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Evaluating the Impact of Shade Patterns on Quality, Bean Grades, Caffeine Content and Yield of Arabica Coffee (*Coffea Arabica* L.) in the Western Ghats of India

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ABSTRACT

Coffee is a significant commercial crop in India, predominantly grown in the southern states, with the Western Ghats playing a pivotal role due to their unique biodiversity and climate. This two-year study (2022-2023 harvesting seasons) evaluated the performance of arabica coffee (Coffea arabica L.) under four distinct shade patterns: two-tier native species, mixed species (native and exotic), exotic species (Grevillea robusta), and unshaded conditions. Conducted in a randomized complete block design (RCBD) with five replications, the study assessed the impact of shade management on quality attributes, bean grades, caffeine content and yield. Coffee cultivated under native and mixed species shade exhibited significantly higher proportions of premium-grade beans (84.83% and 84.00%, respectively), improved sensory attributes, and enhanced caffeine content (1.17% and 1.13%, respectively), compared to unshaded conditions. Native shade systems yielded the highest total cup score (75.33) and clean coffee yield (986.65 kg ha^{-1}), highlighting the positive impact of shade on fruit quality, ripening uniformity, and chemical composition. Conversely, unshaded coffee showed poorer quality, lower yields, and increased stress due to direct sunlight. These findings emphasize the role of shade in optimizing coffee quality and yield while maintaining sustainability and biodiversity in agroforestry systems.

Keywords: *Coffee agroforestry, Shade management, Coffea arabica, Bean quality, Yield performance*

INTRODUCTION

Coffee, a globally cherished beverage, is a key commercial crop in India, predominantly cultivated in the southern states. The Western Ghats, a UNESCO World Heritage Site, serves as a prominent coffee-growing region, offering unique ecological and climatic advantages for coffee. The region's shaded plantations are integral to its biodiversity, hosting a wide array of flora and fauna, while also contributing to the livelihoods of millions of smallholder farmers. Shade-grown coffee systems in the Kodagu district of Karnataka exemplify sustainable agricultural practices, covering approximately 33 percent of the district's area and complementing diverse forest landscapes, such as sacred groves, reserve forests and other protected areas [32; 5].Shade management in coffee plantations plays a critical role in influencing both ecological sustainability and coffee quality. Shaded environments provide a stable microclimate that moderates temperature fluctuations, reduces water stress, and enhances soil health through organic matter deposition [22; 11;18]. These systems have been found to delay berry ripening, improve bean size and enhance biochemical composition, resulting in superior cup quality characterized by better aroma, and bodyand acidity [34; 35]. Native shade trees, in particular, foster better nutrient cycling and biodiversity, which further contribute to coffee's sensory and physical attributes [31].

However, the increasing demand for higher coffee yields has led to a shift towards monoculture systems and reduced shade cover in recent years. These changes have been associated with a decline in coffee quality, increased susceptibility to climate-induced stresses, and biodiversity loss. Studies have shown that reduced shade cover accelerates ripening, leading to smaller bean sizes and compromised biochemical profiles [6; 1]. Exotic shade species, such as *Grevillea robusta*, have been reported to be less effective in maintaining optimal microclimatic conditions and biochemical balance compared to native or mixed species [33; 29].The quality of green coffee beans, a determinant of their market value, is influenced by inherent genetic traits and environmental conditions. Key biochemical compounds such as caffeine, chlorogenic acids and sucrose are critical to coffee's flavor profile and pharmacological properties. Studies have consistently demonstrated that shade-grown coffee beans exhibit higher levels of these beneficial compounds, contributing to improved flavor complexity and antioxidant properties [11; 30].

With the Western Ghats facing increasing pressure from changing land-use patterns and climatic variability, there is a pressing need to evaluate sustainable shade management practices. The present study, conducted during the 2022–2023 harvesting seasons, investigates the impact of four distinct shade management regimes—native species, mixed species,

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exotic species (*Grevillea robusta*)and unshaded conditions—on the quality attributes, caffeine content, bean grades and yield of arabica coffee. This research aims to provide actionable insights for balancing productivity with environmental sustainability, ensuring the longevity and quality of India's coffee sector.

2 MATERIALS AND METHODS

2.1 Study Location and Climate

The study was conducted at the L and M blocks of the Coffee Research Sub Station (CRSS), Chettalli, located in North Kodagu, Karnataka, India (12°23'N, 75°49'E, 950 m AMSL). Weather data for the 2022–2023 seasons were obtained from the CRSS Meteorological Observatory. Notable variations in climatic conditions were observed during the study period. In 2023, average minimum and maximum temperatures were 18.15 °C and 28.57 °C, respectively, which exceeded both 2022 levels (17.20 °C and 26.58 °C) and the long-term normal (17.36 °C and 27.26 °C). Rainfall in 2022 (2128 mm) surpassed the 2023 levels (1218 mm) and the normal average (1579 mm). Additionally, the number of rainy days in 2023 (89) was lower than in 2022 (117), indicating more intense rainfall events. These climatic variations suggest a warming trend that may influence coffee cultivation strategies. Climatic data trends are presented in Figures 1 and 2.

2.2 Soil Characteristics

The experimental soil is classified as fine-loamy, mixed, isohyperthermic typic haplustepts, with a sandy loam texture. It is deep, well-drained, and derived from weathered granite. Soil analysis revealed slightly acidic pH (5.90), low electrical conductivity (0.23 dSm^{-1}), high organic carbon (2.96%), available phosphorus (72 kg ha^{-1}), available potassium (434 kg ha^{-1}), and medium nitrogen content (515 kg ha^{-1}).

2.3 Experimental Details

The experimental block spanned 20 acres and comprised four shade management regimes:

T_1: Two-tier native species shade (e.g., *Albizzia sp.*, *Ficus sp.*, *Dalbergia sp.*, *Terminalia sp.*, *Pterocarpus marsupium*, *Stereospermum sp.*, *Syzygium jambolana*) with *Erythrina lithosperma* (*Dadap*) in the lower strata.

T_2: Two-tier mixed species shade (native species combined with exotic *Grevillea robusta*).

T_3: Two-tier exotic species shade (predominantly *Grevillea robusta*).

T_4: Unshaded condition (tree cover < 20%).

The blocks were planted with *Coffea arabica* cv. Chandragiri in 2006, with a spacing of 1.8 m × 1.8 m.

2.4 Experimental Design

The experiment followed a randomized complete block design (RCBD) with five replications. Each treatment plot measured 20.12 × 18.29 m and contained 110 coffee plants (11 rows × 10 plants).

2.5 Crop Management

Standard agronomic practices, including nutrition management, weeding, and plant protection, were implemented following the Coffee Guide, Central Coffee Research Institute [3].

2.6 Bean Grades and Quality Analysis

Uniformly ripened coffee fruits (5 kg) were harvested separately from each treatment and processed using the wet method. The wet parchment was dried to approximately 11 per cent moisture content, hulled to produce clean coffee and graded using Mckinnon sieves (5.50, 6.00-, and 6.65-mm screen sizes). The outturn percentage was calculated based on the clean coffee yield relative to weight of dense fruit taken for pulping.For sensory quality analysis, 100 g of roasted coffee was prepared to a light-medium degree at 205 °C (Probat lab roaster). The roasted beans were ground to medium-coarse powderand 10 g of powder was brewed with 250 ml boiling water. After a 5-minute steeping period, sensory evaluation followed a ten-point hedonic scale [4].

2.7 Estimation of Caffeine Content

Caffeine content was estimated using the method developed by [28]. A 1 g sample of ground coffee was placed in a 250 ml conical flask, with 200 ml distilled water and 5 g magnesium oxide (MgO). The mixture was heated in a water bath at 90 °C for 20 minutes, then cooled, filtered (0.45 µm filter), and analyzed using High-Performance Liquid Chromatography (HPLC).

Caffeine content was calculated in per cent on the dry basis by using the following formula.

$$\text{Caffeine content (\% dry basis)} = \left(\frac{mass\ of\ caffeine\ (g)}{\text{mass of dry samples (g)}}\right) \times 100$$

2.8 Statistical Analysis

Data were statistically analyzed using the methods described by Gomez and Gomez (1984). A significance level of p = 0.05 was used for F and t-tests. Critical difference values were calculated where the F-test was significant. Duncan's multiple range test (DMRT) was employed for mean comparison. Statistical analysis was performed using the Web Agri Stat Package developed by ICAR Complex, Goa [15].

3 RESULTS AND DISCUSSION

3.1 Effect of different shade management regimes on quality attributes of arabica coffee

The influence of shade management regimes on coffee quality parameters, including float percentage, dense fruits, outturn, and bean grades, is summarized in Table 1.

Fruit Density and Outturn: Unshaded coffee plants consistently recorded the highest float percentages (4.17% pooled), indicating lower fruit density. In contrast, native species shade and mixed species shade had significantly lower float percentages (3.02% and 3.13%, respectively, pooled), demonstrating enhanced fruit quality under shaded conditions. T_1 also recorded the highest dense fruit percentage (96.98%, pooled) and outturn (16.27%, pooled), followed closely by T_2. Conversely, unshaded systems exhibited the lowest dense fruit percentage (95.83%, pooled) and outturn (15.79%, pooled).

Bean Grades: Shade management significantly affected the bean grades of Arabica coffee. Coffee grown under native and mixed species shade yielded the highest proportion of premium 'A' grade beans (>6.65 mm) with pooled values of 84.83 per cent and 84.00 percent, respectively. These treatments significantly outperformed the unshaded system, which produced the lowest proportion of 'A' grade beans (78.83%).The exotic species shade resulted in the highest proportion of 'B' grade beans (>6.00 mm) at 4.17 per cent, followed by T_4 (3.90%). Meanwhile, T_4 produced the highest percentage of lower-quality 'C' grade beans (>5.50 mm) at 5.77 per cent, closely followed by T_3 (5.60%). T_1 and T_2 demonstrated better quality with lower 'C' grade proportions (4.52% and 3.92%, respectively).

Coffee grown under native species shade recorded the lowest proportion of PB grade beans (7.80%), indicating a higher yield of premium-quality beans. Exotic species shade and mixed species shade recorded higher PB grades at 8.30 per cent and 8.22 per cent, respectively, highlighting the impact of shade composition on bean quality.

The findings highlight the positive role of shade management, particularly native and mixed species, in enhancing fruit density, outturn and premium-grade bean production. Shade mitigates environmental stress by regulating temperature and moisture levels, fostering healthier plants with denser fruits and improved quality. The reduced float percentages and higher dense fruit proportions in shaded systems align with earlier findings by [13; 27], which emphasize the role of shade in improving microclimatic conditions and reducing stress-related fruit defects.Shade trees, particularly native species, create optimal conditions for producing larger, denser beans with superior quality, as previously reported by [12; 19]. Unshaded systems, while promoting faster fruit maturation, compromise quality due to increased exposure to sunlight and stress, which negatively affect flavor and bean size.These results accentuate the importance of integrating shade management practices, particularly through native tree species, to optimize coffee production. This approach not only enhances coffee quality and marketability but also contributes to biodiversity conservation and the sustainability of agroforestry systems.

3.2 Effect of different shade management regimes on cup quality characteristics and per cent caffeine

The pooled data from 2022 and 2023 on cup quality characteristics—aroma/fragrance, flavor, acidity, aftertaste, body, balance and total cup score (TCQS) - demonstrate the influence of various shade management regimes (Figure 3 and 4; Table 2). The results emphasize the significant role of shade in optimizing the sensory profile of coffee. Notably, the treatment with native species shade achieved the highest TCQS (75.33), outperforming the unshaded system with the lowest score (70.05). Native shade positively influenced key parameters, including aroma (6.78), flavor (6.45), body (6.15), balance (6.43), acidity (6.45)and aftertaste (6.48). Mixed species shade also delivered strong results, statistically on par with native shade for most quality traits. In contrast, unshaded coffee consistently showed the lowest scores, highlighting the detrimental effects of excessive sunlight exposure.The caffeine content data across treatments and years (2022–2023) are presented in Table 2. Native shade exhibited the highest caffeine content (1.17%), comparable to mixed species shade (1.13%) but significantly higher than exotic species shade (1.08%) and unshaded conditions (1.05%). The superior caffeine content in shaded treatments can be attributed to optimal light conditions for photosynthesis, improved nutrient cyclingand reduced stress.

Shade-grown coffee benefits from extended maturation periods due to moderated sun exposure, which enhances sugar accumulation and reduces bitterness. These effects contribute to a refined flavor profile, improved bean weight and a balance of chemical compounds critical for cup quality. Research has shown that shaded conditions promote the development of chlorogenic acids, phenolic compounds and other precursors of complex flavor profiles [20; 25. The higher cup quality under native and mixed species shade is likely due to improved microclimatic conditions, diversified organic matter input and balanced nutrient supply.

These factors foster the development of aromatic compounds and biochemical pathways that enhance acidity, body and overall flavor stability [25; 16]. Studies by [12; 19] corroborate these findings, showing that shaded coffee consistently produces higher-quality beans with desirable sensory attributes and premium grades.The enhanced caffeine content under native and mixed species shade aligns with findings from [7; 17]who reported that moderate sunlight exposure boosts photosynthetic rates and energy production, facilitating caffeine synthesis. Improved nutrient availability, especially nitrogen and potassium, further supports this process [8]. Stability in temperature and humidity under shaded conditions reduces thermal stress, enabling plants to allocate more resources to caffeine production [16].

3.3 Effect of different shade management regimes on clean coffee yield

The highest clean coffee yield was observed under native species shade at 0.33 kg plant^{-1}, followed by mixed sp. shade at 0.32 kg plant^{-1}. In contrast, unshaded systems recorded the lowest yield at 0.22 kg plant^{-1}. Although exotic sp. shade (*Grevilia robusta*) provided moderate benefits, it was less effective than native or mixed species shade. Statistically, all shade treatments performed similarly.Pooled data on clean coffee yield (kg ha^{-1}) reinforced that shaded coffee consistently outperformed unshaded systems. Native species shade achieved the highest pooled yields of 986.65 kg ha^{-1}, with individual year yields of 1006.50 kg ha^{-1} (2023) and 966.79 kg ha^{-1} (2022). These were statistically on par with T_2 for pooled data and with T_2 and T_3 for 2022 and 2023. In contrast, the unshaded system recorded significantly lower yields: 663.03 kg ha^{-1}(pooled), 759.00 kg ha^{-1} (2023), and 567.05 kg ha^{-1}(2022) (Table 3).

The higher productivity in shaded systems was attributed to enhanced aboveand belowground micro-environments. Shade moderated air temperatures, wind speeds, radiation, weed growth and water transpiration losses. This stable environment improved the photosynthetic performance of coffee plants, promoting higher dry matter production and sustained yields. Earlier studies, such as [14] highlighted increased productivity under nitrogen-fixing trees like *Erythrina abyssinica*. Shaded systems also fostered biodiversity, supporting beneficial insects, natural predatorsand birds that reduced pest populations, such as the coffee white stem borer (CWSB), which thrives in unshaded conditions.Research by [9; 18] corroborated these findings, emphasizing the role of shade. Studies from [21] in Ethiopia and [23] in Burundi confirmed improved soil fertility, heavier berriesand higher yields under shaded conditions.Optimal shade coverage (15%-54%) significantly benefits coffee yield by improving moisture retention and reducing competition for water, as noted by [10]. [26] highlighted the enhanced biodiversity in shaded systems, promoting ecosystem resilience and stability. Observations by [24; 2] further support these findings, emphasizing the sustainability of shaded coffee systems. As climate change and pest pressures challenge coffee production, shaded systems offer a sustainable strategy by enhancing microclimates, soil health, biodiversityand water conservation, ultimately stabilizing yields.

4 CONCLUSIONS

The study highlights the significant influence of shade management regimes on the quality, yieldand sustainability of arabica coffee production.

Native species shade consistently outperformed other treatments in enhancing key quality attributes such as fruit density, outturn, premium-grade bean proportionand cup quality characteristics. Mixed species shade also delivered strong results, often statistically comparable to native species shade, highlighting the benefits of biodiversity in shade composition. Unshaded systems, while promoting faster fruit maturation, exhibited reduced quality parameters, lower yieldsand higher susceptibility to environmental stress and pests.Shaded coffee systems, particularly those with native and mixed species, created optimal microclimatic conditions that moderated temperature, reduced radiation, and enhanced moisture retention. These improvements fostered superior photosynthetic performance, increased nutrient cyclingand sustained higher clean coffee yields. Additionally, shaded environments supported greater biodiversity, including beneficial insects, birds and predators, contributing to natural pest control and ecosystem resilience.

The results align with existing literature, affirming that shade-grown coffee not only enhances bean quality and yield but also contributes to biodiversity conservation and climate resilience. The superior cup quality and higher caffeine content observed in shaded systems reflect the positive impact of moderated sunlight exposure and improved nutrient availability on biochemical pathways critical for coffee production.This study highlights the importance of integrating agroforestry practices, particularly with native and diverse shade trees, into coffee cultivation systems. As climate change, water scarcityand pest pressures pose increasing challenges to global coffee production, shaded coffee systems offer a sustainable and scalable solution. Future research should focus on optimizing shade tree species selection and coverage levels to maximize coffee quality and yield while ensuring ecological sustainability. This approach will strengthen the adaptability and resilience of coffee agroforestry systems in a rapidly changing environment.

5 Article Type

This manuscript is a Research Article based on a field study evaluating the impact of shade management on coffee quality and yield.

6. Authors' Contribution

Conceptualization and idea: Rudragouda.; Girijesh, G. K.; Nagaraja, J. S. Methodology and design: Veeranna, H. K.; Nagarajappa Adivappar.; Devagiri, G. M.; Dinesh Kumar, M. Data analysis, writing, and interpretation: Rudragouda. Coffee quality analysis and draft editing: Ramya, M.; Tiluttama Mudoi.; Hari Om. Furthermore, the corresponding author declares that this study was conducted as part of his Ph.D. research work.

7 CONFLICT OF INTEREST STATEMENT

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

8 ACKNOWLEDGEMENTS

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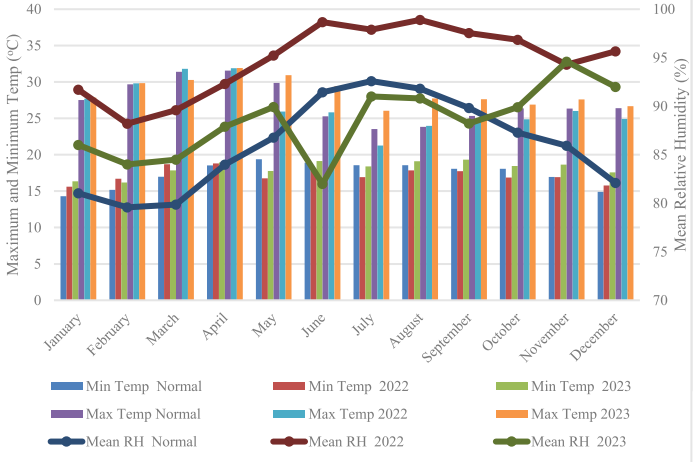

Fig.2: Maximum, Minimum Temprature and Mean Relative Humidity at the experimental location

Table1: Quality attributes of Arabica coffee as influenced by different shademanagement regimes (Two year Pooled)

Treatments	Per cent floats*	Per cent dense fruits *	Per cent Outturn	A Grade Beans (%)	B Grade Beans (%)	C Grade Beans (%)	PB Grade Beans (%)
T_1	3.02 ±0.20 c	96.98 ±0.20 a	16.27±0.09	84.83 ±0.71 a	1.72 ±0.03 d	4.52 ±0.07 c	7.80 ±0.12 d
T_2	3.13 ±0.31 c	96.87 ±0.31 a	16.21±0.10	84.00 ±1.38 a	2.08 ±0.03 c	3.92 ±0.06 d	8.22±0.13 b
T_3	3.73 ±0.24 b	96.27 ±0.24 b	15.94±0.11	81.07 ±0.54 b	4.17 ±0.07 a	5.60 ±0.09 b	8.30 ±0.13 a
T_4	4.17 ±0.24 a	95.83 ±0.24 c	15.79±0.09	78.83 ±0.41 b	3.90 ±0.06 b	5.77±0.09 a	8.12 ±0.13 c
Mean	**3.51**	**96.49**	**16.05**	**82.18**	**2.98**	**4.95**	**8.11**
S.Em±	**0.11**	**0.11**	**0.06**	**0.81**	**0.02**	**0.01**	**0.003**
CD (0.05)	**0.35**	**0.35**	**0.18**	**2.51**	**0.06**	**0.04**	**0.011**

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 two tier exotic sp. shade (ES);
T_4: Coffee grown under relatively unshaded (US) condition (< 20% shade cover)
* Quantity of fruits taken for sample coffee preparation was 5 kg fruits for each treatment.

Table 2: Cup quality characteristics of Arabica coffee as influenced by different shade management regimes (Pooled)

Treatments	Aroma / Fragrance (AQ)*	Flavour (FL) *	Acidity (AC) *	Aftertaste (AS) *	Body (BO) *	Balance (BL)*	Overall (OV)*	Total Cup Score (TCQS) *	Caffeine (%)
T_1	6.78 ±0.03 a	6.45 ±0.08 a	6.45 ±0.14 a	6.48 ±0.07 a	6.15 ±0.12 a	6.43 ±0.08 a	6.38 ±0.04 a	75.33 ±0.32 a	1.17 ±0.07
T_2	6.63 ±0.04 b	6.53 ±0.03 a	6.43 ±0.06 a	6.15 ±0.09 b	6.28 ±0.07 a	6.33 ±0.05 ab	6.43 ±0.06 a	74.53 ±0.48 a	1.13 ±0.01
T_3	6.53 ±0.05 b	6.20 ±0.03 b	6.13 ±0.04 b	6.05 ±0.05 b	5.85 ±0.05 b	6.15 ±0.05 b	6.13 ±0.04 b	73.03 ±0.12 b	1.08 ±0.02
T_4	6.15 ±0.06 c	5.85 ±0.06 c	5.63 ±0.06 c	5.55 ±0.08 c	5.48 ±0.06 c	5.70 ±0.06 c	5.70 ±0.06 c	70.05 ±0.29 c	1.08 ±0.04
Mean	**6.52**	**6.26**	**6.16**	**6.06**	**5.94**	**6.15**	**6.16**	**73.23**	**1.12**
S.Em±	**0.05**	**0.05**	**0.08**	**0.05**	**0.08**	**0.06**	**0.05**	**0.30**	**0.04**
CD (0.05)	**0.15**	**0.15**	**0.26**	**0.14**	**0.24**	**0.19**	**0.16**	**0.94**	**NS**

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 two tier exotic sp. shade (ES);
T_4: Coffee grown under relatively unshaded (US) condition (< 20% shade cover)

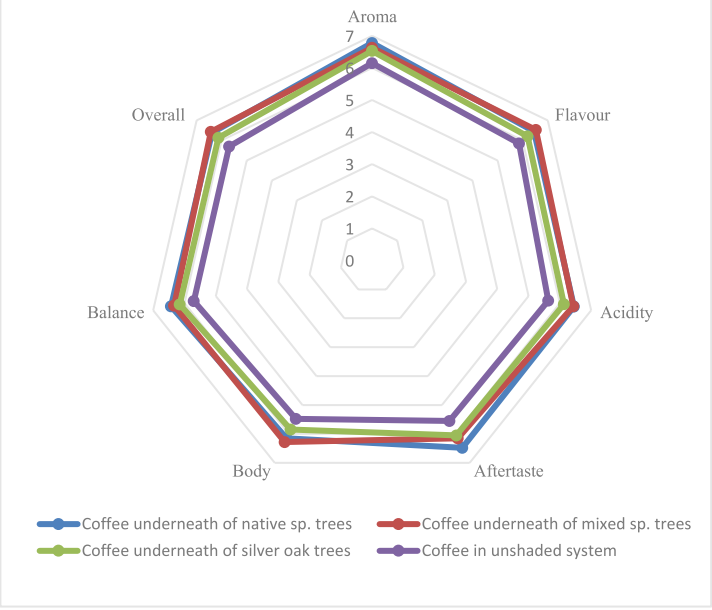

Fig. 3 : Radar graph illustration of cup quality characteristics in Coffee

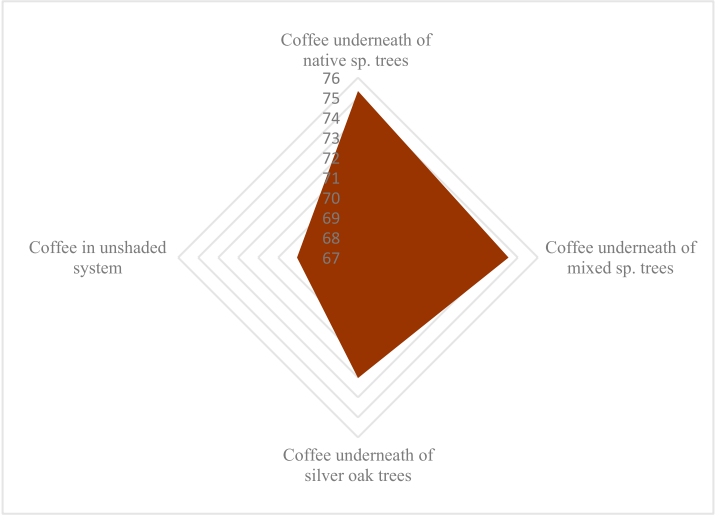

Fig.4 : Radar graph illustration of total cup score (SCAA) in Coffee

Table 3: 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 two tier exotic sp. shade (ES);
T_4: Coffee grown under relatively unshaded (US) condition (< 20% shade cover)

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