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INFLUENCE OF DIFFERENT SUPPORT SYSTEMS ON VEGETATIVE GROWTH, YIELD ATTRIBUTES AND YIELD OF BLACK PEPPER (*PIPER NIGRUM)*

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Abstract

The experiment was conducted to investigate the effect of various biotic (living trees) and abiotic (non-living RCC pole) support systems on vegetative growth, yield attributes, and berry yield of black pepper (*Piper nigrum* L.) in a long-term field trial conducted from 2014 to 2021 at the Spices Research Sub-station, Bangladesh Agricultural Research Institute (BARI), Jaintiapur, Sylhet. The variety 'Jaintia Golmorich-1' was used in the experiment. The treatment comprised eight different supports *viz.,* Jhika tree (*Lannea coromandelica*), Mandar tree (*Erythrina variegata*), Mango tree (*Mangifera indica*), Jackfruit tree (*Artocarpus heterophyllus*), Wild Jamun tree (*Syzygium cumini*), Carambola tree (*Averrhoa carambola*), Areca nut tree (*Areca catechu*) and RCC pole. The experiment was laid out in a randomized complete block design with three replications. The results based on three years' (2019, 2020 and 2021) average data revealed that the maximum number of productive plagiotropes was found under Wild Jamun and Jackfruit tree, respectively. The highest pooled value of spikes per 0.25 m^2 was recorded in Wild Jamun tree (30.93), while spike length was highest from the vines trailed on Jackfruit tree (12.52 cm). Maximum spike weight (17.56 g) was found from Mango tree, whereas the highest number of berries per spike was observed in the vines trailed on Wild jamun (82.53). The longest maturity duration was observed in Mango support (232.11 days), while RCC pole support showed the shortest (194.46 days). Wild Jamun produced the highest fresh yield (15.98 kg) followed by Jackfruit tree (15.88 kg) but the lowest fresh yield was obtained from the vines supported on Mandar tree (3.04 kg) being statistically similar to Jhika tree (3.09 kg) and RCC pole (3.11 kg). The highest dry yield over three years was found in the vines trailed on Jackfruit tree (5.52 kg) closely followed by Wild jamun tree (5.49 kg) but the lowest pooled mean was recorded from Mandar. The highest dry matter percent were observed under Jackfruit tree (35.36%) followed by Areca nut tree (35.19%), Mango tree (35.05%) and RCC pole (34.55%). The experimental results suggested the uses of Jackfruit and Wild Jamun tree as the best living standards providing structural support and favorable microclimatic, also enhanced reproductive efficiency.

Keywords: Black pepper, *Piper nigram*, living and non-living supports, spike traits, berry yield, Sylhet- hill region.

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Introduction

Black pepper (*Piper nigrum* L.), a valuable spice of the family Piperaceae, is popularly known as 'Golmorich' in Bangladesh. It is often called the "King of Spices," which is one of the oldest and most widely traded spices globally (Mathew *et al.*, 2001; Srinivasan, 2007). Its economic significance is underscored by its widespread use in culinary purpose, traditional medicine and the global spice trade (Devasahayam *et al.,* 2010; Verma, 2018). The global production of black pepper was approximately 525,000 metric tons with Vietnam, Brazil, India and Indonesia contributing over 85% of this volume (FAO, 2022). Despite its tropical origin and relatively simple agronomic requirements, black pepper cultivation poses unique challenges particularly in terms of vertical support as this crop is a perennial climbing vine.

Supports structure are essential for the successful growth and productivity of black pepper vines (Chalermchon *et al.*, 2017). These structures enable the plant to receive adequate sunlight, ventilation, and protect the plant from soil-borne diseases. Traditionally, biotic supports i.e., living trees, have been the predominant choice in many parts of South and Southeast Asia. However, with the intensification of pepper cultivation and a shift towards commercial monocultures, abiotic supports such as concrete, wooden and bamboo poles have gained popularity (George, 1981; Purseglove *et al.*, 1981; Ravindran, 2000; Thangselvabal *et al.*, 2008). Biotic supports such as *Gliricidia sepium*, *Erythrina indica*, and *Albizia lebbeck* offer several advantages, including ecological services like nitrogen fixation, organic matter contribution through leaf litter, and enhancement of biodiversity (Thomas *et al.*, 2008). Conversely, abiotic supports-particularly, concrete poles offer uniformity, structural durability and reduced susceptibility to pests and diseases that can affect host trees. In countries like Vietnam and Brazil concrete supports have facilitated high-density planting and mechanized operations (Menon *et al.*, 1982; Kurien *et al.*, 1985; Reddy *et al.*, 1992; FAO, 2020). Both support systems present a trade-off between ecological sustainability and commercial efficiency. Biotic supports are more environmentally sustainable and inexpensive in the long term but require careful management to prevent nutrient competition and shading (Sivaraman *et al.,* 1999). Additionally, host trees may harbor pests or fungal pathogens that can affect pepper vines (Anandaraj and Sarma, 2003). As many as 31 tree species were found to be serving as good biotic standards (Salam *et al.,* 1991), among them, *Erythrina indica, Erythrina lithosperma, Garuga pinnata*, *Gliricidia sepium*, *Gliricidia maculata, Ailanthus malabarica, Areca catechu,* mango and jackfruit are the popular living supports (Dinesh *et al.*,

2005) for peppers. While, abiotic supports remain free from biological interference as it is resource-intensive and requires higher investment. In warmer regions, concrete poles may also alter the microclimate around vines, potentially stressing the plants during extreme temperatures (Thomas *et al.*, 2008). Despite the widespread use of both systems, empirical studies that evaluate their relative performance-especially in terms of growth parameters, yield, cost-effectiveness, and ecological footprint are limited. This knowledge gap is particularly pronounced in regions where commercial black pepper cultivation is relatively new, such as Bangladesh.

In Bangladesh, black pepper is an emerging crop with considerable potential for commercial cultivation (Ahmed *et al.*, 2010) in north-eastern Sylhet region, south-eastern Chattogram Hill Tracts and some other parts of north-west region. The Bangladesh Agricultural Research Institute (BARI) introduced black pepper as a high-value spice crop in the country aiming to diversify the rural economy, reduce dependency on import and promoting sustainable agriculture in hilly areas (Rahman *et al.*, 2020). The only cultivar currently recommended by BARI is ‘Jaintia Golmorich-1.’However, cultivation practices including the ideal support system for this cultivar under Bangladesh conditions are still to be optimized. Although the findings regarding support systems for successful cultivation of black pepper is available in Southeast Asia, Bangladesh lacks region-specific, comparative agronomic studies on support systems. The findings developed in foreign countries like Vietnam and India are not feasible in our country owing to the variation of socio-economic conditions, landholding patterns and ecological variables. For instance, concrete poles may be cost-effective for large commercial farms but smallholder farmers in Bangladesh may find them financially burdensome without government or institutional support. Biotic supports may provide natural shade and reduce the risk of sun scorch during dry seasons but may also increase fungal disease incidence during prolonged wet periods; while, abiotic supports may facilitate better disease control through improved ventilation but could increase vine exposure to heat and light stress (Purseglove *et al.*, 1981; Anandaraj and Sarma, 2003; Thomas *et al.*, 2008). Therefore, it needs to know the impact of biotic and abiotic supports in black pepper cultivation, especially in the specific context of Bangladesh for developing scalable, farmers-friendly cultivation models. Keeping the above facts in mind, the experiment was carried out to evaluate the influence of biotic and abiotic support systems on vegetative growth, yield attributes and berry yield of black pepper cv. ‘Jaintia Golmorich-1’ under AEZ 22 of Bangladesh.

Materials and Methods

Study Location

The field experiment was conducted at the Spices Research Sub-station, Citrus Research Station (CRS), Bangladesh Agricultural Research Institute (BARI), located at Jaintiapur upazila, of Sylhet District (25.13562° N latitude, 92.13217° E longitude and 34 m altitude). This region lies within the Agro Ecological Zone-22 (Northern and Eastern Piedmont Plains) of Bangladesh and is characterized by small hillocks in the midst of plain lands.

The experimental location experiences a tropical monsoon climate characterized by high humidity, warm temperatures and heavy rainfall. The average annual rainfall ranges from 4,000 to 5000 mm with the majority occurring during the monsoon season (May to September). This includes heavy showers and thunderstorms. While the monsoon season is prominent, there's a shorter dry season typically from November to February with cold and relatively clear weather.

The crop can tolerate a maximum temperature of 40 °C and a minimum temperature of 10°C (Nair *et al.*, 2021). The mean annual temperature fluctuates between 9°C and 32°C and the area typically experiences high humidity (above 70%) year-round making it suitable for black pepper cultivation (Bhuyan *et al.*, 2015). The experimental location is characterized by undulating terrain with well-drained hill soils. The soil is typically sandy loam to silty loam, acidic in reaction and moderately fertile. The soils are strongly acidic with some areas exhibiting extremely acidic conditions (pH < 4.5). Soil pH is a key soil property that determines acidity or alkalinity and influences nutrient availability and crop growth (O'Kennedy, 2022). The variation in soil types and acidity levels can affect crop growth and agricultural practices.

Experimental design and treatments

The experiment was laid out in a randomized complete block design with eight treatments and three replications from 2014 to 2021. Each experimental unit consisted of one standard or support with four black pepper saplings per standards, resulting in a total of 24 black pepper vines). The treatments comprised seven plant species as living (biotic) support and RCC pole as one abiotic support *viz.*, T_1= Jhika tree, T_2= Mandar tree, T_3= Mango tree, T_4= Jackfruit tree, T_5= Wild Jamun tree, T_6= Carambola tree, T_7= Areca nut tree and T_8= RCC (Reinforced Cement Concrete) pole.

Brief description of the biotic and abiotic supports

In this study, seven biotic (living) support species and one abiotic (non-living) support as RCC pole were used. Their brief discussion is furnished below:

Jhika tree (*Lannea coromandelica* (Houtt.) Merr.), a medium to large deciduous tree grows to a height of 10–15 meters with a straight, moderately thick trunk and a rounded spreading crown. The tree exhibits moderate growth and a light to medium canopy density allowing sufficient sunlight penetration for photosynthesis while providing necessary structural support (Orwa *et al.*, 2009). This tree is tolerant to drought conditions; periodic pruning and its deciduous nature ensures reduced shading during the winter months. Additionally, the tree does not strongly compete with shallow-rooted pepper vines for nutrients and water (Sarkar and Bandyopadhyay, 2013).

Mandar tree (*Erythrina variegata* L.), a nitrogen-fixing, deciduous tree is commonly used as a live support in traditional pepper gardens in India and Sri Lanka. It grows rapidly up to 15 m with a straight trunk and minimal lateral branches. Its coarse bark offers excellent anchorage for pepper roots and its light canopy ensures minimal shading, which is essential for balanced photosynthesis and reproductive development in pepper vines (Ravindran, 2000; Zachariah *et al.*, 2004).

Mango tree (*Mangifera indica* L.), is widely grown in the Sylhet region. Although it offers strong structural support due to its robust trunk, its dense spreading canopy can restrict light penetration and air circulation, potentially hampering spike development and fruit set in pepper. Regular pruning is necessary to make mango trees suitable as pepper standards (Nair, 2011).

Jackfruit tree (*Artocarpus heterophyllus* Lam.) is another common support option in Bangladesh. It features a thick trunk and moderate canopy growing 10–15 m tall. It is valued for dual-purpose cultivation—support and fruit yield. However, its broad leaves can create shade stress to the pepper vines if not managed appropriately. Its deep root system ensures limited competition with the shallow-rooted pepper vine (Singh *et al.*, 2006).

Wild Jamun tree (*Syzygium cumini* L) is well adapted to tropical conditions having straight trunk and upright growth that make it physically suitable for pepper vine support. However, its dense canopy requires frequent thinning to maintain optimal light availability for the vine (Ahmed *et al.*, 2010).

Carambola tree (*Averrhoa carambola* L.) is a small size tree (6–8 m) having thin branches and light canopy which offer favorable light conditions during the early stages of vine growth. However, its delicate branching structure and limited height make it less suitable for long-term pepper cultivation unless properly trained and pruned (Ravindran, 2000).

Areca nut tree (*Areca catechu* L.) is a tall, slender palm with its upright growth habit and single smooth trunk make it a common support species for black pepper, especially in Kerala and other parts of South Asia. Its minimal canopy promotes excellent light conditions for pepper (Nair, 2011; Zachariah *et al.*, 2004).

RCC (Reinforced Cement Concrete) pole is a non-living structural support for black pepper vine. RCC poles are durable and uniform in height (15 × 15 cm rectangular shape typically 2.5 m) but they do not contribute to the microclimate regulation, soil enrichment or biodiversity as found in living supports. They are commonly used in modern commercial pepper plantations (Singh *et al.*, 2006; Ahmed *et al.*, 2010).

Crop Establishment and Management

Each support type was planted maintaining 4×4 m spacing on May 2014 and established, where the pepper vines saplings raised from two node cuttings were transplanted on May 2017. The biotic supports were regularly managed with fertilizer, irrigation, pruning and maintained to facilitate vertical vine growth and to reduce excessive shading. The RCC poles of 2.5 m in height were embedded 0.5 m into the soil for structural stability. Prior to planting, the land was cleared, tilled and leveled to ensure uniformity. Four circular pits (45 × 45 × 45 cm) were prepared by digging the soil at the base of each support. The pits were filled with a mixture of topsoil and 5 kg decomposed cowdung, 25 g P and, 100 g dolomite, 20 g S, 1 g B and 1 g Zn during March before rainy season. Four well-rooted black pepper saplings (cv. 'Jaintia Golmorich-1') were transplanted at the base of each support on May 2017. Each sapling was top-dressed with 50 g N and 25 g K in June during rainy season and again was fertilized with 5 kg decomposed cowdung, 25 g N and 25 g K during September after rainy season (Bhuyan *et al.*, 2015). Regular cultural practices were followed included weeding, training of vines along the supports using ropes and pruning of biotic supports to maintain light and airflow. In the following years each vine was administrated with organic and inorganic fertilizers as per BARI recommendations (decomposed cow dung @ 5 kg, P @ 25 g and, dolomite @ 100 g, S @ 20 g, B @ 1 g and Zn@ 1 g. in March–before rainy season, N @ 50 g and K @ 25 g top dressing in June–during rainy season and decomposed cow dung @ 5 kg, N @ 25 g and K @ 25 g during September–after rainy season). Irrigation was applied to the vines during dry spells using a hose pipe system and proper drainage system was maintained to prevent water-logging during the monsoon. A thick (5 cm) organic mulch layer (dry grasses, and leaf litter) was applied around each vine and also around the base of the support trees to conserve soil moisture and to manage soil temperature during winter, as well as to suppress weeds. The vines were infested with several insects and diseases and they were managed with insecticides (Imitaf 20 SL [imidachloprid]) and fungicides (Indofil M-45 [Mancozeb]) based on visual monitoring. Sanitation was strictly followed to minimize the incidence of fungal diseases like foot rot or quick wilt (*Phytophthora capsici*). After two years of plantation, the pepper vines flowered in May 2019 and berries matured in December 2019. Pepper spikes were harvested at physiological maturity, indicated by a color change of the bottom berries from green to yellow or red. Harvesting was done manually and the berries were separated, boiled in hot water (100°C) and oven-dried for 5–7 days (when moisture reached to 10-12%), and stored in moisture-proof containers for further data collection.

Data Collection

Data collection was started after flowering and fruiting of pepper vines. Observations were recorded across three consecutive years 2019, 2020 and 2021. Measurements were recorded during the same phenological stage (active growth and reproductive phases) each year. Data integrity was ensured by standardizing the sampling procedures and calibrating instruments regularly. Data were recorded from all 24 plots (4 vines under one support as 1 plot × 8 treatments × 3 replications). When necessary, sampling was done within a standardized 0.25 m^2 area around each vine. The parameters were grouped into three major categories: vegetative growth traits, reproductive traits and yield traits, which were as follows:

Vegetative growth parameters

Among the vegetative growth parameters vine height (m), vine spreading—E-W and N-S (cm), number of plagiotropes (fruiting vines) per 0.25 m^2, length of individual plagiotropes (cm), number of leaves lateral^{-1} (plagiotrope), average leaf area lateral^{-1} (cm^2) and thickness (diameter) of internode (cm) were recorded.

Reproductive parameters

Among the reproductive parameters number of spikes per 0.25 m^2, individual spike length (cm), individual spike weight (g), number of berries spike^{-1}, spike compactness (number of berries cm^{-1} and duration of spike maturity (days) was recorded.

Berry yield and yield attributes

Fresh weight of 100 well-developed berries (g), dry weight of 100 well developed berries (g), volume of 100 berries (cm^3), fresh yield vine^{-1} (kg), dry yield vine^{-1} (kg) and dry matter content (%) in berries were recorded.

Statistical Analysis

All recorded data were analyzed with the help of R 4.2.0 program and mean separation was done by Least Significant Difference (LSD) test at the 5% level of significance ($p \leq 0.05$).

Results and Discussion

Effect of biotic and abiotic supports on vegetative growth parameters

Vine height: The vine height of black pepper ('Jaintia Golmorich-1') was significantly influenced by different biotic and abiotic supports used over the three years of study (2019–2021) (Table 1). Among the treatments, Mango support exhibited the highest vine length across two years (6.50 m in 2020 and 7.14 m in 2021) with pooled data over three years showing a mean of 6.55 m, which was closely followed by Wild Jamun (6.49 m). The maximum vine length in 2019 was obtained from Wild Jamun support (6.12 m) followed by mango support (6.02 m). The pooled means given by mango and wild jamun supports was followed by Jack fruit support (5.63 m). In contrast, the lowest vine length was recorded across the three years with a pooled mean of 2.33 m in Jhika support. RCC pole support gave better result (2.68 m) than Cambola (2.54) and Mandar (2.57) supports across all the years. Areca nut support performed better than others except Mango, Jackfruit and wild Jamun supports.

This variation might be attributed to the structural and physiological characteristics of the support trees. Vigorous and upright-growing trees like mango and Wild Jamun provide a robust vertical scaffold which allows the pepper vines to climb freely and attained impressive lengths. Moreover, the moderate shade under these trees creates ideal conditions for optimal photosynthesis and vine elongation (Nair, 2011). On the other hand, Jhika and Mandar had lower canopy height and moderate trunk strength which may limit the upward growth of the vines. However, these tree species compete with young vines for light and nutrients at the early stages, restricting vine vigor (Ravindran, 2000). Vines trailed on RCC poles exhibited an intermediate length, which was significantly lower than that observed on mango and wild jamun trees but significantly higher than that on Jhika and Mandar trees. This indicates that non-living (abiotic) supports can be useful in tight spaced areas but they may not provide the same growth enhancing microenvironment that suitable living standards (live trees) offered. These findings are in consonance with Anandaraj *et al.* (2014) who reported that black pepper responds well to living standards that provide mechanical support, favorable microclimatic and soil-root interactions.

East–West vine spreading: Significant differences were observed across treatments for vine spreading in East–West direction (Table 1). The widest spread was recorded in Wild Jamun (1.85 m in 2019, 2.15 in 2021 and 1.98 m in pooled mean, respectively) closely followed by Jackfruit support (1.81 m in 2019, 2.15 m in 2020 and 1.97 m in pooled mean, respectively). In 2020, Jackfruit support (1.96 m) performed better than Wild Jamun support (1.95 m) with regard to East-West vine spreading. These results suggested that, the pepper vines on broad-canopy trees benefitted from horizontal support and reduced inter-vine competition allowing lateral branches to expand more freely. In contrast, the narrowest East-west vine spreading was recorded in Areca nut support (0.65 m in pooled) followed by Mandar tree (0.72 m in pooled) and RCC Pole (0.79 m in pooled) in all the three years. The narrowest vine spread in East-west direction probably due to the erect growth habit and relatively narrow vertical structure of Mandar, Areca nut and RCC pole supports, which do not favor horizontal development of plagiotrops (fruiting vines). Due to their relatively lower canopy size and height, thereby limiting lateral branching and light interception (Sasikumar *et al.*, 2016).

North–South vine spreading: In the North–South direction as well, Jackfruit and Wild Jamun supports continued to show superior performance (Table 1). The highest North-South spread was recorded in Jackfruit support (1.90 m in 2020, 2.09 m in 2021, respectively followed by Wild Jamun support (1.86 m in 2020 and 2.05 m in 2021). In 2019, Wild Jamun support gave the maximum North-South spread (1.79 m) followed by Jackfruit support (1.75 m). The similar pooled mean (1.91 m) over three years was produced by both Jackfruit and Wild Jamun supports. In pooled mean, the second highest North-South spread (1.42 m) was recorded in Carambola support. This direction of spreading is critical for maximizing sunlight capture throughout the day and enhancing overall canopy efficiency. The spreading behavior also reflects the adaptability of pepper vines to the canopy architecture of the support trees, where broad and well-structured crowns allow symmetrical development. The minimum North–South spreading was observed with RCC poles (0.66 m in 2019, 0.69 m in 2020, 0.71 m in 2021 with a pooled mean of 0.68 m) being statistically similar with Areca nut support (0.67 m in 2019, 0.69 m in 2020 and 0.72 m in 2021 with a pooled mean of 0.69 m) followed by and Mandar support (0.76 m in 2019, 0.79 m in 2020 and 0.81 m in 2021 with a pooled mean of 0.79 m). Such results gave the idea that, a limited physical structure and a lack of living interaction limit the optimal canopy development. The superiority of Jackfruit and

Wild Jamun as support trees can be attributed not only to physical structure but also the partial shade, organic litter contribution and ecological synergy with black pepper vines. These support trees mimic the traditional models of forest-edge cultivation where black pepper evolved naturally (Nair, 2011; Sasikumar *et al.*, 2016).

Table 1. Effect of biotic and abiotic supports on vine height and vine spreading (E-W and N-S) of black pepper vines

Treatments	Vine height (m)				Vine spreading (m)							
					East–West				North–South			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	2.25	2.33	2.40	2.33	1.43	1.48	1.52	1.48	1.20	1.25	1.29	1.25
Mandar	2.48	2.58	2.65	2.57	0.69	0.73	0.75	0.72	0.76	0.79	0.81	0.79
Mango	6.02	6.50	7.14	6.55	1.07	1.17	1.28	1.17	0.96	1.02	1.13	1.04
Jackfruit	5.15	5.59	6.15	5.63	1.81	1.96	2.15	1.97	1.75	1.90	2.09	1.91
Wild Jamun	6.12	6.36	6.99	6.49	1.85	1.95	2.15	1.98	1.79	1.86	2.05	1.91
Carambola	2.44	2.56	2.63	2.54	1.37	1.43	1.47	1.42	1.37	1.43	1.47	1.42
Areca nut	4.90	5.09	5.24	5.08	0.63	0.66	0.68	0.65	0.67	0.69	0.72	0.69
RCC pole	2.59	2.69	2.76	2.68	0.76	0.79	0.81	0.79	0.66	0.69	0.71	0.68
LSD (0.05)	0.10	0.08	0.09	0.08	0.04	0.02	0.03	0.03	0.03	0.02	0.03	0.03
CV%	1.38	1.13	1.19	1.12	1.79	1.07	1.13	1.18	1.54	1.15	1.44	1.47

Number of Plagiotropes (per 0.25 m²): The number of plagiotropes per 0.25 m² was significantly influenced by different types of support structure across 3 years (2019–2021) (Table 2). Across three years (2019–2021), highest number of plagiotropes per 0.25 m^2 was consistently recorded under Wild Jamun support, with values of 15.56, 16.21, 17.83 in 2019, 2020 and 2021 respectively, resulting in a pooled mean of 16.53. The second highest plagiotropes per 0.25 m^2 (No.) were recorded under RCC Pole with values of 15.53, 16.11, 16.60 in 2019, 2020 and 2021 respectively with pooled mean of 16.08. In contrast, the lowest number of plagiotropes per 0.25 m^2 was observed under Carambola, which produced 7.77, 8.08, and 8.32 over the same period, with a pooled mean of 8.06 followed by mandar producing 8.77, 9.17, 9.45 across the years with 9.13 pooled value. Plagiotropes, being the lateral branches responsible for spike and fruit development, are a critical component of vine architecture and productivity. Trees like Wild Jamun and Jackfruit, which have a broader canopy, favorable branch spacing and partial shade, provide an ideal physical and microclimatic structure that supports vigorous lateral growth. On the other hand, Mandar and Carambola can have insufficient structural branching or create excessive shading or nutrient competition, thereby limiting lateral shoot proliferation (Ravindran *et al.*, 2000; Anandaraj *et al.*, 2014). Interestingly, RCC poles also supported a higher number of plagiotropes indicating that non-living supports can still promote considerable lateral branching if managed with proper spacing and pruning. However, the absence of organic interaction limits the other biological benefits those seen in living standards (Nair, 2011).

Number of productive plagiotropes (per 0.25 m²): Productive plagiotropes followed a similar trend like plagiotrope number (Table 2). The highest number of productive plagiotropes per 0.25 m^2 was obtained from the vines trained on Wild jamun (14.56 in 2019, 15.11 in 2020 and 16.62 in 2021 with a pooled mean of 15.43) followed by the vines trained on Jackfruit (12.62 in 2019, 13.63 in 2020 and 15.00 in 2021 with a pooled mean of 13.75) and the vines trained on RCC pole (11.66 in 2019, 12.12 in 2020 and 12.48 in 2021 with a pooled mean of 12.08). The vines trailed on Areca nut gave statistically similar results of the vines trained on RCC pole. Jhika support gave also the identical result of Mandar support. The lowest number of plagiotrope per 0.25 m^2 was found in Carambola support (6.80 in 2019, 7.06 in 2020 and 7.27 in 2021 with a pooled mean of 7.04). This suggests that not only the quantity of lateral branches but also their exposure to favorable environmental conditions determine their productivity. The significantly higher values under Wild Jamun and Jackfruit supports can be attributed to enhanced light availability, better branch positioning and potentially beneficial root interactions that promote flower and spike initiation (Sasikumar *et al.*, 2016). Supports like Mandar and Carambola may not provide sufficient vigor or support to encourage spike formation, possibly due to shading, weak branching or restricted airflow. These findings reinforce the importance of selecting support trees that balance light, structure and biological synergy with pepper vines (Zachariah *et al.*, 2011).

Table 2. Effect of biotic and abiotic supports on number of plagiotropes (per 0.25 m2), number of productive plagiotropes (per 0.25 m2) of black pepper vines

Treatments	Plagiotropes/0.25 m^2 (No.)				Productive plagiotropes/0.25 m^2 (No.)			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	14.59	15.22	15.68	15.16	7.77	8.08	8.32	8.06
Mandar	8.77	9.17	9.45	9.13	7.77	8.06	8.30	8.04
Mango	10.75	11.74	12.91	11.80	9.72	10.51	11.56	10.59
Jackfruit	13.59	14.67	16.13	14.79	12.62	13.63	15.00	13.75
Wild Jamun	15.56	16.21	17.83	16.53	14.56	15.11	16.62	15.43
Carambola	7.77	8.08	8.32	8.06	6.80	7.06	7.27	7.04
Areca nut	11.65	12.10	12.46	12.07	11.65	12.10	12.46	12.07
RCC pole	15.53	16.11	16.60	16.08	11.66	12.12	12.48	12.08
LSD (0.05)	0.17	0.14	0.15	0.14	0.15	0.13	0.15	0.13
CV%	0.80	0.61	0.65	0.61	0.83	0.68	0.75	0.67

Individual plagiotrope length (cm): The length of individual plagiotrope was also significantly influenced by different types of support (Fig. 1). The longest plagiotrope was produced on Jackfruit support (36.91 cm in 2019, 39.90 cm in 2020 and 43.89 cm in 2021 with a pooled mean of 40.23 cm), followed by Carambola support (34.99 cm in 2019, 36.41 cm in 2020 and 37.51 cm in 2021 with a pooled mean of 36.30 cm) and Wild Jamun (33.03 cm in 2019, 34.35 cm in 2020 with a pooled over three years 35.05 cm except 2021). In 2021, Wild Jamun support gave the similar result of Carambola support. Surprisingly, despite lower counts, Carambola support was recorded with a relatively long plagiotropes possibly indicating a compensatory growth response under stress conditions. Areca nut support showed the shortest plagiotrope length (15.54 cm in 2019, 16.17 cm in 2020 and 16.66 cm in 2021 with a pooled mean of 16.12 cm) followed by Mandar support (17.61 cm in 2019, 18.57 cm in 2020 and 19.13 cm in 2021 with a pooled mean of 18.44 cm), while Jhika support and RCC poles also recorded relatively lower values (16.12–24.27 cm). Shorter plagiotrope, while Areca nut and RCC poles also recorded relatively lower values (23.30-23.36 cm in 2018, 24.37-24.40 cm in 2020 and 25.10 cm in 2021 with a pooled mean of 24.27-24.30 cm). Shorter plagiotropes often interpret to reduce fruiting nodes and photosynthetic capacity per laterals, which may affect yield potential negatively. The plagiotrope length is a function of light interception, internodal elongation and hormonal regulation, all of which are influenced by the nature of the support. Vigorous support trees like Jackfruit, which provide ample lateral space and moderate shade seem to create optimal conditions for extended lateral growth and enhanced the plant's reproductive capacity (Anandaraj *et al.*, 2014; Nair, 2011).

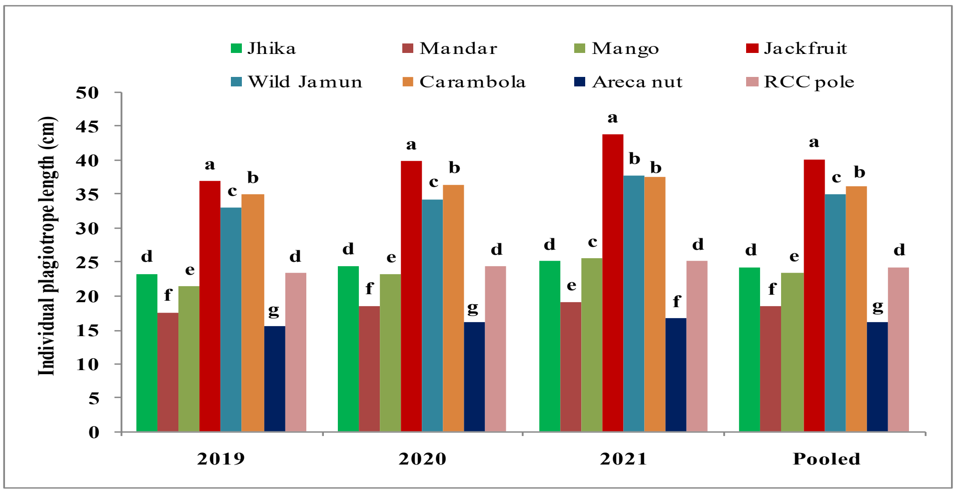

Fig. 1. Effect of biotic and abiotic supports on individual plagiotrope length (cm) of black pepper vines. Figures placed on each bar having similar letter (s) don not differ significantly at p≤0.05 by LSD test.

Number of leaves per lateral: The number of leaves per lateral was significantly influenced by the different support structures in all years (Table 3). In 2019 and 2020, the maximum number of leaves per lateral was recorded from the vines trailed on Mandar tree (15.66 and 16.52 respectively) closely followed by the vines grown on Jackfruit tree (14.59 and 15.82 in 2019 and 2020respectively) and RCC pole (13.67 and 14.34 in 2019 and 2020 respectively). In 2021, the vines trailed on Jackfruit gave the highest number of leaves per lateral (17.40) followed by the vines trailed on Mandar tree (17.02) and RCC pole (14.77). The highest pooled value was recorded in Mandar support with 16.40 leaves per lateral followed by Jackfruit support (15.93) and RCC pole (14.26). Conversely, Areca nut supports produced the lowest leaf numbers with pooled values of 9.28 followed by Mango with 9.28 respectively. Despite its lower performance in other growth parameters, Mandar demonstrated a remarkable ability to support leaf production per lateral. This may be due to its fast growth, open canopy structure and nitrogen-fixing potential which can indirectly enhance vine foliage (Anandaraj *et al.*, 2014). However, more leaves per lateral do not always translate to higher productivity if the leaf size and photosynthetic efficiency are compromised (Nair, 2011). In contrast, the lower leaf number from Mango and Areca nut supports could be attributed to denser canopy or competition for nutrients and water leading to stunted lateral growth and reduced leaf formation (Sasikumar *et al.*, 2016).

Average leaf area per lateral (cm²): During 2019, in terms of leaf area, the vines trailed on RCC pole recorded the highest average leaf area per lateral (1087.69 cm^2) followed by the vines grown on Carambola tree (1047.58 cm^2) and Jackfruit tree (1015.03 cm^2) and its lowest value was obtained from the vines supported on Areca nut support (560.55 cm^2) and Mandar tree (569.61 cm^2). In 2020, the maximum leaf area per lateral was observed in RCC pole support (1128.41 cm^2) followed by Jackfruit support (1094.75 cm^2) and Carambola support (1086.81 cm^2) and the lowest leaf area was noticed on Areca nut support (581.54 cm^2) closely followed by Mandar support (590.93 cm^2). But in 2021, the vines grown on Jackfruit tree gave the maximum average leaf area per lateral (1204.23 cm^2) followed by the vines trailed on RCC pole (1162.26 cm^2) and Wild Jamun support (1141.53 cm^2) and the minimum average leaf area per lateral was recorded from the vines supported on Areca nut tree (598.98 cm^2) followed by Mandar tree (608.66 cm^2). The highest pooled average leaf area per lateral was recorded from the vines grown on RCC pole (1126.26 cm^2) followed by the vines trailed on Jackfruit tree (1104.67 cm^2), Carambola tree (1084.60 cm^2) and Wild Jamun (1059.86 cm^2). The lowest values were recorded the vines trained on Areca nut tree (580.36 cm^2) followed by Mandar tree (589.73 cm^2). This finding highlights a trade-off between leaf number and leaf size. Mandar, despite having the most leaves per lateral, produced smaller leaves on average suggesting limited individual leaf expansion, possibly due to excessive shoot competition or suboptimal light conditions (Ravindran *et al.*, 2000). On the other hand, RCC poles and Jackfruit supports facilitated the development of fewer but significantly larger leaves which is beneficial for maximizing photosynthetic surface area and assimilate production. Larger leaves are often associated with improved photosynthetic efficiency and biomass accumulation (Zachariah *et al.*, 2011). This could explain the better overall performance of vines supported on Jackfruit and RCC poles in yield-related traits observed in earlier tables.

Table 3. Effect of biotic and abiotic supports on number of leaves lateral^{-1}, average leaf area lateral^{-1}, of black pepper vines

Treatments	Leaves lateral^{-1} (No.)				Average leaf area lateral^{-1} (cm^2)			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	11.75	12.39	12.77	12.30	657.16	681.77	702.22	680.39
Mandar	15.66	16.52	17.02	16.40	569.61	590.93	608.66	589.73
Mango	8.73	9.43	10.37	9.51	694.86	749.42	824.37	756.22
Jackfruit	14.59	15.82	17.40	15.93	1015.03	1094.75	1204.23	1104.67
Wild Jamun	11.70	12.25	13.47	12.48	1000.30	1037.76	1141.53	1059.86
Carambola	10.67	11.08	11.41	11.05	1047.58	1086.81	1119.41	1084.60
Areca nut	8.83	9.37	9.65	9.28	560.55	581.54	598.98	580.36
RCC pole	13.67	14.34	14.77	14.26	1087.69	1128.41	1162.26	1126.12
LSD (0.05)	0.23	0.12	0.13	0.13	12.19	10.62	11.64	10.32
CV (%)	1.11	0.55	0.55	0.60	0.84	0.70	0.72	0.68

Internode thickness of laterals (cm): Internodal thickness is a vital structural trait affecting vine strength, nutrient transport, and overall vine vigor. In 2019, both Mango and Jackfruit support recorded the thickest laterals (0.69 cm) closely followed by Areca nut support (0.68 cm) and Wild jamun support (0.59 cm) being identical with Carambola support (0.59 cm) but Mandar support gave the lowest internode thickness (0.34 cm) (Fig. 2). In 2020 and 2021, the vines trailed on Jackfruit tree recorded the highest internode thickness (0.77 cm and 0.85 cm respectively) followed by Mango tree support (0.76 cm and 0.84 cm respectively) and Areca nut support (0.73 cm and 0.75 cm respectively). The vines grown on Jhika tree gave the lowest values of internode thickness (0.51 cm and 0.53 cm respectively followed by RCC pole (0.53 cm and 0.55 cm respectively). The pooled mean of internode thickness was found highest from the vines trailed on Jackfruit tree (0.77), which was statistically similar to the vines grown on Mango tree (0.76 cm) followed by Areca nut tree (0.71 cm) and Wild Jamun tree (0.64 cm). In contrast, Mandar (0.35 cm) and Jhika (0.51 cm) produced the thinnest laterals in respect of pooled mean of internode thickness. Thicker internodes are indicative of vigorous and healthy vascular development, suggesting better internal resource transport and support capacity. Mango and Jackfruit being large and well-branched support trees, likely offer structural and microclimatic advantages that encourage substantial lateral development. On the other hand, due to poor internode thickness of vines on Mandar trees reinforces its limited structural utility despite the high leaf count. The RCC pole, a non-living support noted the internode thickness (0.52 cm), possibly due to a lack of biotic interaction that living supports can provide (e.g., shade modulation, root-microbe interaction) (Nair, 2011).

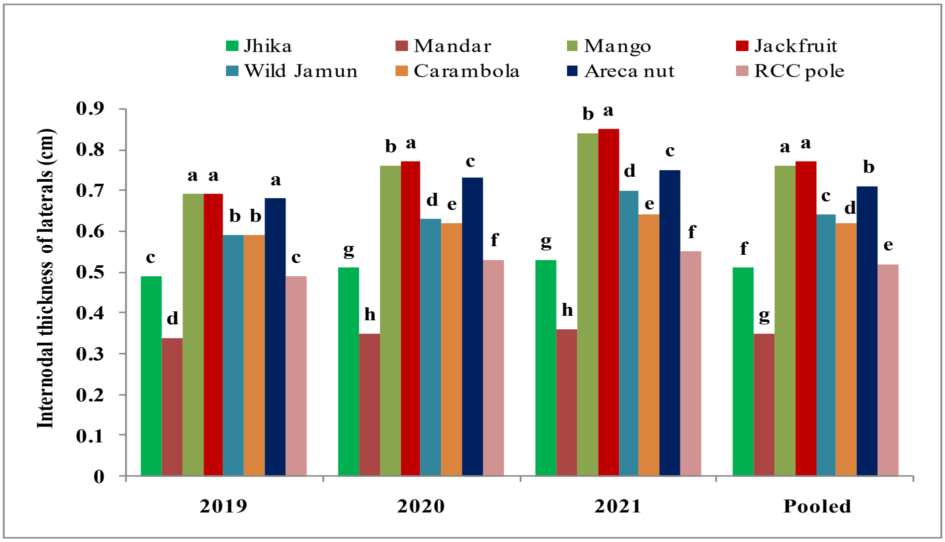

Fig. 2. Effect of biotic and abiotic supports on internode thickness of laterals (cm) of black pepper vines Figures placed on each bar having similar letter (s) don not differ significantly at $p \leq 0.05$ by LSD test.

Effect of biotic and abiotic supports on reproductive parameters

Number of spikes (per 0.25 m²): The data clearly indicate that, both living and non-living support had significant influence on spike production (Fig. 3). In 2019 and 2020, the maximum number of spikes per 0.25 m^2 was obtained from the vines trailed on Wild Jamun (29.15 and 30.31 respectively) followed by Jhika tree (26.24 and 27.29 respectively) and Jackfruit tree (24.33 and 26.38 respectively) and RCC pole (18.44 and 19.16 respectively). The lowest number of spikes was observed from the vines trailed on Carambola tree (13.65 and 14.30 respectively) followed by Areca nut support (15.53 and 16.13, respectively). In 2021, the pepper vines grown Jamun tree recorded the highest number of spikes (33.34) followed by those grown on Mandar (17.30) and Jhika tree (28.11) but the vines supported on Carambola tree gave the lowest number of spikes (14.73). The highest pooled number of spikes was recorded in Wild Jamun (30.93) followed by Jhika (27.21) and Jackfruit (26.57). The lowest pooled mean of number of spikes was produced on Carambola (14.23) and Areca nut support (16.09). The superior performance of Wild jamun may be attributed to its favorable canopy structure, which offers partial shade, reducing temperature stress, allowing enough light for optimal flowering and spike formation. Such moderated light levels have previously been reported to promote reproductive development in black pepper (Ravindran *et al.*, 2000; Sasikumar *et al.*, 2016). Similarly, the moderate light and moisture conditions under Jackfruit and Jhika canopies might have supported enhanced flowering. In contrast, Areca nut and Carambola, due to either excessive shading or poor compatibility with pepper physiology may restrict light interception and nutrient availability, leading to lower spike counts (Nair, 2011; Anandaraj *et al.*, 2014).

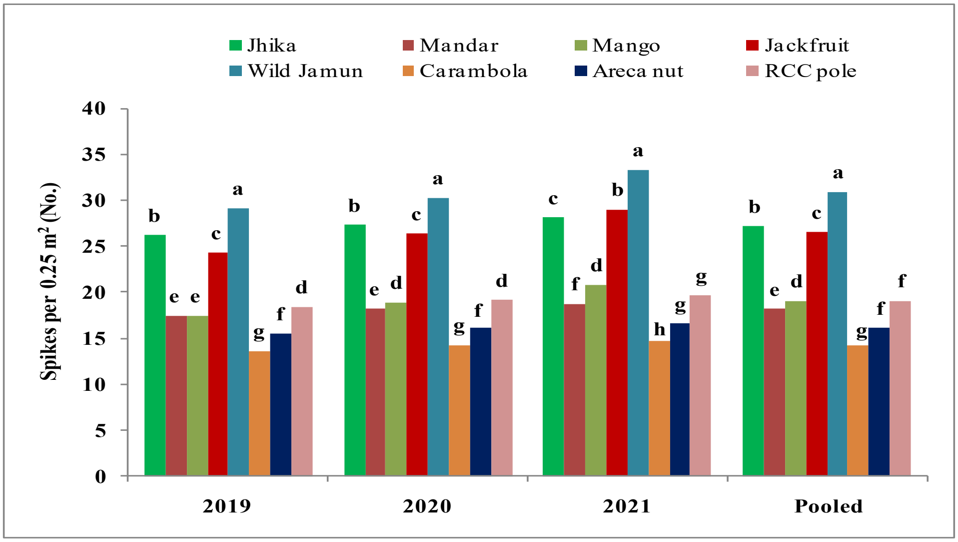

Fig. 3. Effect of biotic and abiotic supports on number of spikes per 0.25 m^2 of black pepper vines Figures placed on each bar having similar letter (s) don not differ significantly at p≤0.05 by LSD test.

Individual spike length (cm): Spike length, a direct indicator of floral development and reproductive health was also significantly influenced by the support system (Table 4). In 2019, the longest spikes were observed in Areca nut (12.23 cm) followed by both RCC pole and Wild Jamun (12.03 cm). The shortest spike length was recorded from the vines trailed on Carambola support (9.81 cm) followed by Mango support (9.81 cm). In 2020 and 2021, the pepper vines trailed on Jackfruit tree gave the maximum spike length (12.87 cm and 12.75 cm respectively) followed by Areca nut tree (12.68 cm and 12.56 cm respectively). The lowest spike length was found from the vines trailed on Carambola (10.17 cm and 10.07 cm) followed by Mandar tree (10.57 cm and 10.47 cm) respectively. The pooled mean of spike length was recorded highest from the vines trailed on Jackfruit (12.52 cm) followed by Areca nut (12.49), Wild Jamun (12.29 cm) and RCC pole (12.29 cm). Contrary, the shortest pooled spikes were observed in Carambola (10.02 cm) followed by Mango (10.38 cm) and Mandar (10.41 cm).

Wild jamun and Jackfruit, both possessing broader canopies with regulated light penetration, seem to provide a microenvironment conducive to reproductive growth. These findings are in line with earlier studies, suggesting that balanced light and moisture favor floral organ elongation in black pepper (Zachariah *et al.*, 2011). Interestingly, RCC poles, despite being non-living, supported good spike elongation, possibly due to reduced root-zone competition and customized microclimate management (e.g., drip irrigation, optimal spacing). Mango and Mandar, while beneficial in some vegetative traits may create dense shade effects (especially Mango), restricting light-dependent floral differentiation and spike elongation (Ravindran *et al.*, 2000). Faisal *et al*. (2024) reported that they used three support trees *viz.*, Jackfruit, Mango and Chapalish among them, the vines trailed on Jackfruit produced maximum spike length closely followed by Mango support.

Individual spike weight (g): The most vital yield parameter, spike weight showed significant variation across the treatments (Table 4). In 2019, the heaviest spikes were found in the vines trailed on Mandar (16.84 g) which was statistically similar to the vines grown on Mango (16.75 g) followed by Wild Jamun (15.86 g) and Jackfruit (14.80 g) but the lowest spike weight was recorded from the vines supported on Jhika tree (11.41 g) and followed by Carambola tree (11.94 g). In 2020, 2021 and pooled mean, the maximum spike weight was recorded from the vines grown on Mango tree (18.06 g, 17.87 g and 17.56 g respectively) followed by Mandar tree (17.47 g, 17.30 g and 17.20 g respectively) and Wild Jamun tree (16.46 g, 16.29 g and 16.20 g respectively) and Jackfruit tree (15.96 g, 15.80 g and 15.52 g respectively. The lowest spike weight was observed in Jhika tree (11.84 g, 11.72 g and 11.65 g respectively) followed by Carambola (12.39 g, 12.27 g and 12.20 g respectively) and RCC pole (13.94 g, 13.80 g and 13.72 g respectively). The unexpectedly higher spike weight in pepper vines trailed on Mango and Mandar trees may be a result of fewer but more resource-enriched spikes. Limited spike numbers may have led to more photosynthates allocation per spike, thereby increasing weight. This phenomenon agrees the concept of source-sink balance, where fewer sinks (spikes) receive greater assimilate flow resulting in larger individual organ weights (Nair, 2011; Sasikumar *et al.*, 2016). On the other hand, RCC pole, although promoting moderate spike length and number showed relatively lower spike weight, possibly due to higher spike load and limited biotic interaction from the support trees. This might lead to dilution of available nutrients per spike and reduced individual weight. These results corroborate earlier findings by Anandaraj *et al.* (2014) and Zachariah *et al.* (2011), who noted that the choice of support trees greatly influences the physiological and yield dynamics of black pepper, primarily through shade modulation, competition levels and support longevity.

Table 4. Effect of biotic and abiotic supports on number of spikes per 0.25 m^2 spikes, individual spike length, individual spike weight of black pepper vines

Treatments	Individual spike length (cm)				Individual spike weight (g)			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	11.19	11.60	11.48	11.43	11.41	11.84	11.72	11.65
Mandar	10.19	10.57	10.47	10.41	16.84	17.47	17.30	17.20
Mango	9.89	10.67	10.57	10.38	16.75	18.06	17.87	17.56
Jackfruit	11.93	12.87	12.75	12.52	14.80	15.96	15.80	15.52
Wild Jamun	12.03	12.48	12.35	12.29	15.86	16.46	16.29	16.20
Carambola	9.81	10.17	10.07	10.02	11.94	12.39	12.27	12.20
Areca nut	12.23	12.68	12.56	12.49	14.19	14.71	14.57	14.49
RCC pole	12.03	12.48	12.35	12.29	13.44	13.94	13.80	13.72
LSD (0.05)	0.06	0.04	0.04	0.04	0.11	0.10	0.10	0.09
CV (%)	0.28	0.21	0.21	0.20	0.43	0.38	0.39	0.36

Berries per spike (No.): The number of berries per spike showed significant variation across different support types (Table 5). The maximum number of berries per spike was observed in the vines trailed on Wild jamun (80.65 in 2019, 83.90 in 2020 and 83.06 in 2021 with a pooled mean of 82.53) followed by the vines grown Mandar (78.68 in 2019, 81.78 in 2020 and 80.96 in 2021 with a pooled mean of 80.47) and Jackfruit (78.12 in 2020 and 77.34 in 2021 with a pooled mean of 75.82 over three years) and Areca nut (76.76 in 2020, 75.99 in 2021 with a pooled mean of 75.53 over three years). In 2019, the vines trailed on Areca nut gave higher number of berries per spike (73.83) than those of Jackfruit (72.02). The lowest values of berries per spike were recorded in Mango support (62.21 in 2019, 67.31 in 2020 and 66.63 in 2021 with a pooled mean of 65.38) and Carambola (66.17 in 2019, 69.02 in 2020 and 68.32 in 2021 with a pooled mean of 67.83). The higher berry count under the vines grown on Wild jamun and Mandar may be attributed to their ability to maintain moderate light levels, creating an environment that supports prolonged flowering and better fruit set. Similar findings were reported by Sasikumar *et al.* (2016), who observed that light intensity significantly affects flower retention and fruit development in black pepper. The relatively poor performance under Mango and Carambola supports could be due to excessive shading which negatively influences reproductive success by limiting photosynthetic efficiency and hormonal balance (Nair, 2011). Faisal *et al*. (2024) reported that they used three support trees *viz.*, Jackfruit, Mango and Chapalish among them, the vines trailed on Jackfruit produced maximum number no. of fruits spike-1 closely followed by Mango support.

Spike compactness (berries cm^{-1} of spike): Spike compactness which denotes the distribution of berries along the spike was significantly influenced by the support standards (Table 5). In 2019, the vines trailed on Jackfruit tree gave the maximum spike compactness (8.75 cm^{-1} of spike) followed by the vines grown on both Carambola and Jhika tree (7.80), RCC pole (7.78), Mandar (7.77) and Mango (7.76). The lowest spike compactness was recorded from the vines grown on Wild jamun (6.80) followed by Areca nut (6.84). In 2020, 2021 and pooled mean over three years, the highest compactness was found in the vines trailed on Jackfruit (9.47, 9.39 and 9.20 respectively) followed by the vines supported on Mango (8.38, 8.30 and 8.15 respectively) and Jhika (8.18, 8.09 and 8.02 respectively) which was identical with the vines trailed on Carambola (8.16, 8.08 and 8.01 respectively). Conversely, in 2020, 2021 and pooled mean over three years, the lowest spike compactness was observed in Wild jamun (7.08, 7.01 and 6.96 respectively) followed by Areca nut (7.18, 7.11 and 7.04 respectively). Although Wild jamun produced the highest number of berries, its low compactness suggests longer spike length with more dispersed berry arrangement, possibly due to extended internode development within the inflorescence (spike). In contrast, Jackfruit likely induced shorter spike internodes or more intense flowering clusters, resulting in denser spike structures (Ravindran *et al.*, 2000). Such compactness is often associated with cultivar genetics and environmental modulation through support systems. Compact spikes are generally preferred in commercial pepper due to their higher market appeal and easier processing (Anandaraj *et al.*, 2014).

Duration of spike maturity (days): The number of days taken for spike maturity in different support systems also differed significantly (Table 5). The longest maturity duration was observed in Mango support (221.27 days in 2019, 238.73 days in 2020 and 236.34 days in 2021 with a pooled mean of 232.11 days) followed by Jackfruit (219.37 days in 2019, 236.76 days in 2020 and 234.39 days in 2021 with a pooled mean of 230.17 days) and Wild jamun (218.42 days in 2019, 226.77 days in 2020 and 224.51 days in 2021 with a pooled mean of 223.23 days). In contrast, RCC pole support (190.26 days in 2019, 197.54 days in 2020 and 195.57 days in 2021 with a pooled mean of 194.46 days) showed the shortest duration, followed by Mandar (204.85 days in 2019, 212.76 days in 2020 and 210.63 days in 2021 with a pooled mean of 209.41 days) and Jhika (205.78 days in 2019, 213.64 days in 2020 and 211.50 days in 2021 with a pooled mean of 210.31 days). The extended duration under Mango and Jackfruit supports could be attributed to their shaded microclimate which may slow down the ripening process due to reduced photosynthetic activity and temperature. While longer duration may allow more resource accumulation, it could also delay harvest, affecting market dynamics (Nair, 2011; Zachariah *et al.*, 2011). On the other hand, RCC poles allow full sunlight exposure which may accelerate fruit maturity due to increased photosynthesis, temperature, and transpiration rates. However, such faster development might compromise berry quality if not managed properly (Ravindran *et al.*, 2000). The results are in agreement with the results of the previous studies emphasizing that support tree characteristics (shade, moisture regulation, root competition) directly influence reproductive efficiency and crop duration in black pepper (Anandaraj *et al.*, 2014; Sasikumar *et al.*, 2016; Nair, 2011).

Table 5. Effect of biotic and abiotic supports on berries spike^{-1}, spike compactness and duration to spike maturity of black pepper vines

Treatments	Berries spike^{-1} (No.)				Spike compactness (No.) (Berries cm^{-1} length of spike)				Duration to spike maturity (Days)			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	69.07	71.99	71.27	70.78	7.80	8.18	8.09	8.02	205.78	213.64	211.50	210.31
Mandar	78.68	81.78	80.96	80.47	7.77	8.08	8.00	7.95	204.85	212.76	210.63	209.41
Mango	62.21	67.31	66.63	65.38	7.76	8.38	8.30	8.15	221.27	238.73	236.34	232.11
Jackfruit	72.02	78.12	77.34	75.82	8.75	9.47	9.39	9.20	219.37	236.76	234.39	230.17
Wild Jamun	80.65	83.90	83.06	82.53	6.80	7.08	7.01	6.96	218.42	226.77	224.51	223.23
Carambola	66.17	69.02	68.32	67.83	7.80	8.16	8.08	8.01	213.51	221.61	219.39	218.17
Areca nut	73.83	76.76	75.99	75.53	6.84	7.18	7.11	7.04	210.62	218.65	216.47	215.25
RCC pole	67.00	69.60	68.90	68.50	7.78	8.11	8.03	7.98	190.26	197.54	195.57	194.46
LSD (0.05)	0.37	0.28	0.27	0.27	0.05	0.03	0.02	0.03	0.53	0.60	0.59	0.52
CV (%)	0.29	0.21	0.21	0.21	0.39	0.23	0.18	0.21	0.14	0.15	0.15	0.14

Effect of biotic and abiotic supports on characteristics of hundred well developed berries

Fresh Weight of 100 Berries (g): The fresh weight of 100 well-developed berries was significantly influenced by support types (Table 6). In 2019, the vines trailed on Areca nut produced the maximum 100 well-developed berries' fresh weight (9.24 g) followed by those grown on Jackfruit tree (9.16 g), Mango tree (9.04 g) and both Jhika and Wild Jamun tree (8.98 g). The lowest fresh weight was obtained from the vines supported on Carambola (8.71 g) followed by RCC pole (8.88 g). In 2020, 2021 and pooled mean over three years, the highest fresh weight was recorded in the vines trailed on Jackfruit (9.88 g in 2020, 9.78 g in 2021 and 9.60 g respectively) followed by Mango support (9.75 g, 9.66 g and 9.48 g respectively) and Areca nut (9.59 g and 9.49 g and 9.44 g respectively) and Jhika (9.32 g, 9.23 g and 9.18 g respectively) and the lowest value was observed under Carambola (9.03 g, 8.93 g and 8.89 g respectively) followed by RCC pole (9.21 g, 9.12 g and 9.07 g respectively). The superior performance of jackfruit in fresh berry weight may be linked to its canopy architecture which provides moderate light interception, adequate humidity and reduced evapotranspiration losses fostering better cell expansion and turgidity in developing berries. This corroborates the findings of Ravindran *et al.* (2000), who noted that microclimatic conditions greatly influence the physical development of black pepper berries. Faisal *et al.* (2024) reported that they used three support trees *viz.*, Jackfruit, Mango and Chapalish among them, the vines trailed on Jackfruit produced maximum 100 fresh weight closely followed by Mango support.

Dry Weight of 100 Berries (g): Dry weight reflects the true biomass accumulation in berries. The dry weight of 100 well developed berries followed almost the same trend of fresh weight (Table 6). The dry weight was significantly influenced by different support types (Table 6). In 2019, the vines grown on Areca nut gave the maximum 100 well-developed berries' dry weight (3.28 g) followed by those trailed on Jackfruit tree (3.18 g), Mango tree (3.11 g) and RCC pole (3.10 g) but the lowest dry weight was obtained from the vines supported on Carambola (2.93 g) followed by Mandar tree (2.96 g). In 2020 and 2021, the highest dry weight was recorded from the vines grown on Jackfruit (3.43 g and 3.40 g respectively) followed by areca nut support (3.40 g and 3.36 g respectively) and Mango (3.36 g and 3.32 g respectively) and RCC pole (3.21 g and 3.18 g respectively) but the lowest value was observed under Carambola (3.02 g and 2.99 g respectively) followed by Mandar (3.07 g and 3.04 respectively). This consistency between high fresh and dry weights suggests that berries from Jackfruit and Areca nut supports possess higher photosynthate accumulation and translocation efficiency, possibly aided by better source–sink dynamics (Sasikumar *et al.*, 2016). The dry matter content is a critical determinant of pepper quality, as it directly relates to oleoresin and piperine content, a key quality parameter for spice processing (Nair, 2011). Faisal *et al*. (2024) reported that they used three support trees *viz.*, Jackfruit, Mango and Chapalish among them, the vines trailed on Jackfruit produced maximum 100 dry fruit weight closely followed by Mango support.

Volume of 100 Berries (cm³): Berry volume followed the similar trend to weight parameters. The volume of 100 well developed berries was significantly affected by different biotic and abiotic supports (Table 6). In 2019, the vines grown on Areca nut gave the maximum volume (7.88 cm^3) which was statistically similar to those trailed on Jackfruit tree (7.84 cm^3) and followed by Mango tree (7.61 cm^3), Jhika tree (7.57 cm^3), Wild jamun (7.57 cm^3), RCC pole (7.55 cm^3) and Mandar tree (7.55 cm^3) but the lowest dry weight was obtained from the vines supported on Carambola (7.30 cm^3). In 2020 and 2021, the highest volume was recorded from the vines grown on Jackfruit (8.61 cm^3 and 8.52 cm^3 respectively), followed by Mango support (8.19 cm^3 and 8.11 cm^3 respectively) and Areca nut (8.17 cm^3 and 8.09 cm^3 respectively) and Jhika (7.87 cm^3 and 7.78 cm^3 respectively) being identical with Wild Jamun (7.87 cm^3 and 7.79 cm^3 respectively). The lowest value of volume was observed under Carambola (7.59 cm^3 and 7.52 cm^3 respectively). The pooled mean of volume over three years produced the highest volume was obtained from the vines trailed on Jackfruit tree (8.32 cm^3) which was followed by

Areca nut (8.05 cm^3), mango (7.97 cm^3) and Wild jamun (7.75 cm^3) being identical with Jhika (7.74 cm^3) but the lowest volume was noticed in the vines grown on Carambola support (7.47 cm^3). When volume and weight data interpreted together, it becomes clear that Jackfruit and Areca nut trees provide a physiologically balanced environment for pepper vines enhancing both berry size and quality. These findings support the results of Anandaraj *et al.* (2014), who emphasized the role of support systems' microclimate on fruit morphology.

Table 6. Effect of biotic and abiotic supports on characteristics of hundred (100) well developed berries of black pepper vines

Treatments	Characteristics of hundred (100) well developed berries											
	Fresh weight (g)				Dry weight (g)				Volume (cm^3)			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	8.98	9.32	9.23	9.18	3.03	3.14	3.11	3.09	7.57	7.87	7.78	7.74
Mandar	8.96	9.30	9.21	9.16	2.96	3.07	3.04	3.02	7.55	7.84	7.76	7.72
Mango	9.04	9.75	9.66	9.48	3.11	3.36	3.32	3.26	7.61	8.19	8.11	7.97
Jackfruit	9.16	9.88	9.78	9.60	3.18	3.43	3.40	3.34	7.84	8.61	8.52	8.32
Wild jamun	8.98	9.31	9.22	9.17	3.08	3.20	3.17	3.15	7.57	7.87	7.79	7.75
Carambola	8.71	9.03	8.93	8.89	2.93	3.02	2.99	2.98	7.30	7.59	7.52	7.47
Areca nut	9.24	9.59	9.49	9.44	3.28	3.40	3.36	3.34	7.88	8.17	8.09	8.05
RCC pole	8.88	9.21	9.12	9.07	3.10	3.21	3.18	3.17	7.55	7.83	7.75	7.71
LSD (0.05)	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.08	0.02	0.02	0.03
CV (%)	0.07	0.07	0.08	0.07	0.17	0.36	0.36	0.27	0.61	0.13	0.16	0.21

Effect of biotic and abiotic supports on fresh yield and dry yield per vine and dry matter percentage

Fresh Yield Vine^{-1} (kg): Fresh berry yield per vine was significantly influenced by the treatments (Fig. 4). In 2019, the vines trailed on Wild Jamun produced the highest yield (15.64 kg) which was followed by those supported on Jackfruit (15.14 kg) and Mango (9.82 kg) but the lowest fresh yield was obtained from the vines supported on Mandar (2.98 kg) being statistically similar to Jhika tree (3.03 kg) and RCC pole (3.03 kg). In 2020 and 2021, the vines trailed on Jackfruit produced the highest yield (16.31 kg and 16.16 kg) followed by Wild Jamun (16.23 kg and 16.08 kg) respectively. On the Other hand, the lowest fresh yield was obtained from the vines supported on Mandar (3.09 kg and 3.06 kg) followed by Jhika tree (3.14 kg and 3.11 kg) and RCC pole (3.17 kg and 3.14 kg) respectively. For Pooled Data, Wild Jamun produced the highest yield (15.98 kg) followed by Jackfruit (15.88 kg) but the lowest fresh yield was obtained from the vines supported on Mandar (3.04 kg) being statistically similar to Jhika tree (3.09 kg) and RCC pole (3.11 kg). This yield advantage in Jackfruit and Wild jamun could be attributed to their favorable microclimatic effects—providing optimal shade, humidity and organic matter from leaf litter, which collectively enhance flowering, fruit set and berry retention (Sasikumar *et al.*, 2016). Moreover, the spreading canopy of Jackfruit ensures diffused light, improving photosynthesis without causing stress (Ravindran *et al.*, 2000) found the lowest fresh berry yield from the black pepper vines trailed on *Erythrina lithosperma* and the highest yield from the vines grown on *Termialia bellerica* and reported the reasons behind the better result is the total surface area available for the vines cling to the support trees and the distribution of sunlight under them. Faisal *et al*. (2024) reported that they used three support trees *viz.*, Jackfruit, Mango and Chapalish among them, Mango support produced maximum yield closely followed by Jackfruit support.

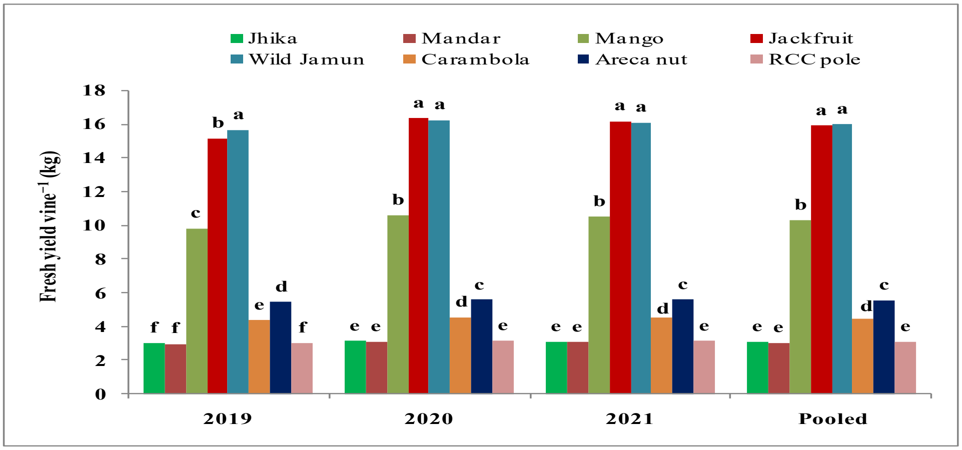

Fig. 4. Effect of biotic and abiotic supports on fresh yield vine^{-1} (kg) of black pepper vines.
Figures placed on each bar having similar letter (s) don not differ significantly at p≤0.05 by LSD test.

Dry Yield Vine^{-1} (kg): Different support systems exerted a significant influence on dry berry yield per vine in all three years of experimentation (Table 7). In 2019, the highest dry yield per vine was recorded from the vines trailed on Wild Jamun (5.38 kg) followed by the vines grown on Jackfruit (5.26 kg) and Mango (3.38 kg) but the lowest yield was obtained from the vines supported on Mandar (0.98 kg) being identical with Jhika (1.02 kg) and RCC pole (1.05 kg). In 2020 and 2021, the vines trailed on Jackfruit produced the maximum dry yield (5.67 kg and 5.61 kg respectively) followed by the vines grown on Wild Jamun (5.58 kg and 5.52 kg respectively) and Mango (3.64 kg and 3.60 kg respectively) and Areca nut (2.00 kg and 1.98 kg). The vines supported on Mander tree gave the lowest yield (1.02 kg and 1.02 kg respectively) which was statistically similar to Jhika (1.06 kg and 1.05 kg respectively) and RCC pole (1.09 kg and 1.08 kg respectively). The pooled mean of dry yield over three years was found highest in the vines trailed on Jackfruit (5.52 kg) closely followed by Wild jamun (5.49 kg) and then followed by

Mango (3.54 kg) and Areca nut (1.97 kg) but the lowest pooled mean was recorded from Mandar (1.00 kg) being identical with Jhika (1.04 kg) and RCC pole (1.07 kg). Dry yield indicates that Jackfruit and Wild Jamun supports again outperformed other treatments. Dry yield is critical for post-harvest returns and spice quality. Higher dry matter in Jackfruit and Wild jamun treatments reflects improved nutrient uptake, translocation and water-use efficiency—possibly due to better rhizosphere conditions created by organic litter decomposition from the support trees (Anandaraj *et al.*, 2014).

Dry matter in berries (%): Dry matter percentage is a strong indicator of spice quality, especially piperine and oleoresin content. In 2019, the maximum dry matter percent was recorded from the pepper vines grown on Areca nut (34.45%) followed by RCC pole (33.83%), Jack fruit (33.72%) and Wild Jamun (33.36%) but the lowest from Mandar (32.03%). In 2020 and 2021, the vines trailed on Jackfruit gave the maximum dry matter percent (36.36% and 36.00% respectively) followed by Mango (36.04% and 35.68% respectively) and Areca nut (35.70% and 35.39% respectively) but the lowest dry matter percent was observed in Mandar (33.23% and 32.92% respectively). The highest pooled values of dry matter percent were observed under Jackfruit (35.36%) followed by Areca nut (35.19%), Mango (35.05%) and RCC pole (34.55%). The lowest dry matter (pooled) content was recorded in Mandar (32.73%) followed by Jhika (33.40%), Carambola (33.37%). Although RCC poles produced moderate yields, the dry matter content was comparatively high, indicating less water content and higher concentration of solids which may be favorable for certain processing requirements. However, the superior combination of high yield and high dry matter under Jackfruit trees makes it the most efficient support system. This aligns with the reports by Nair (2011), who noted that biological support contributes to organic nutrient cycling and reduce water stress tend to enhance the biochemical density in spice crops.

Table 7. Effect of biotic and abiotic supports on fresh yield vine^{-1}, dry yield vine^{-1} and dry matter percentage in barriers of black pepper vines

Treatments	Dry yield vine^{-1} (kg)				Dry matter in barriers (%)			
	2019	2020	2021	Pooled	2019	2020	2021	Pooled
Jhika	1.02	1.06	1.05	1.04	32.70	33.92	33.57	33.40
Mandar	0.98	1.02	1.01	1.00	32.03	33.23	32.92	32.73
Mango	3.38	3.64	3.60	3.54	33.42	36.04	35.68	35.05
Jackfruit	5.26	5.67	5.61	5.52	33.72	36.36	36.00	35.36
Wild Jamun	5.38	5.58	5.52	5.49	33.36	34.61	34.26	34.07
Carambola	1.47	1.53	1.51	1.50	32.67	33.89	33.55	33.37
Areca nut	1.93	2.00	1.98	1.97	34.45	35.7	35.39	35.19
RCC pole	1.05	1.09	1.08	1.07	33.83	35.09	34.74	34.55
LSD (0.05)	0.10	0.09	0.09	0.08	0.04	0.05	0.06	0.05
CV (%)	2.27	1.90	1.93	1.83	0.08	0.08	0.09	0.08

Conclusion

The experimental results demonstrated that Jackfruit, Wild Jamun and Mango were the most effective biotic supports (living standards) across vegetative, reproductive and yield parameters. Jackfruit excelled in promoting strong vine growth, larger leaf area, spike compactness and superior berry traits, while Wild Jamun offered the highest fresh and dry yield per vine along with optimal spike and berry development. Mango also contributed positively to berry size and dry matter content making it suitable for black pepper production. RCC poles as abiotic support performed better for leaf growth and early maturity but they failed to produce superior result with regard to vine productivity. Areca nut showed its potentiality for use in agroforestry systems but failed to show its performance like Jackfruit, Mango and Wid Jamun. Mandar, Carambola and Jhika repeatedly showed inferior result and are not recommended as supports for high-yielding black pepper production. It is concluded that structurally compatible and ecologically supportive living standards—particularly Jackfruit and Wild Jamun—can significantly enhance sustainable black pepper cultivation. RCC poles can be used where space, light or infrastructure limits the use of trees. However, farmers have to bear in mind regarding low productivity of RCC pole and should compensate through intensive management.

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