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Litter Dynamics and Nutrient Contributions in Arabica Coffee Agroforestry Systems Under Varied Shade Regimes in the Central Western Ghats, India

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ABSTRACT

Coffee agroforestry systems (CAS) are increasingly recognized as an effective climate change mitigation strategy due to their ability to sequester carbon. However, most studies on CAS have focused on the management and productivity of coffee plants, with limited attention to litterfall dynamics and their contribution to soil nutrients, particularly in Indian coffee plantations. In this study, quantified and compared litterfall dynamics in arabica coffee (*Coffea arabica* L.) grown under different shade patterns. Litterfall collected from designated quadrants was analyzed using standard soil testing procedures. Results showed significant variation in litterfall across treatments, ranging from 3.43 to 13.54 MT ha^{-1}. The highest litterfall was recorded under exotic species shade with 13.54 MT ha^{-1}, followed by native species shade with 11.68 MT ha^{-1}. In terms of nutrient contributions to the soil, coffee grown under native species shade recorded the highest addition of nitrogen (301.37 kg ha^{-1}) and phosphorus (22.19 kg ha^{-1}), significantly exceeding other treatments. Conversely, potassium addition was highest under exotic species shade (257.30 kg ha^{-1}). The findings suggest that coffee grown under a two-tier mixed shade system, comprising both native and exotic species, benefits from enhanced litterfall dynamics and improved nutrient contributions to the soil compared to unshaded systems. To promote soil health and sustainability, policy incentives should encourage the adoption and maintenance of two-tier mixed shade systems in coffee plantations.

INTRODUCTION

Coffee cultivation in India, rooted in the biodiverse landscapes of the Western and Eastern Ghats, represents a unique blend of ecological sustainability and agricultural productivity. The traditional coffee-growing regions of Karnataka, Kerala and Tamil Nadu trace their origins to the pioneering efforts of colonial planters, which were later advanced by Indian successors. Over time, coffee cultivation extended to newer regions such as Andhra Pradesh, Odisha and the northeastern states, where it emerged post-independence as a catalyst for the socio-economic development of tribal communities (Raghuramulu and Rudragouda, 2017). In these regions, coffee cultivation not only drives economic activity but also plays a pivotal role in fostering rural livelihoods. Unlike many other coffee-producing countries, Indian coffee is predominantly cultivated under agroforestry systems. These systems integrate coffee plants with a canopy of native shade trees, creating a multi-strata cropping system interspersed with high-value intercrops such as black pepper, cardamom, orange, banana and avocado. This traditional practice ensures biodiversity conservation, supports ecosystem services such as carbon sequestration and soil stabilization, and enhances microclimatic conditions favorable for coffee production (Vaast *et al*., 2006). Notably, Indian coffee cultivation in the Western and Eastern Ghats contributes significantly to preserving these ecologically sensitive biodiversity hotspots. However, changing cultivation practices and climate variability pose challenges to the sustainability of Indian coffee agroforestry systems. Over the past few decades, coffee growers have increasingly shifted from shaded, biodiverse systems toward more intensive, mono shade-based practices aimed at maximizing yields. These shifts have resulted in reduced shade cover, diminished biodiversity and altered microclimatic conditions, which together exacerbate the effects of climate variability on coffee yield and quality (Chengappa *et al*., 2017). Similar challenges have been observed globally in other coffee-producing countries such as Brazil, Colombia, and Vietnam, where excessive rainfall, temperature fluctuations and reduced biodiversity have led to significant declines in coffee production (Cristancho *et al*., 2012; Bunn *et al*., 2015).

Research highlights the ecological and agronomic importance of shaded coffee systems in mitigating the effects of climatic stressors. Shade trees moderate extreme temperatures, reduce soil erosion, enhance soil organic carbon (SOC) levels and improve nutrient cycling through leaf litterfall and decomposition processes (Somarriba *et al*., 2004). In agroforestry systems, litterfall serves as a primary pathway for the return of organic matter and nutrients such as nitrogen (N) and phosphorus (P) to the soil. These nutrients are critical for maintaining soil fertility and sustaining long-term agricultural productivity. Additionally, the decomposition of organic matter enriches soil organic carbon pools, sequestering atmospheric carbon dioxide and contributing to climate change mitigation. The dynamics of litterfall production vary widely across different ecological and management contexts. Tropical agroforestry systems, such as coffee plantations, exhibit significant variation in litterfall quality and quantity due to factors such as shade tree species, stand characteristics and climatic conditions (Kim *et al*., 2010). Empirical evidence from studies conducted in Central America and Sub-Saharan Africa highlights the role of litterfall in sustaining SOC levels, moderating nutrient cycling and improving soil health (Negash and Starr, 2013). However, research on litterfall dynamics in Indian coffee agroforestry systems, particularly in the Central Western Ghats, remains limited, despite their ecological significance and contribution to sustainable coffee cultivation. The Central Western Ghats offer an ideal setting to study the interplay of shade regimes, litterfall dynamics and nutrient cycling in coffee agroforestry systems. This region, characterized by diverse ecological conditions and traditional agroforestry practices, provides a valuable opportunity to explore how shade management influences litter production, carbon sequestration and nutrient flux. Seasonal and annual patterns of litterfall production, along with the decomposition and mineralization processes, directly impact soil fertility and crop productivity in these systems. Moreover, litter dynamics under varied shade regimes can offer insights into optimizing coffee agroforestry practices to enhance ecosystem services and maintain ecological resilience. This study aims to address the existing knowledge gap by evaluating the leaf litter dynamics and nutrient contributions in arabica coffee agroforestry systems under varied shade conditions in the Central Western Ghats of India. Specifically, the research focuses on understanding the seasonal patterns of litterfall production, the associated carbon (C) and nitrogen (N) inputs to the soil, and the implications of different shade regimes on nutrient cycling and soil organic matter. By analyzing these dynamics, the study seeks to provide empirical evidence to support sustainable coffee cultivation practices that balance productivity with biodiversity conservation and ecosystem health. The findings will contribute to the broader understanding of agroforestry systems' role in mitigating climate change, enhancing soil fertility and fostering sustainable agricultural development in tropical coffee-growing regions.

MATERIALS AND METHODS

Study Location and Climate

The study was conducted at the Coffee Research Sub Station (CRSS), Chettalli, North Kodagu, Karnataka (12°23'N, 75°49'E, 950 m AMSL). Weather data for 2022–2023, obtained from the CRSS Meteorological Observatory, revealed significant deviations in temperature and rainfall from historical averages. In 2023, the average minimum and maximum temperatures were

18.15 °C and 28.57 °C, respectively, exceeding those in 2022 (17.20 °C and 26.58 °C) and the long-term normal (17.36 °C and 27.26 °C). Rainfall also exhibited notable variations: total precipitation in 2022 (2128 mm) was significantly higher than in 2023 (1218 mm) and the historical norm (1579 mm). Additionally, the number of rainy days decreased from 117 in 2022 to 89 in 2023, suggesting increased rainfall intensity per event. Monthly trends indicated warming during January–February, heavy rainfall in March–April, and a substantial temperature rise in June 2023. The highest rainfall occurred in July–August, with extreme precipitation in 2022. The period from September to December showed a general warming trend, particularly in minimum temperatures. These climatic variations highlight the need for adaptive strategies in coffee cultivation. Detailed climate data is presented in Table 1.

Table 1: Meteorological data recorded during experimental period (2022 and 2023) and the normal at Coffee Research Sub Station, Chettalli, Kodagu

Months	Min Temp (°C)			Max Temp (°C)			Mean RH (%)			Rainfall (mm)			Rainy days (no)		
Year	Normal	2022	2023	Normal	2022	2023	Normal	2022	2023	Normal	2022	2023	Normal	2022	2023
January	14.30	15.60	16.36	27.52	27.70	27.85	81.04	91.70	86.00	3.00	0.00	21.00	0.21	0.00	1.00
February	15.17	16.70	16.19	29.68	29.80	29.83	79.58	88.20	84.00	4.49	0.00	0.00	0.44	0.00	0.00
March	16.97	18.70	17.84	31.40	31.80	30.28	79.86	89.60	84.50	25.83	33.00	12.00	1.97	5.00	2.00
April	18.54	18.80	18.95	31.55	31.90	31.91	83.98	92.30	87.89	76.85	120.00	13.75	5.95	9.00	2.00
May	19.37	16.77	17.77	29.87	25.93	30.94	86.76	95.22	89.92	103.81	232.00	194.45	8.13	13.00	11.00
June	18.91	17.82	19.14	25.28	25.82	29.43	91.43	98.66	82.00	304.84	121.00	47.10	18.26	19.00	7.00
July	18.56	16.93	18.41	23.54	21.26	26.04	92.59	97.89	91.00	406.40	701.00	553.72	22.51	21.00	30.00
August	18.55	17.85	19.11	23.83	23.98	27.73	91.80	98.90	90.80	293.18	619.50	57.40	20.03	22.00	7.00
September	18.07	17.74	19.32	25.34	24.92	27.64	89.81	97.55	88.23	135.25	124.80	102.95	11.67	11.00	16.00
October	18.07	16.86	18.45	26.37	24.87	26.90	87.27	96.84	89.90	145.53	121.20	131.92	10.31	10.00	5.00
November	16.94	16.91	18.64	26.34	26.01	27.59	85.93	94.28	94.60	68.25	25.50	76.06	5.08	5.00	7.00
December	14.90	15.77	17.57	26.40	24.93	26.66	82.10	95.66	92.00	12.08	30.00	7.66	1.00	2.00	1.00
Total/Avg.	**17.36**	**17.20**	**18.15**	**27.26**	**26.58**	**28.57**	**86.02**	**94.73**	**88.40**	**1579.49**	**2128.00**	**1218.01**	**105.54**	**117.00**	**89.00**

Soil Type and Properties

The experimental plot soil is classified as fine loamy mixed isohyperthermic Typic Haplastepts with a sandy loam texture (Table 2). It is deep, well-drained, very dark brown to red, gravelly loam derived from weathered granite. Soil samples were collected (0–30 cm depth), air-dried, sieved (2 mm) and analyzed for physical and chemical properties. The results indicated slightly acidic pH (5.90), low electrical conductivity (0.23 dSm^{-1}), high organic carbon (2.96%), available phosphorus (72 kg ha^{-1}), and potassium (434 kg ha^{-1}), while available nitrogen was moderate (515 kg ha^{-1}).

Table 2: Initial physical and chemical properties of soil of the experimental site

Properties	Values obtained	Remarks	Method followed	Reference
Soil physical parameters				
Mechanical analysis (%)		Textural class - Sandy clay loam	International pipette method	Piper, 1966
Sand (%)	67.00			
Silt (%)	4.00			
Clay (%)	29.00			
Soil chemical properties				
Soil pH (1:2.5 soil water suspension)	5.90	Acidic	Potentiometric method	Jackson, 1973
Electrical Conductivity (dS m^{-1})	0.23	Normal	Conductometric method	Jackson, 1973
Organic Carbon (%)	2.96	High	Walkley and Black wet oxidation method	Jackson, 1973

Available Nitrogen (kg ha^{-1})	515	Medium	Alkaline potassium permanganate method	Subbaiah and Asija, 1956
Available phosphorus (P_2O_5 kg ha^{-1})	72	High	Colorimetric method by using Bray's extractant	Jackson, 1973
Available potassium (K_2O kg ha^{-1})	434	High	Flame photometer method	Jackson, 1973

Experimental Details

The study site spans 20 acres with varying shade patterns: native tree shade, mixed native and exotic shade, predominantly exotic shade (*Grevillea robusta*) and relatively open conditions (<20% tree cover). The native shade trees (e.g., *Albizia spp., Ficus spp., Dalbergia spp., Terminalia spp., Pterocarpus marsupium, Syzygium jambolana*) form an upper canopy, while *Erythrina lithosperma* constitutes the lower tier. The experimental blocks (L and M) were planted with Coffea arabica cv. Chandragiri in 2006 at 1.8 m × 1.8 m spacing, with stabilized plants over 15 years old.

Experimental Design

A Randomized Complete Block Design (RCBD) was implemented with five replications. Each treatment plot measured 20.12 m × 18.29 m (110 plants per plot). The treatments included T_1: Coffee under two-tier native shade (NS); T_2: Coffee under two-tier mixed shade (MS); T_3: Coffee under two-tier exotic shade (ES) and T_4: Coffee under relatively unshaded conditions (US)

Crop Management

Routine agronomic practices, including bush management, nutrition, weeding, plant protection, and cultural operations, were followed as per the Coffee Guide (*Anon.,* 2023).

Litterfall and Nutrient Contribution

Litterfall was collected monthly (January–December 2023) from three 1 m × 1 m quadrants per treatment. Samples were air-dried, oven-dried at 60°C, and weighed (g m^{-2}), then expressed as kg ha^{-1}. Composite soil samples were collected post-harvest, processed (air-dried, powdered, sieved to 2 mm), and analyzed for nutrient content using standard procedures.

Nutrient Recycling via Litterfall

Ten grams of cumulative dried composite litter per treatment was powdered, thoroughly mixed and analyzed for major nutrient content as per standard protocols (Table 3).

Table 3: Methods used for analysis of litter and soil samples

SN	Determinations	Method followed	Reference
1	Carbon content	Walkley and Black's oxidation method	Jackson (1973)
2	Digestion of plant sample	Wet digestion of litter samples with H_2SO_4 and digestion mixture (K_2SO_4:$CuSO_4.5H_2O$: Se in the	Jackson (1973)

		proportion of 100:20:1) till green residue was obtained for nitrogen estimation	
3	Nitrogen content	Microkjeldahl distillation method usingGerhartz-Vapodest distillation unit	Piper (1966)
4	Digestion of sample with di-acid mixture	Digestion with of litter sample with di-acid mixture HNO_3: H_2ClO_4 (10:4)	Johnson and Ulrich (1959)
5	Phosphorus content	Vanado-molybdo phosphoric acid yellow colour method	Jackson (1973)
6	Potassium content	Analysis of suitable aliquot of acid digested plant material by Flame photometer	Jackson (1973)

Statistical Analysis

Data were analyzed following Gomez and Gomez (1984), with significance tested at p = 0.05. ANOVA was performed using the Web Agri. Stat. Package (Jangam & Thali, 2004). Duncan's multiple-range test (DMRT) was used to compare treatment means where significant differences were observed.

RESULTS AND DISCUSSION

Effect of Different Shade Management Regimes on Litterfall / Residue Fall Dynamics

The dynamics of litterfall / residue fall i.e., total litterfall and litterfall pattern as influenced by various shade management regimes are presented in Table 4 and illustrated in Figure 1. Litterfall /residue fall refers to the shedding of leaves, twig sand other organic material from plants within agro forestry systems (AFS). The dynamics of litterfall are influenced by a range of factors including the species composition, climate and environmental conditions of the system. Understanding litterfall dynamics is critical for nutrient cycling, soil health and maintaining ecosystem services in agroforestry systems. The composition and timing of litterfall contribute to soil organic matter, influence microbial communities and can affect plant growth and water retention. The amount of litterfall varies from 3.43 to 13.54 MT ha^{-1}. Litterfall dynamics varied notably across the treatments. T_3 (Exotic sp. shade) recorded significantly higher litterfall of 13.54 MT ha^{-1} (1354.23 g m^{-2}) followed by T_1 (native sp. shade) recorded 11.68 MT ha^{-1} (1168.09 g m^{-2}), also showing strong litter production and T_2 (mixed sp. shade) produced 10.08 MT ha^{-1} (1007.66 g m^{-2}), slightly lower than T_1 and T_3 but still substantial. In contrast, T_4 (unshaded systems) had recorded the lowest litterfall of 3.43 MT ha^{-1} (343.28 g m^{-2}), emphasizing the lack of organic input in unshaded environments.

Table 4: Quantity of litter fall of in Arabica coffee as influenced by different shade management regimes

Months / Treatments	Quantity of litter fall (g m^{-2})						
	T_1	T_2	T_3	T_4	Mean	S.Em±	CD (0.05)
JAN	85.30 ±6.76 b	83.26 ±6.60 b	150.00 ±11.89 a	12.48 ±0.99 c	**82.76**	**4.45**	**13.72**
FEB	165.90 ±13.15 b	170.26 ±13.49 b	210.00 ±16.64 a	10.00 ±0.79 c	**139.06**	**7**	**21.56**
MAR	88.11 ±6.98 a	72.11 ±5.71 b	68.00 ±5.39 b	20.00 ±1.58 c	**62.06**	**2.33**	**7.17**
APR	75.00 ±5.94 b	69.02 ±5.47 c	77.54 ±6.14 a	69.00 ±5.47 c	**72.64**	**0.34**	**1.05**
MAY	99.69 ±7.90 c	111.80 ±8.86 b	125.69 ±9.96 a	81.80 ±6.48 d	**104.75**	**1.48**	**4.55**
JUN	68.59 ±5.44 a	53.60 ±4.25 b	21.00 ±1.66 c	15.00 ±1.19 c	**39.55**	**2.04**	**6.29**
JULY	54.60 ±4.33 a	33.44 ±2.65 c	38.00 ±3.01 b	20.00 ±1.58 d	**36.51**	**1.13**	**3.49**
AUG	21.00 ±1.16 c	30.48 ±2.42 b	54.00 ±4.28 a	31.00 ±2.46 b	**34.12**	**1.11**	**3.43**
SEPT	47.50 ±3.76 b	52.20 ±4.14 a	40.00 ±3.17 c	35.00 ±2.77 d	**43.68**	**0.61**	**1.87**

OCT	198.60 ±15.74 b	159.36 ±12.63 c	225.00 ±17.83 a	10.00 ±0.79 d	**148.24**	**7.61**	**23.45**
NOV	188.80 ±14.96 b	87.84 ±6.96 c	250.00 ±19.81 a	18.00 ±1.43 d	**136.16**	**8.19**	**25.23**
DEC	75.00 ±5.94 c	84.29 ±6.68 b	95.00 ±7.53 a	21.00 ±1.66 d	**68.82**	**2.61**	**8.04**
Total (g m^{-2})	1168.09±92.57 b	1007.66±79.85 c	1354.23±107.32 a	343.28±27.20 d	**968.32**	**34.88**	**107.46**
Total (Mt ha^{-1})	11.68±0.93 b	10.08±0.80 c	13.54±1.07 a	3.43±0.27 d	**9.68**	**0.35**	**1.07**

T_1: Coffee grown under two tier Native Sp. Shade (NS); T_2: Coffee grown under two tier Mixed sp. (both native & exotic) Shade (MS); T_3: Coffee grown under mono / two tier Exotic Sp. Shade (ES); T_4: Coffee grown under relatively open / Un Shaded (US) condition (< 20% shade cover)

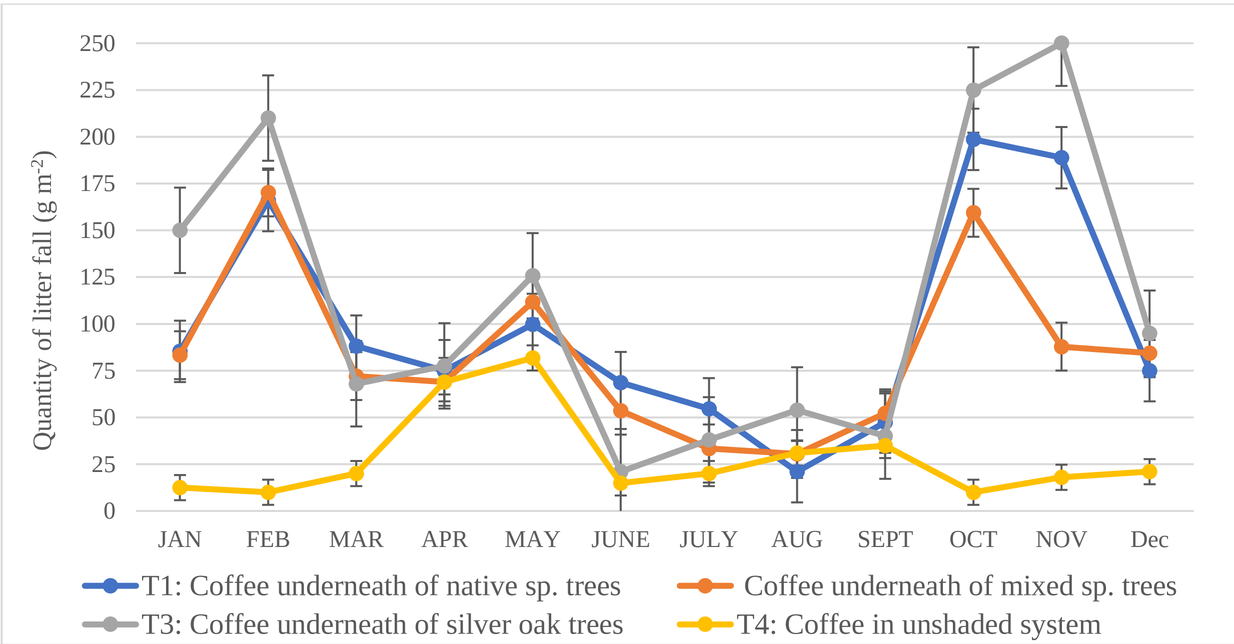

Fig 1: Month wise litter fall dynamics under different treatments

The total litterfall dynamics across the year showed clear seasonal patterns influenced by tree species and shade systems. T_3 (exotic sp. shade) consistently recorded significantly higher litterfall, especially during the fall months, with the highest litterfall observed in November (250 g m^{-2}) and October (225 g m^{-2}). Silver oak contributed significantly to organic matter, with peaks observed in January (150 g m^{-2}), February (210 g m^{-2}) and May (125.69 g m^{-2}). exotic sp. shade demonstrated a clear seasonal leaf drop pattern. T_1 (native sp. shade) and T_2 (mixed sp. shade) displayed similar litterfall dynamics, generally lower than T_3 but still substantial. Both treatments recorded their highest in October (substantial increases) and November, but experienced notable drops in March and December. T_1 and T_2 showed a noticeable increase in May, suggesting improved litter dynamics during this time. T_4 (unshaded systems) consistently had the lower litterfall throughout the year. Overall, the dynamics of litterfall were strongly influenced by tree species and seasonal changes, with shaded systems (particularly silver oak) contributing much higher organic matter than unshaded systems. The results highlighted the effectiveness of shaded systems in promoting litterfall, which is essential for maintaining soil health and fertility in coffee cultivation. Treatments that having optimum shade trees, significantly enhance organic matter accumulation compared to unshaded systems. The variation in litterfall dynamics and annual differences in different shade management regimes mainly due to the fact of variation in tree species composition, seasonal changes, management activities, timing of leaf senescence, age of the stand etc. The interplay of these factors contributes to the observed variations in litterfall across different treatments and months.

The month-wise litter/residue fall exhibited a bimodal distribution pattern, with peaks occurring from January to March and again from October to December, alongside management-induced drops in April and May due to pruning activities (Fig. 1). The peaks during these months could be attributed to the increased sunlight, which influences the litterfall rhythm in forests. This phenomenon facilitates the replacement of old leaves with new, more efficient ones, optimizing canopy photosynthesis. Such leaf shedding acts as an adaptive mechanism, enhancing the tree's ability to harness sunlight effectively (Carswell *et al.,* 2002). The quantity of litterfall observed in this study aligns closely with previous research findings. For instance, Petit-Aldana*et al.* (2019) reported similar litterfall values in coffee monocultures and intercropped systems with *Gliricidia sepium.* Similarly, Chandrappa (2005) reported that litterfall in coffee AFS varies from 10,076 to 13,920 kg ha^{-1} yr^{-1}. The findings also in consistent with Xiao *et al.* (2020), who attributed seasonal variations in litterfall to climatic factors and the physiological responses of trees. The increase in litterfall in unshaded systems during April and May, due to pruning, indicates that management practices can temporarily boost litterfall. However, the decline in litterfall during June and July reflected the natural cycle of tree growth and recovery following pruning, as documented by Rodriguez *et al.* (2023). Month wise analysis effectively illustrates the dynamic nature of litterfall across different treatments, emphasizing the superior organic contributions of shaded system compared to unshaded systems. The clear seasonal patterns observed reinforce the importance of tree species selection and management practices in agroforestry and land restoration efforts.

Nutrient Content of Litter Residue and Its Total Nutrient Contribution to The Soil

The different shade management systems differed significantly with respect to nutrient concentration and the total nutrient contribution from litter residue to the soil (Table 5 and Figure 2). The exotic sp. shade system (T_3) registered the highest carbon content of 67.00 per cent, which was significantly superior over rest of the treatments. The next best treatment w.r.t organic carbon was T_2 (mixed sp. shade) (43 %). The treatment T_2 and T_4 and T_1 and T_2 are on pare with each other. T_1 (native sp. shade) exhibited the highest nitrogen concentration (2.58 %), significantly superior over remaining treatments. T_2 (2.35%) and T_4 (2.42 %) and T_3 (1.65 %). Whereas T_2 and T_4 were found statistically on par and both are significantly better than T_3. Similarly, phosphorus content in native sp. shade (T_1) was highest (0.19%), which was significantly higher than T_2 (0.17%) and T_3 (0.11%) and at par with unshaded system T_4 (0.18%). Contrasting to above the unshaded treatment (T_4) statistically excelled over rest of the treatment by registering the higher potassium content of 2.65 per cent. Next best treatment w.r.t potassium content was mixed sp. shade (2.10). Regards to total amount of nutrients added to soil (kg ha^{-1}) through litter residue, coffee grown underneath of silver oak (exotic sp. shade) trees (T_3) contributed significantly higher carbon to the soil (9073.34 kg ha^{-1}) than the other treatments, particularly T_4 (unshaded condition) added the least (1441.78kg ha^{-1}). This was almost double the quantity as that carbon sequestered with T_1 and T_2. Whereas T_1 and T_2 are comparable with respect to amount carbon sequestered. With regard to major nutrient added to the soil through litterfall, the higher nitrogen and phosphorous addition was noticed with native sp. shade (301.37 and 22.19 kg ha^{-1}) which was significantly superior over rest of the shade management practices. The next best treatment was mixed sp. shade with addition of 236.8 and 17.13 kg ha^{-1}, respectively. The least was with unshaded condition (83.07 and 6.18 kg ha^{-1}). The amount of nitrogen and phosphorus addition under exotic sp. shade treatment was significantly lower than T_1 and T_2. Conversely, the exotic sp. shade recorded the highest potassium addition through litterfall (257.30 kg ha^{-1}) and found significantly superior over rest of the treatments.

Table 5: Concentration of nutrients in litter samples (per cent) and total amount of nutrients (kg ha^{-1}) added to the soil through litter in Arabica coffee as influenced by different shade management regimes

Treatments	Average nutrient content in the letter mass (%)				Amount of nutrients added to the soil (kg ha^{-1}) through litter			
	Carbon	Nitrogen	Phosphorus	Potassium	Carbon	Nitrogen	Phosphorus	Potassium
T_1	39.00±3.09c	2.58±0.20 a	0.19±0.02 a	1.90±0.15 c	4555.55±361 b	301.37±23.88 a	22.19±1.76 a	221.94±17.59 b
T_2	43.00±3.41b	2.35±0.19 b	0.17±0.01 b	2.10±0.17 b	4332.94±343 b	236.80±18.77 b	17.13±1.36 b	211.61±16.77 b
T_3	67.00±5.31 a	1.65±0.13 c	0.11±0.01 c	1.90±0.15 c	9073.34±719 a	223.45±17.71 b	14.90±1.18 c	257.30±20.39 a
T_4	42.00±3.33bc	2.42±0.19 b	0.18±0.01 b	2.65±0.21 a	1441.78±114 c	83.07±6.58 c	6.18±0.49 d	90.97±7.21 c
Mean	47.75	2.25	0.16	2.14	4850.90	211.17	15.10	195.45
S.Em±	1.03	0.03	0.003	0.03	249.79	7.28	0.53	5.73
CD (0.05)	3.16	0.10	0.010	0.09	769.68	22.45	1.63	17.67

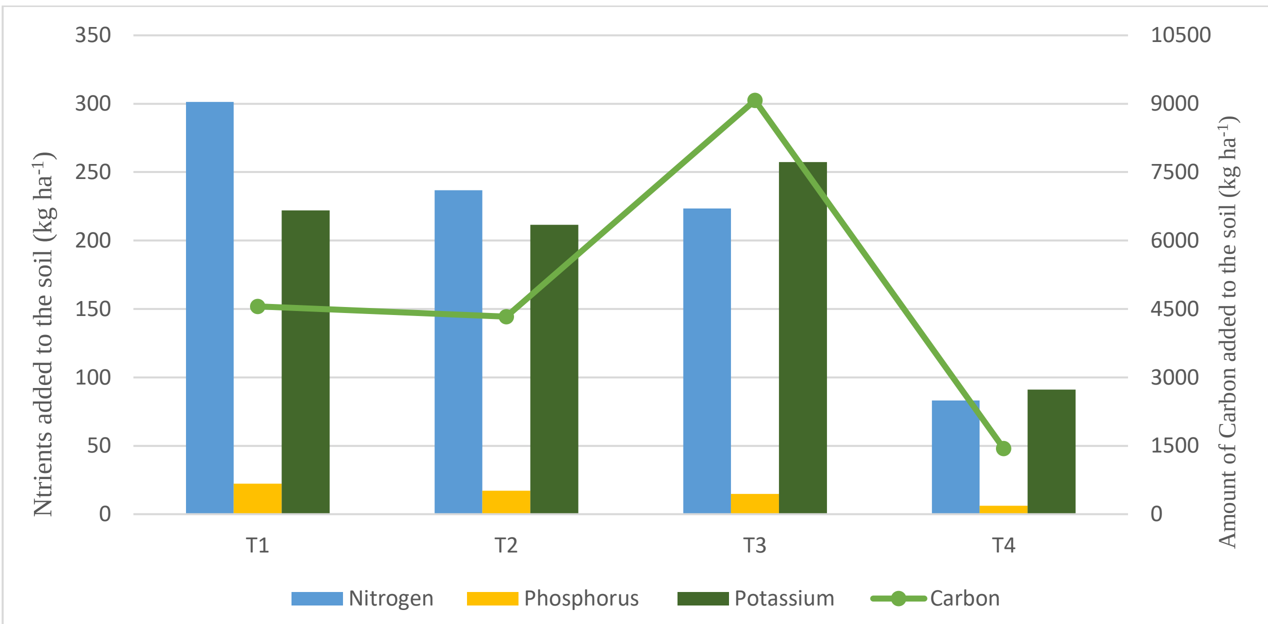

Fig 2: Amount of nutrients added to the soil (kg ha^{-1}) through litter

The results indicated that different shade management regimes significantly affected both the nutrient concentration in litter and the total nutrient contribution to the soil. Native sp. shade (T_1) consistently provided the highest concentrations of nitrogen and phosphorus, while silver oak shade system (T_3) contributed the most carbon and potassium, highlighting the importance of shade management in optimizing nutrient dynamics. Different shade species provide varying levels of canopy cover and microclimate conditions, influencing litter composition and decomposition rates. The chemical composition of litter from different tree species affects nutrient content. Native species in T_1 might produce litter that was richer in nitrogen and phosphorus, while silver oak might be contribute more carbon due to its leaf structure and decay rates. The interaction between litter and soil microorganisms can affect nutrient availability. High-quality (narrow C:N ratio of litter particularly legumes sp. and lesser lignin content) litter may enhance microbial activity, leading to faster decomposition and nutrient release. Also, different management practices associated with each shade system (e.g., pruning, litter removal) can impact the amount and quality of litter that contributes to soil nutrients and presence of different shade species may lead to varying levels of competition for nutrients. Overall, these factors interplay to create the observed differences in nutrient concentrations and contributions from litter across the various shade management treatments. Chemical composition is an intrinsic property of the litter that decides its turnover rates and nutrient cycling in terrestrial ecosystem (Jamaludheen and Kumar, 1999; Meier and Bowman, 2008). Kumar *et al.* (2019), who found that certain tree species, particularly those with extensive leaf litter and biomass, contribute to higher soil carbon levels. Farfan and Urrego (2007) observed that nitrogen concentration in arabica coffee with shade trees around 3 per cent which is more than the unshaded coffee (2.5 %). Furthermore, Notaro *et al.* (2014), reported nitrogen content in leaf litter across three coffee production systems ranging from 2.46 to 2.99 per cent. Higher nitrogen content might be due to the presence of higher nitrogen fixing trees (*Erythrina indica, Albizia lebbeck*) which contributes higher amount of nitrogen. The higher nitrogen concentration in T_1 (2.58%) contrasts with T_3 (1.65%), indicating that native species may have a greater capacity for nitrogen fixation or retention in soil compared to silver oak. This observation is consistent with studies by Smith *et al.* (2020), which noted that native species often enhance soil fertility through deeper root systems and more efficient nutrient cycling. T_1's ability to maintain higher nitrogen levels might be attributed to its litter composition, which can decompose more rapidly, releasing nitrogen back into the soil. Similarly, T_1 also exhibited the highest phosphorus concentration (0.19%), which is essential for plant growth and development. This is in line with findings from Jones *et al.* (2018), where native species were shown to outcompete non-native ones in terms of nutrient uptake efficiency. As per Winston *et al.* (2005) optimum range of P in coffee plantations around the world is 0.15 to 0.20 per cent, the coffee plantation under native shade aligns with this range. However, coffee plantations under monoculture shade exhibited comparatively lower P content which may be attributed to remobilization of phosphorous before abscission which limits P concentration in *G. robusta* leaf litter (Nesper *et al.,* 2019). The observed dynamics of litterfall and nutrient cycling across different treatments demonstrate the complex interactions between tree species, shading effects and soil nutrient profiles. These findings emphasize the importance of selecting appropriate species for shade systems, particularly in agroforestry and restoration projects.

Effect of Different Shade Management Regimes on Soil Reaction and Soil Organic Carbon (%)

The effects of different shade management regimes on soil pH and soil organic carbon content at the end of the harvest season for the years 2022 and 2023 were summarized in Table 6. The soil pH values for the various treatments during the experimental period displayed minor fluctuations. The overall mean pH across treatments was 6.13 for both years. Statistical analysis indicated that there were no significant differences (NS) in soil pH among the treatments. However, native species shade (T_1) and mixed species shade (T_2) treatments consistently showed pH values ranging from 6.15 to 6.20 (pooled). In contrast, the mono shade of silver oak (T_3) recorded pH values of 6.09 in 2022 and 6.10 in 2023, resulting in a pooled mean of 6.10. The unshaded system (T_4) exhibited slightly lower pH values, with 6.04 in 2022 and 6.14 in 2023, leading to a pooled mean of 6.09. Shaded conditions (T_1 to T_3) reduced soil erosion, thereby helping to maintain soil structure and nutrient levels, which in turn helped to sustain soil pH levels. Conversely, unshaded areas experienced greater erosion and leaching of basic cations, such as calcium and magnesium, leading to lower pH values. Additionally, the type of shade species (native vs. exotic) affected soil chemistry differently. Native and mixed species contributed to more balanced soil health, while some exotic species potentially led to imbalances, influencing pH.

Table 6: Post harvest nutrient status as influenced by different shade management regimes in Arabica coffee (pooled)

Treatments	Soil reaction (pH)	Soil Organic Carbon (%)	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
T_1	6.15 ±0.49	3.14±0.02	545.4±3.1 ^{a}	77.7±3.8 ^{a}	490.8±5.5 ^{a}
T_2	6.20 ±0.49	3.14±0.02	541.5±7.9 ^{ab}	75.5±6.0 ^{a}	477.9±3.8 ^{b}
T_3	6.10 ±0.46	3.16±0.02	525.7±3.9 ^{bc}	70.8±4.7 ^{b}	477.5±2.9 ^{b}
T_4	6.09 ±0.39	3.02±0.01	516.6±4.8 ^{c}	65.1±4.3 ^{c}	452.9±3.6 ^{c}
Mean	6.13	3.11	532.3	72.3	474.8
S.Em±	0.06	0.02	5.90	1.39	3.84
CD (0.05)	NS	0.05	18.18	4.29	11.85

T_1: Coffee grown under two tier Native Sp. Shade (NS); T_2: Coffee grown under two tier Mixed sp. (both native & exotic) Shade (MS); T_3: Coffee grown under mono / two tier Exotic Sp. Shade (ES); T_4: Coffee grown under relatively open / Un Shaded (US) condition (< 20% shade cover) / Initial Chemical Properties of Soil: PH: 5.90; OC %: 3.10; Available N: 515, P: 72 and K: 434

On the other hand, soil organic carbon (SOC) content varied significantly across the treatments. T_1 (native species shade) reported SOC levels of 3.12 percent in 2022 and 3.16 percent in 2023, with a pooled mean of 3.14 percent. T_2 (mixed species shade) exhibited SOC values of 3.11 percent in 2022 and 3.17 percent in 2023, also leading to a pooled mean of 3.14 percent. T_3 (exotic species shade) recorded SOC levels of 3.12 percent in 2022 and 3.19 percent in 2023, resulting in a pooled mean of 3.16 percent. T_4 (unshaded) showed the lowest SOC content, with 3.01 percent in 2022 and 3.02 percent in 2023, culminating in a pooled mean of 3.02 percent. Statistical analysis revealed non-significant differences among treatments T_1 to T_3, while T_4 was significantly lower. The shaded system supported a more diverse and stable ecosystem, promoting higher organic matter inputs through leaf litter, root biomass, and decomposition. In contrast, the unshaded treatment (T_4) had less organic input, resulting in lower SOC. Furthermore, shade trees typically had better moisture retention, which was favourable for both plant growth and microbial activity. Higher moisture levels enhanced decomposition rates and organic matter accumulation, leading to increased SOC.

Available Primary Nutrient (kg ha^{-1})

The status of available primary nutrients (nitrogen, phosphorus and potassium) in the soil at the end of the harvest season during the experimental period was presented in Table 6. The data were reported for the years 2022 and 2023, along with pooled means. The available NPK levels varied significantly across treatments. Native species shade (T_1) had the highest nitrogen, with a pooled mean of 545.4 kg ha^{-1}, while mixed species shade (T_2) followed closely with a pooled mean of 541.5 kg ha^{-1}. Exotic species shade recorded a mean of 525.7 kg ha^{-1}, significantly lower than T_1 and T_2. Unshaded conditions yielded the lowest nitrogen levels, with a pooled mean of 516.6 kg ha^{-1}. Similarly, pooled data for phosphorus availability revealed significant variation across treatments. Native species shade (T_1) had a pooled mean of 77.7 kg ha^{-1}, while mixed species shade (T_2) recorded a pooled mean of 75.5 kg ha^{-1}, which was comparable to T_1. Exotic species shade exhibited a pooled mean of 70.8 kg ha^{-1}. Unshaded conditions (T_4) showed the lowest pooled mean of 65.1 kg ha^{-1}. Pooled data for potassium availability showed significant variation across treatments. Native species shade (T_1) had a pooled mean of 490.8 kg ha^{-1}. Mixed species shade (T_2) recorded a pooled mean of 477.9 kg ha^{-1}, while T_3 exhibited a pooled mean of 477.5 kg ha^{-1}, with both T_2 and T_3 being comparable. Unshaded conditions (T_4) had the lowest pooled mean of 452.9 kg ha^{-1}.The individual year data for nitrogen, phosphorus, and potassium status followed trends that were largely consistent with those of the pooled data.

Treatments with native or mixed species shade (T_1 and T_2) consistently registered higher levels of available nitrogen, phosphorus, and potassium compared to unshaded conditions (T_4). The variations in available NPK across different shade management regimes in arabica coffee cultivation could be attributed to several scientific factors. Shaded environments typically experienced greater leaf litterfall and biomass accumulation, particularly with native and diverse shade species due to their high nutrient concentration. This organic matter contributed to soil nutrient pools as it decomposed, enhancing nitrogen, phosphorus and potassium availability. Shaded systems often supported a richer microbial community, which played a crucial role in nutrient cycling and these areas tended to retain more moisture, which was vital for nutrient availability and microbial activity. The results agreed with the findings of Jha *et al.* (2014), who demonstrated that shaded coffee systems, particularly those involving native species, significantly enhanced nitrogen availability due to increased organic matter inputs from leaf litter and root biomass. This was further supported by the work of Perfecto and Vandermeer (2002), which emphasized that diverse shade could boost nitrogen cycling through enhanced microbial activity and root interactions. In contrast, the lower nitrogen availability in unshaded conditions (T_4) reflected the findings of Asare *et al.* (2018) and Sauvadet *et al.* (2019), which suggested that the absence of shade led to reduced nutrient cycling and lower overall soil fertility. Research by Panta and Parajulee (2021) indicated that shade trees contributed to improved soil nutrient status, particularly phosphorus, through enhanced organic matter decomposition and microbial activity. Djukic *et al.* (2011) highlighted the role of organic matter in enhancing potassium retention in the soil. The variations in nutrient availability observed across different shade management treatments emphasized the significance of incorporating shade into coffee cultivation practices. These findings not only supported previous research but also provided a compelling case for sustainable management strategies that prioritized shade to optimize soil fertility and enhance coffee production.

Clean Coffee Yield

The clean coffee yield realized as influenced by different shade management regimes varied statistically both for pooled as well as individual year 2022 and 2023 (Table 7). The coffee grown under native sp. shade (T_1) registered the highest clean coffee yield of 0.33 kg $plant^{-1}$. Silver oak shade (T_3) yielded moderately at 0.28 kg $plant^{-1}$. Silver oak provided some benefits as shade, it was not as effective as native or mixed species. Statistically, all shade treatments paralleled each other. In contrast, the unshaded system (T_4) recorded the significantly lowest yield at 0.22 kg $plant^{-1}$. Similarly, pooled data on clean coffee yield (kg ha^{-1}) revealed that coffee grown under shade environments out yield the performance of coffee grown under unshaded / open condition (T_4). Among the different shade management practices, native sp. shade (T_1) registered the highest yield of 986.65, 1006.50 and 966.79 kg ha^{-1}for pooled, 2023 and 2022 data, respectively. This was found statistically on par with T_2 for pooled data and with both T_2 and T_3 during 2022 and 2023. The coffee grown under unshaded condition recorded significantly lower clean coffee yield compared to all shade management treatments both during individual years as well as pooled over years (663.03, 759.00 and 567.05 kg ha^{-1}for pooled, 2023 and 2022, respectively).

Table 7: Clean coffee yield (kg plant^{-1}) and clean coffee yield (kg ha^{-1}) of Arabica coffee as influenced by different shade management regimes

Treatments	Clean coffee yield (kg plant^{-1})			Clean coffee yield (kg ha^{-1})		
	2022	2023	Pooled	2022	2023	Pooled
T_1	0.32±0.02 a	0.33±0.02 a	0.33±0.02 a	966.79±59.68 a	1006.50±53.44 a	986.65±47.92 a
T_2	0.31±0.03 a	0.34±0.01 a	0.32±0.02 a	942.15±75.92 a	1015.03±41.99 a	978.59±58.36 ab
T_3	0.26±0.02 a	0.31±0.01 a	0.28±0.02 a	791.08±68.32 a	929.50±42.96 a	860.29±47.85 b
T_4	0.19±0.01 b	0.25±0.03 b	0.22±0.02 b	567.05±42.07 b	759.00±80.46 b	663.03±53.76 c
Mean	0.27	0.31	0.29	816.77	927.51	872.14
S.Em±	0.02	0.01	0.01	58.50	35.39	40.26
CD (0.05)	0.06	0.04	0.04	180.27	109.05	124.05

T_1: Coffee grown under two tier native sp. shade (NS); T_2: Coffee grown under two tier mixed sp. (both native & exotic) shade (MS); T_3: Coffee grown under mono / two tier exotic sp. shade (ES); T_4: Coffee grown under relatively open / unshaded (US) condition (< 20% shade cover)

These results suggested that native and mixed species trees provided an optimal microclimate for coffee plants, likely due to better moisture retention, reduced temperature extremes and improved soil quality. The biodiversity in native and mixed species could have enhanced ecological resilience, offering more consistent growth conditions. Silver oak, while often used in agroforestry systems, might not have aligned well with coffee cultivation due to its growth characteristics and water demands compared to native species. Under unshaded conditions, the plants exposed to direct sunlight, lead to higher stress, increased water loss and potential damage during hot periods. Thus, reduced growth and yield in T_4treatment. This reinforced the understanding that coffee as a shade-tolerant species, thrived in environments that mimicked its natural habitat. The higher yield per unit area in agroforestry systems of coffee production was also attributed to the fact that shaded coffee systems altered both the above and belowground microenvironments. Shaded plants exhibited greater biochemical and physiological potential for high dry matter production, which helped them to maintain high coffee yields in the long term. Additionally, well-established facts indicated that shaded environments resulted in reductions in air temperatures, wind speeds, radiation levels, weed growth and coffee water transpiration losses. Under shade, the photosynthetic performance of coffee plants potentially benefited from the reduction in irradiation. Research findings indicates that shaded coffee systems often support a higher diversity of flora and fauna, leading to a more resilient agricultural ecosystem (Perfecto *et al.,* 2004). This biodiversity can enhance the stability of coffee production by mitigating the risks associated with pest outbreaks. Gao

(2018) noted that optimal shade coverage (15% to 54%) positively influences coffee yield by improving moisture retention and reducing competition for water. This is particularly important in regions where water scarcity is of concern. The study conducted by Nibasumba *et al.* (2011) in Burundi also revealed improved growth metrics of coffee with higher coffee yield, heavier berries and berry thickness with intercropping of coffee and bananas (Coffee grown under banana shade). Observations are also in consistent with findings those by Kufa *et al.,* 2007; Partelli *et al.* (2014); Gleison *et al.* (2016) and Amanuel Tilahun Etafa (2022). The importance of shade in coffee yields is well-supported by various studies, indicating that it offers numerous benefits from improved microclimates and soil health to enhanced biodiversity and water conservation. As the coffee industry faces challenges such as climate change and pest pressures, adopting shaded coffee systems could be a viable strategy for sustainable production.

CONCLUSION

This study highlights the crucial role of shade management in regulating litter dynamics, nutrient contributions, soil health and clean coffee yield in Arabica coffee agroforestry systems in the Central Western Ghats, India. The results demonstrate that shaded systems, particularly those with native and mixed tree species, significantly enhance litterfall, leading to increased organic matter accumulation and improved soil fertility. The exotic species shade contributed the highest carbon and potassium, while native species shade provided superior nitrogen and phosphorus enrichment. These variations in nutrient dynamics underscore the importance of shade tree selection in optimizing nutrient cycling and soil sustainability.

Furthermore, shade management regimes influenced soil organic carbon levels, with shaded treatments (T_1–T_3) showing significantly higher SOC compared to unshaded systems (T_4). The availability of primary nutrients (NPK) was also highest under native and mixed species shade, reinforcing the benefits of diverse shade species for soil enrichment and long-term ecosystem stability. Importantly, the study confirms that coffee grown under shaded environments outperformed unshaded systems in clean coffee yield, with the highest productivity recorded under native shade. This finding accentuates the ecological and agronomic advantages of shade-grown coffee, as it fosters a stable microclimate, improves soil health and sustains higher yields. These results emphasize the necessity of integrating diverse native tree species into coffee agroforestry systems for sustainable production. Given the increasing challenges posed by climate change and soil degradation, shade-based management strategies should be prioritized to enhance coffee resilience, maintain ecosystem services and ensure long-term agricultural sustainability. Future research should focus on optimizing shade tree compositions to maximize coffee yield while balancing ecological benefits, thereby promoting climate-smart and environmentally sustainable coffee farming practices.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest associated with this manuscript.

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