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Comparative Growth and Yield Performance of Rhizomatous Crops under *Bambusa vulgaris*-Based Agroforestry in Semi-Arid Bundelkhand, India

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ABSTRACT

Agroforestry offers sustainable solutions for enhancing agricultural productivity in semi-arid regions facing erratic rainfall and soil degradation. This study evaluated the growth and yield performance of three shade-tolerant rhizomatous crops - turmeric (*Curcuma longa* L. var. BSR 1), ginger (*Zingiber officinale* Rosc. var. Bansi Local), and colocasia (*Colocasia esculenta* L. var. Barua Sagar Local) under a Bambusa vulgaris based agroforestry system in Bundelkhand, India. The experiment was conducted at the Forestry Research Farm, RLBCAU, Jhansi, between 2024-2026 using a Randomized Block Design with six treatments and five replications. The bamboo was approximately five years old (planted in September 2019) at the time of the experiment. Results demonstrated that bamboo-based agroforestry significantly enhanced crop performance compared to sole cropping. Turmeric recorded the highest yield of 8.85 t ha^{-1} under agroforestry versus 7.38 t ha^{-1} in sole cropping (19.9% increase). Similarly, colocasia yielded 8.02 t ha^{-1} compared to 6.79 t ha^{-1} (18.1% increase), and ginger produced 7.01 t ha^{-1} versus 6.25 t ha^{-1} (12.2% increase). Plant height and leaf production were consistently superior in agroforestry treatments, attributed to favorable microclimate modification, reduced heat stress, and improved moisture retention under bamboo canopy. These findings demonstrate that Bambusa vulgaris-based agroforestry systems represent a viable, sustainable land-use strategy for semi-arid Bundelkhand, with turmeric emerging as the most productive intercrop

INTRODUCTION

Agroforestry, defined as the deliberate integration of woody perennials with agricultural crops on the same land management unit, has emerged as a critical strategy for achieving global food security and sustainable development goals (Nair, 1993; Jose, 2009). Globally, agroforestry systems cover approximately 1 billion hectares, providing essential ecosystem services including biodiversity conservation, soil fertility enhancement, and diversified production streams for smallholder farmers (Mbow et al., 2014; Kumar et al., 2024). The Intergovernmental Panel on Climate Change (IPCC) has recognized agroforestry as a key climate-smart agricultural practice capable of enhancing agricultural resilience in vulnerable regions (IPCC, 2019).

The Bundelkhand region of central India, spanning parts of Uttar Pradesh and Madhya Pradesh, exemplifies the challenges confronting semi-arid agricultural landscapes. Characterized by erratic and scanty rainfall (averaging 800-900 mm annually), prolonged dry spells, highly eroded soils with low organic carbon content (0.3-0.5%), and poor irrigation infrastructure, Bundelkhand experiences frequent droughts and widespread crop failures (Singh et al., 2014; Dhyani et al., 2013). Traditional monoculture systems have proven unsustainable, leading to declining soil fertility, reduced water availability, and diminished agricultural productivity. In this context, agroforestry systems offer a promising alternative by integrating trees with agricultural crops to enhance resource-use efficiency, improve microclimate, and provide multiple products (Dev et al., 2020; Abidi et al., 2024; Chichaghare et al., 2026).

Bamboo (*Bambusa* spp. and *Dendrocalamus* spp.) represents an ideal tree component for agroforestry systems in semi-arid regions due to its rapid growth, minimal water requirements, extensive root system for soil stabilization, and multiple economic uses (Nath et al., 2015; Dev et al., 2017;

Kleinhenz &Midmore, 2001). Bamboo-based agroforestry systems have demonstrated significant potential for enhancing land productivity, improving soil health, and providing supplementary income to farmers (Akoto et al., 2020; Hani et al., 2024). The light canopy structure of bamboo allows sufficient light penetration for shade-tolerant understory crops while simultaneously moderating microclimate through reduced temperature extremes and enhanced moisture retention (Wu et al., 2023; Xu et al., 2023).

Rhizomatous crops such as turmeric (*Curcuma longa* L.), ginger (*Zingiber officinale*Rosc.), and colocasia (*Colocasia esculenta* L.) are well-suited for integration into bamboo-based agroforestry systems due to their shade tolerance, high economic value, and compatibility with tree components (Kandiannan et al., 2011; Dhanyashri et al., 2020). Turmeric, a perennial herbaceous plant belonging to the Zingiberaceae family, is cultivated primarily for its rhizomes, which contain curcumin and are widely used in culinary, medicinal, and cosmetic applications. Ginger, also from the Zingiberaceae family, is valued for its pungent rhizomes rich in gingerol and other bioactive compounds. Colocasia, a member of the Araceae family, produces starchy corms and cormels that serve as important food sources in tropical and subtropical regions (Lebot, 2009; Onwueme, 1999).

Despite the recognized potential of bamboo-based agroforestry, systematic empirical evidence on the performance of rhizomatous crops under bamboo canopy in semi-arid conditions remains limited. Although several studies have demonstrated the potential of bamboo-based agroforestry with different intercrops, there remains a lack of comparative information on the growth and yield performance of shade-tolerant rhizomatous crops under Bambusa vulgaris-based agroforestry in the semi-arid Bundelkhand region.Understanding the biophysical interactions between bamboo and understory crops - particularly light interception, soil moisture dynamics, nutrient competition, and microclimate modification - is essential for optimizing system design and management (Rao et al., 1998; Jose et al., 2004; Kumar et al., 2024).

The present study was designed to address this knowledge gap by evaluating the growth and yield performance of three economically important rhizomatous crops - turmeric, ginger, and colocasia - under *Bambusa vulgaris*-based agroforestry in the semi-arid Bundelkhand region. The specific objectives were to: (i) assess the growth parameters (plant height, number of leaves) of turmeric, ginger, and colocasia under bamboo-based agroforestry compared to sole cropping; (ii) quantify the yield performance of these crops under both systems; and (iii) identify the most suitable rhizomatous crop for integration into bamboo-based agroforestry in semi-arid conditions.

MATERIALS AND METHODS

Details of the Experimental Site

The field experiment was conducted at the G24 Block, Forestry Research Farm, Rani Lakshmi Bai Central Agricultural University (RLBCAU), Jhansi, Uttar Pradesh, India (25°27′N latitude, 78°35′E longitude, 271 m above mean sea level) during the 2024-25 and 2025-26 growing season. The experimental site is located in the Bundelkhand region, characterized by a semi-arid climate with hot, dry summers and cool winters. The mean annual rainfall is approximately 850 mm, concentrated primarily during the monsoon season (July-September). The soil is classified as Typic Ustochrept (USDA Soil Taxonomy) with sandy loam texture, pH (7.44 - 7.56), low organic carbon content (0.30 – 0.38 %), and moderate available nitrogen (157.99 – 175.37 kg ha^{-1}), phosphorus (8.20 – 9.66 kg ha^{-1}), and potassium (153.33 – 167.54 kg ha^{-1}).

Experimental Details

The experiment was laid out in a Randomized Block Design (RBD) with six treatments and five replications, resulting in 30 experimental plots. Each plot measured 6 m × 6 m (36 m^2) with 1 m buffer zones between adjacent plots to minimize edge effects and inter-plot interference. The bamboo component consisted of five-year-old *Bambusa vulgaris*, planted in September 2019 at a spacing of 6 m × 8 m.

The six treatments comprised three bamboo-based agroforestry systems and three corresponding sole cropping systems: T1:*Bambusa vulgaris* + *Curcuma longa* L. (Turmeric var. BSR 1), T2:*Curcuma longa* L. as sole crop (Control), T3:*Bambusa vulgaris* + *Zingiber officinale*Rosc. (Ginger var. Bansi Local), T4:*Zingiber officinale*Rosc. as sole crop (Control), T5:*Bambusa vulgaris* + *Colocasia esculenta* L. (Colocasia var. Barua Sagar Local) and T6:*Colocasia esculenta* L. as sole crop (Control).

Healthy, disease-free rhizomes of Turmeric, Ginger and corms of Colocasia were procured from the Department of Horticulture, RLBCAU, Jhansi. Planting was carried out in the first week of July 2024, coinciding with the onset of monsoon rains. All crops were planted at a uniform spacing of 30 cm × 50 cm. Prior to planting; the experimental plots were prepared by deep plowing followed by harrowing and leveling. Well-decomposed farmyard manure (FYM) was incorporated at the rate of 25 t ha^{-1} two weeks before planting. Basal fertilizer application consisted of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) at the rates of 60:50:50 kg ha^{-1} for turmeric, 75:50:50 kg ha^{-1} for ginger, and 100:60:60 kg ha^{-1} for colocasia, following recommended practices (Kandiannan et al., 2011; Lebot, 2009). Nitrogen was applied in three split doses (basal, 45 days after planting, and 90 days after planting), while phosphorus and potassium were applied as basal doses. Irrigation, weed management and earthing up were done as per crop requirements. Harvesting was conducted in the first week of March 2025 (approximately 240 days after planting) when the foliage showed signs of senescence and yellowing. The rhizomes/corms were carefully excavated, cleaned, and weighed immediately after harvest to determine fresh weight and yield.

Observations Recorded

The following growth and yield parameters were recorded:

Growth parameters: - Plant height (cm): Measured from ground level to the tip of the longest leaf at 60, 120, and 180 days after sowing (DAS) from five randomly selected plants

Table 1: Plant height (cm) of turmeric, ginger, and colocasia at different growth stages (60, 120, and 180 DAS) under bamboo-based agroforestry and sole cropping systems (pooled data).

Crop	Treatment	60 DAS	120 DAS	180 DAS
Turmeric	T1 (Agroforestry)	76.15 ± 0.29	124.63 ± 0.62	129.82 ± 0.31
	T2 (Sole crop)	72.33 ± 0.26	106.86 ± 0.57	112.54 ± 0.51
Ginger	T3 (Agroforestry)	28.86 ± 0.86	42.71 ± 0.97	45.88 ± 1.27
	T4 (Sole crop)	24.64 ± 0.74	35.86 ± 0.73	38.57 ± 0.67
Colocasia	T5 (Agroforestry)	35.52 ± 0.18	65.80 ± 0.33	95.39 ± 0.23
	T6 (Sole crop)	29.47 ± 0.21	56.06 ± 0.24	81.55 ± 0.23

Note: Values are mean ± SEM (n = 5).

per plot. - Number of leaves per plant: Counted at 60, 120, and 180 DAS from the same five tagged plants.

Yield parameters: - Primary rhizome/corm weight(g plant^{-1}): Determined by weighing the primary rhizome/mother corm immediately after harvest. - Total fresh rhizome/corm weight (g plant^{-1}): Combined weight of primary rhizome/mother corm and secondary rhizomes/cormels. - Yield (t ha^{-1}): Calculated based on total fresh weight per plant and plant population per hectare.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate for Randomized Block Design using statistical software (SPSS version 26.0), and treatment effects were evaluated at the 5% level of significance ($p \leq 0.05$). Treatment means are presented as mean ± standard error of the mean (SEM) for all parameters. Pooled analysis across two consecutive years (2024 and 2025) was performed to assess treatment consistency and stability.

RESULTS AND DISCUSSION

Plant Height

Plant height is a critical indicator of vegetative growth and overall crop vigor, directly influencing photosynthetic capacity and ultimately yield potential. The results revealed significant differences in plant height among treatments across all three growth stages (60, 120, and 180 DAS) for all three crops (Table 1, Fig. 1). For turmeric, plants grown under bamboo-based agroforestry (T1) consistently exhibited significantly greater height than sole cropping (T2) across all growth stages. At 180 DAS, agroforestry turmeric attained a mean height of 129.82 cm compared to 112.54 cm in sole cropping, representing a 15.4% increase. Similarly, ginger plants under agroforestry (T3) reached 45.88 cm at 180 DAS versus 38.57 cm in sole cropping (T4), a 19.0% improvement. Colocasia demonstrated the most pronounced response, with agroforestry plants (T5) achieving 95.39 cm compared to 81.55 cm in sole cropping (T6), representing a 17.0% increase.

The superior plant height observed in agroforestry treatments can be attributed to several complementary mechanisms. First, the bamboo canopy provides partial shade that reduces photoinhibition and heat stress, particularly during the hot summer months (April-June) when temperatures frequently exceed 42°C in Bundelkhand (Wu et al., 2023). Shade-tolerant species such as turmeric, ginger, and colocasia exhibit enhanced photosynthetic efficiency under moderate shade (30-50% light reduction) compared to full sunlight, as excessive radiation can lead to photodamage and reduced carbon assimilation (Kumar et al., 2024). Second, the bamboo canopy moderates soil and air temperature, reducing evapotranspiration and maintaining more favorable moisture conditions for crop growth (Kokila et al., 2024). Third, bamboo litter contributes organic matter and nutrients to the soil, potentially enhancing nutrient availability for intercropped species (Akoto et al., 2020; Xu et al., 2023).

These findings align with previous studies demonstrating enhanced growth of understory crops in bamboo-based agroforestry systems. Dev et al. (2020) reported improved growth parameters of sesame and chickpea under *Dendrocalamusstrictus* in semi-arid central India, attributing the benefits to microclimate amelioration and reduced moisture stress. Similarly, Hani et al. (2024) observed enhanced food crop production under *Dendrocalamus asper* agroforestry systems, emphasizing the role of canopy architecture in optimizing light distribution.

NUMBER OF LEAVES PER PLANT

Leaf number is a key determinant of photosynthetic surface area and consequently influences biomass accumulation and yield. The data revealed that bamboo-based agroforestry significantly increased leaf production in all three crops compared to sole cropping (Table 2). At 180 DAS, turmeric plants under agroforestry (T1) produced 10.03 leaves compared to 7.57 leaves in sole cropping (T2), representing a 32.5% increase. Ginger exhibited 25.41 leaves under agroforestry (T3) versus 21.73 leaves in sole cropping (T4), a 16.9% improvement. Colocasia showed the most substantial relative increase, with 6.12 leaves under agroforestry (T5) compared to 5.13 leaves in sole cropping (T6), representing a 19.3% enhancement.

The enhanced leaf production in agroforestry systems reflects improved growing conditions that favor vegetative development. Reduced heat stress and more stable soil moisture under bamboo canopy create favorable conditions for leaf initiation and expansion (Wu et al., 2023; Kokila et al., 2024). Additionally, the moderated microclimate reduces leaf senescence rates, allowing plants to maintain functional photosynthetic tissue for longer periods. The observed pattern is consistent with the shade-tolerance characteristics of these crops, which have evolved mechanisms to maximize light capture under forest understory conditions through increased leaf area and chlorophyll concentration (Kumar et al., 2024).

Table 2: Number of leaves per plant of turmeric, ginger, and colocasia at different growth stages (60, 120, and 180 DAS) under bamboo-based agroforestry and sole cropping systems (pooled data).

Crop	Treatment	60 DAS	120 DAS	180 DAS
Turmeric	T1 (Agroforestry)	4.38 ± 0.02	11.96 ± 0.05	10.03 ± 0.06
	T2 (Sole crop)	3.70 ± 0.01	9.19 ± 0.05	7.57 ± 0.03
Ginger	T3 (Agroforestry)	15.52 ± 0.35	28.58 ± 0.60	25.41 ± 0.73
	T4 (Sole crop)	12.59 ± 0.57	24.23 ± 0.76	21.73 ± 1.37
Colocasia	T5 (Agroforestry)	3.77 ± 0.07	6.10 ± 0.04	6.12 ± 0.04
	T6 (Sole crop)	3.26 ± 0.04	4.96 ± 0.07	5.13 ± 0.06

Note: Values are mean ± SEM (n = 5).

Table 3: Primary rhizome/corm weight, total fresh rhizome/corm weight and yield of turmeric, ginger, and colocasia under bamboo-based agroforestry and sole cropping systems (pooled data).

Crop	Treatment	Primary rhizome/corm weight (g plant^{-1})	Total fresh rhizome/corm weight (g plant^{-1})	Yield (t ha^{-1})
Turmeric	T1 (Agroforestry)	136.61 ± 0.55	216.16 ± 0.65	8.85 ± 0.16
	T2 (Sole crop)	111.01 ± 0.36	182.79 ± 0.35	7.38 ± 0.13
Ginger	T3 (Agroforestry)	26.74 ± 1.92	90.50 ± 3.95	7.01 ± 0.11
	T4 (Sole crop)	19.86 ± 1.35	66.32 ± 1.38	6.25 ± 0.21
Colocasia	T5 (Agroforestry)	150.04 ± 1.37	530.10 ± 3.37	8.02 ± 0.09
	T6 (Sole crop)	125.32 ± 2.01	433.22 ± 4.57	6.79 ± 0.31

Note: Values are mean ± SEM (n = 5).

It is noteworthy that turmeric exhibited a decline in leaf number from 120 DAS to 180 DAS in both systems, reflecting the natural phenological progression toward reproductive maturity and rhizome bulking, during which resources are preferentially allocated to underground storage organs rather than foliage maintenance. This pattern is typical for turmeric and has been documented in previous studies (Kandiannan et al., 2011).

Primary Rhizome/Corm Weight, Total Fresh Weight, and Yield

The primary rhizome/mother corm represents the initial underground storage organ from which secondary rhizomes and cormels subsequently develop, and its weight is a useful early indicator of carbohydrate partitioning to belowground sinks. Bamboo-based agroforestry significantly enhanced primary rhizome/corm weight in all three crops compared to sole cropping (Table 3). Colocasia recorded the highest primary corm weight under agroforestry (T5), attaining 150.04 g plant^{-1} compared to 125.32 g plant^{-1} in sole cropping (T6), a 19.7% increase. Turmeric followed closely, with agroforestry plants (T1) producing 136.61 g plant^{-1} against 111.01 g plant^{-1} in sole cropping (T2), representing a 23.1% increase. Ginger recorded the lowest absolute primary rhizome weight but exhibited the greatest relative gain among the three crops, rising from 19.86 g plant^{-1} under sole cropping (T4) to 26.74 g plant^{-1} under agroforestry (T3), a substantial 34.6% increase. This disproportionately larger relative response in ginger suggests that early rhizome initiation in this crop is particularly sensitive to the ameliorated microclimate beneath the bamboo canopy, consistent with reports that ginger is highly susceptible to heat and moisture stress during the early rhizome-development phase (Kandiannan et al., 2011; Kokila et al., 2024).

A similar trend was evident for total fresh rhizome/corm weight, which includes both the primary rhizome/corm and its associated secondary rhizomes/cormels (Table 3). Colocasia again recorded by far the highest total fresh weight, with agroforestry plants (T5) producing 530.10 g plant^{-1} against 433.22 g plant^{-1} under sole cropping (T6), a 22.4% increase, reflecting the species' characteristic profuse cormel proliferation (Lebot, 2009; Onwueme, 1999). Turmeric under agroforestry (T1) attained 216.16 g plant^{-1} compared with 182.79 g plant^{-1} in sole cropping (T2), an 18.3% increase, while ginger showed the largest proportional improvement among the three crops, rising from 66.32 g plant^{-1} under sole cropping (T4) to 90.50 g plant^{-1} under agroforestry (T3), a 36.5% increase. The consistently greater relative response of ginger for both primary and total rhizome/corm weight indicates that secondary rhizome development in this crop is especially responsive to reduced heat load and improved soil moisture status under the bamboo canopy (Wu et al., 2023; Kokila et al., 2024).

Yield, the ultimate measure of crop performance and economic viability, followed the same pattern of superiority under bamboo-based agroforestry across all three crops (Table 3; Fig. 2). Turmeric recorded the highest absolute yield of 8.85 t ha^{-1} under agroforestry (T1) compared to 7.38 t ha^{-1} in sole cropping (T2), representing a substantial 19.9% increase. Colocasia yielded 8.02 t ha^{-1} under agroforestry (T5) versus 6.79 t ha^{-1} in sole cropping (T6), an 18.1% improvement. Ginger produced 7.01 t ha^{-1} under agroforestry (T3) compared to 6.25 t ha^{-1} in sole cropping (T4), representing a 12.2% increase.

The superior rhizome/corm weight and yield performance in bamboo-based agroforestry can be attributed to the cumulative effects of improved growth parameters (plant height and leaf number) and favorable microclimate conditions throughout the growing season. The bamboo canopy creates a buffered microenvironment characterized by reduced temperature extremes, lower vapor pressure deficit, and enhanced soil moisture retention - all of which are particularly beneficial in semi-arid conditions where heat and moisture stress are major yield-limiting factors (Wu et al., 2023; Kokila et al., 2024; Chichaghare et al., 2026). These results highlight the role of bamboo-based agroforestry in enhancing microclimate buffering capacity, which is particularly critical under semi-arid conditions characterized by high temperature variability and moisture stress.

The observed yield improvements are consistent with recent findings from bamboo agroforestry systems in diverse agroecological zones. Dev et al. (2020) reported enhanced productivity of sesame and chickpea under *Dendrocalamusstrictus* in semi-arid central India, attributing the benefits to improved resource-use efficiency and complementarity between tree and crop components. Akoto et al. (2020) documented significant yield increases of maize and cassava under bamboo agroforestry in Ghana, along with improvements in soil organic carbon and nutrient status. Xu et al. (2023) demonstrated enhanced yield of *Polygonatumcyrtonema* under Moso bamboo agroforestry, linked to improved soil quality and microbial activity.

The differential response among the three crops is noteworthy. Turmeric exhibited the highest absolute yield and the greatest relative yield increase (19.9%), suggesting superior adaptation to the modified microclimate under bamboo canopy. This may be related to turmeric's shade tolerance and its ability to maintain high photosynthetic rates under moderate shade conditions (Kandiannan et al., 2011; Kumar et al., 2024; Choudary et al., 2025). Colocasia, despite showing substantial yield improvement (18.1%), exhibited slightly lower relative gains than turmeric, possibly reflecting its higher moisture requirements and sensitivity to competition for soil water during the critical corm development phase (Lebot, 2009; Onwueme, 1999). Ginger, while benefiting significantly from agroforestry (12.2% increase), showed the lowest absolute yield among the three crops, consistent with its generally lower yield potential and longer maturity period.

The enhanced performance of rhizomatous crops under bamboo agroforestry also reflects favorable biophysical interactions. Bamboo's deep root system (extending 2-3 m depth) occupies a different soil profile than the shallow-rooted rhizomatous crops (primarily 0-30 cm depth), minimizing direct competition for water and nutrients while potentially facilitating hydraulic lift - the nocturnal redistribution of water from deep to shallow soil layers (Rao et al., 1998; Jose et al., 2004). Furthermore, bamboo litter decomposition contributes organic matter and nutrients, potentially enhancing soil fertility and microbial activity (Akoto et al., 2020; Xu et al., 2023).

Fig. 3 provides a comparative visualization of primary rhizome/corm weight, total fresh rhizome/corm weight, and yield across the three crops under both cropping systems. The grouped bar chart illustrates that colocasia consistently produced the largest total fresh corm weight among the three crops, while turmeric maintained the highest yield despite a comparatively lower total fresh weight, reflecting differences in moisture content and bulk density of the harvested rhizomes/corms among species. Ginger, despite recording the lowest absolute values for both rhizome/corm weight and yield, showed the most pronounced relative improvement under agroforestry across all three parameters, underscoring its high sensitivity to microclimate amelioration beneath the bamboo canopy.

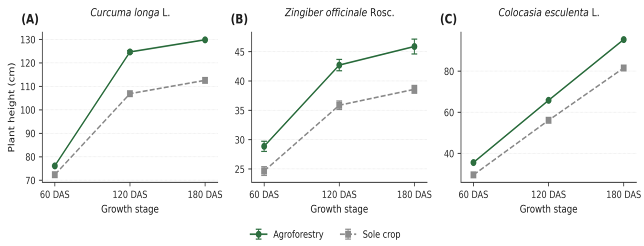

Figure 4: Plant height (cm) of turmeric (Curcuma longa L.), ginger (Zingiber officinaleRosc.), and colocasia (Colocasia esculenta L.) at different growth stages (60, 120, and 180 DAS) under bamboo-based agroforestry and sole cropping systems.

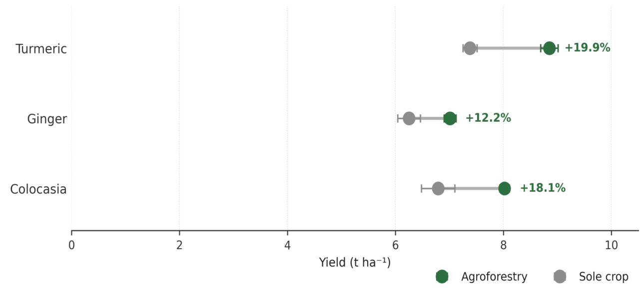

Figure 5: Yield advantage (t ha^{-1}) of bamboo-based agroforestry over sole cropping for turmeric, ginger, and colocasia. Points represent treatment means ± SEM; connecting lines indicate the magnitude of yield gain under agroforestry, with the percentage increase over sole cropping shown alongside each comparison

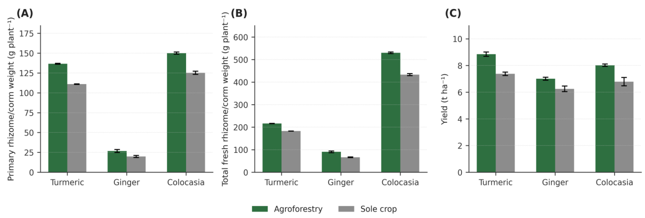

Figure 6: Comparison of rhizome/corm characteristics and yield of turmeric, ginger, and colocasia under bamboo-based agroforestry and sole cropping systems. (A) Primary rhizome/corm weight (g plant^{-1}), (B) Total fresh rhizome/corm weight (g plant^{-1}), (C) Yield (t ha^{-1}).

CONCLUSION

This study provides robust empirical evidence that *Bambusa vulgaris*-based agroforestry significantly enhances the growth and yield performance of shade-tolerant rhizomatous crops in semi-arid conditions. All three crops - turmeric, ginger, and colocasia - exhibited superior plant height, leaf production, and yield under bamboo-based agroforestry compared to sole cropping, with yield improvements ranging from 12.2% to 19.9%. Turmeric emerged as the most productive and best-adapted intercrop, achieving 8.85 t ha^{-1}

under agroforestry versus 7.38 t ha^{-1} in sole cropping. The observed benefits are attributed to favorable microclimate modification under bamboo canopy, including reduced temperature extremes, enhanced soil moisture retention, and reduced heat stress - factors that are particularly critical in semi-arid regions characterized by erratic rainfall and high evapotranspiration. The complementary resource-use patterns between bamboo and rhizomatous crops, combined with the economic value of both components, make bamboo-based agroforestry a viable and sustainable land-use strategy for the Bundelkhand region and similar semi-arid environments.

These findings have important implications for agricultural development policy and extension programs in semi-arid regions. Promotion of bamboo-based agroforestry with high-value rhizomatous crops can contribute to multiple Sustainable Development Goals, including poverty alleviation (SDG 1), food security (SDG 2), climate action (SDG 13), and life on land (SDG 15). Future research should focus on long-term system dynamics, economic analysis, carbon sequestration potential, and optimization of bamboo-crop spatial arrangements to maximize productivity and sustainability.

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