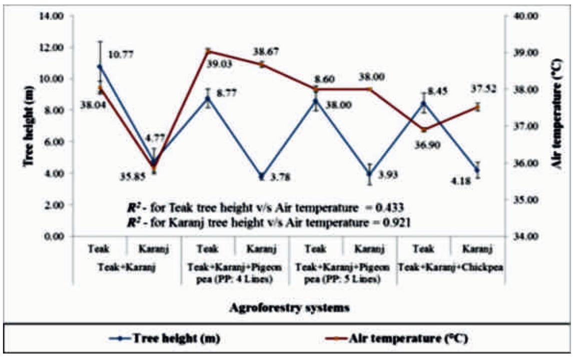

Fig. 12 Effect of tree height on air temperature (°C) under 1 m radial periphery of the tree species.

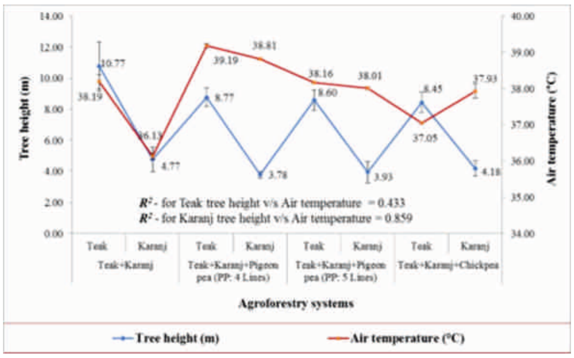

Fig. 13 Effect of tree height on air temperature (°C) at the centre between two trees.

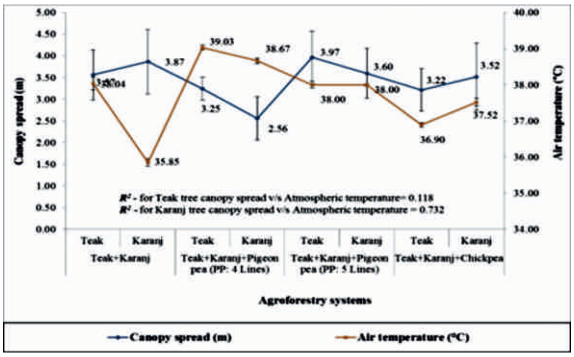

Fig. 14 Effect of canopy spread on air temperature (°C) under 1 m radial periphery of the tree species.

However, a negative correlation between canopy spread and PAR was evident. Wider canopies, such as that of Karanj in the Teak+Karanj+Pigeon Pea (4 lines) system, resulted in significant light reduction beneath the canopy. Similar light attenuation effects have been reported in Jatropha curcas-based systems, where increased canopy cover led to reduced PAR under and between trees (Subbulakshmi *et al.* 2019). Maghembe and Redhead (1982) also emphasized that, in agroforestry, light competition often surpasses competition for soil nutrients or moisture in influencing crop performance.

Interestingly, PAR recorded at the centre between trees was generally higher than that under the immediate periphery of individual trees, suggesting that appropriate spatial arrangements and canopy architecture can optimize light distribution within agroforestry systems. Furthermore, the importance of shade management is reinforced by Steffan-Dewenter *et al.* (2007), who reported a notable increase of up to 4°C in temperature upon the removal of shade trees, underscoring the interplay between canopy structure and microclimate.

Temperature Regulation

Tree morphology significantly influenced temperature dynamics under different systems. A positive relationship between tree height and air temperature was observed in treatments such as Teak+Karanj and Teak+Karanj+Pigeon Pea (4 lines), where taller trees contributed to localized warming beneath their canopies. However, this pattern was inconsistent across all systems, with some configurations exhibiting an inverse relationship due to variations in canopy density and spatial arrangements. These findings align with Singh *et al.* (2019), who documented reduced temperatures near the bases of tree species like Babool, Neem, and Mahua compared to open field conditions. It is evident that tree architecture, particularly canopy density and branching patterns, modulates solar radiation interception, influencing the thermal environment beneath.

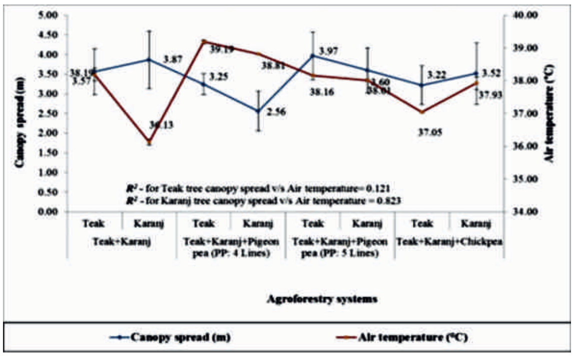

Fig. 15 Effect of canopy spread on air temperature (°C) at the centre between two trees

Earlier studies by Lotufo Bueno-Bartholomei and Labaki (2003) and Lin *et al.* (2010) further emphasized that tree species with denser canopies and broader branching patterns, such as Ficus benjamina, are more effective in attenuating solar radiation and moderating temperature extremes compared to species with sparser canopies like Ficus religiosa.

Moreover, leaf morphology and arrangement influence the degree of shading and thermal modification, as suggested by Fahmy *et al.* (2010), supporting the present study's findings that species with greater canopy spread provide enhanced microclimatic benefits.

Relative Humidity Dynamics

The present study demonstrates that agroforestry systems significantly influence the microclimatic variable of relative humidity (RH) around tree trunks, particularly at varying radial distances up to 5 meters from the tree base. Notably, the RH levels differed across systems and tree species, with the Teak + Karanj system exhibiting the highest increase (10.90%) in relative humidity compared to the control. This highlights the role of tree species composition and spatial arrangement in modulating the microenvironment.

The Karanj tree emerged as a key contributor to RH enhancement, showing a strong and positive correlation ($R^2 = 0.824$) with RH, much higher than Teak. This effect can be attributed to Karanj's dense foliage, greater transpiration potential, and its broader canopy architecture, which collectively aid in moisture retention and reduced air circulation near the trunk zone. Conversely, in systems like Teak + Karanj + Pigeon pea, taller tree height appeared to correspond with lower RH values under the canopy, suggesting that factors like canopy density and foliage structure may override mere tree height in influencing microclimatic humidity.

Interestingly, the canopy spread was also found to have a positive and strong correlation with RH (R^2 =

0.730), suggesting that wider tree canopies do contribute to localized humidity increase, though the relationship is not entirely linear. This aligns with the findings of Singh *et al.* (2019), who reported enhanced shading and reduced evapotranspiration as key mechanisms behind higher RH under tree cover. Additionally, Steffan-Dewenter *et al.* (2007) emphasized the importance of shade trees, noting a 12% RH decline upon their removal from agroforestry systems that further reinforcing the ecological significance of maintaining tree cover.

These findings underscore that beyond species selection, morphological traits such as canopy spread, height, and branching patterns are pivotal in optimizing the microclimate, particularly under multitier agroforestry configurations.

Implications for Agroforestry Design and Management

The interplay between plant morphology and microclimate observed in this study highlights the importance of selecting tree species and system configurations that balance both productivity and environmental modification. Systems incorporating species with moderate to high canopy spread and optimal tree heights can effectively enhance microclimatic conditions, promoting air temperature regulation, light/PAR availability and improvement in relative humidity.

Moreover, appropriate tree spacing and tier arrangements are essential to avoid excessive light competition while maximizing the positive microclimatic impacts of the overstory. These considerations are crucial for enhancing the resilience of agroforestry systems, particularly under changing climatic scenarios.

5. CONCLUSION

The present study substantiates that plant morphological traits, particularly tree height and canopy spread, significantly influence microclimatic parameters such as light availability, air temperature, and relative humidity under multitier agroforestry systems. These findings reinforce the need for careful system design, species selection, and management interventions to harness the full ecological and production benefits of agroforestry in diverse landscapes.

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DECLARETIONS

Conflict of interest

The authors report no competing interest.

Data availability

All data are available in the paper. However, additional field data can be available upon reasonable request after the article's publication.

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