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An assessment of productivity potential, biological feasibility and economic viability of castor based relay intercropping system in Rainfed Alfisols of Karnataka

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Abstract
A field experiment was conducted at the Zonal Agricultural Research Station (ZARS), University of Agricultural Sciences, GKVK, Bengaluru during the *kharif* and *rabi* season of 2022-23 and 2023-24 to evaluate the feasibility of a castor-based relay intercropping system under rainfed alfisols of Karnataka. The experiment followed a split-plot design, comprising four main plot treatments involving different crop geometries combined with fingermillet intercropping, four subplot treatments consisting of various relay intercropping system and seven treatments under sole cropping for comparison. The study results revealed that the wider paired row planting of castor (60-240 cm x 45 cm) combined with fingermillet intercropping significantly outperformed other cropping geometries. This system recorded the highest pooled values dry matter accumulation (145.26 g $plant^{-1}$), seed yield (1442 kg ha^{-1}), stalk yield (4417 kg ha^{-1}), castor equivalent yield (2868 kg ha^{-1}), land equivalent ratio (1.88), rain water use efficiency (3.97 kg ha-mm^{-1}), system profitability (₹ 452.25 ha-day^{-1}) and net return per rupee invested (₹ 2.08 Re^{-1}) compared to narrow paired row planting (45-240 cm x 30 cm) and skipped row planting systems (120 cm x 60 cm and 90 cm x 60 cm). Interestingly, fingermillet grain and straw yield was significantly higher under skipped row planting of castor than in other geometries. In terms of relay intercropping, fieldbean relay intercropping has outperformed with significantly higher dry matter accumulation (26.41 g $plant^{-1}$) than compared to sorghum (25.40 g $plant^{-1}$), horsegram (24.16 g $plant^{-1}$) and cowpea (22.58 g $plant^{-1}$) relay intercropping system. However, in castor based relay intercropping system paired row planting of castor (60-240 cm x 45 cm) with fingermillet intercropping followed by fieldbean relay intercropping recorded the higher seed yield (1446 kg ha^{-1}), stalk yield (2636 kg ha^{-1}), castor equivalent yield (2881 kg ha^{-1}), land equivalent ratio (1.89) rain water use efficiency (3.98 kg ha-mm^{-1}), system profitability (₹ 459.98 ha-day^{-1}) and net return per rupee invested (₹ 2.17 Re^{-1}) surpassing all other relay intercropping combinations.

Keywords: Castor, relay intercropping, yield, equivalent yield and system profitability

Introduction

Climate change poses substantial challenges to agriculture by adversely affecting crop productivity, soil health and resource efficiency, especially in rainfed systems (Kabato *et al*., 2025) [10]. To address these issues, it is crucial to develop more resilient cropping systems, and intercropping emerges as a viable adaptation strategy. Intercropping is the practice of growing two or more crops together enhances spatial and temporal diversity, thereby improving resource use efficiency, strengthening agro-ecological stability, and contributing to food security and increased farm income under climate stress (Bedoussac *et al*., 2015) [2]. By combining crops with different rooting depths and growth habits, intercropping ensures more effective use of water and nutrients than monocropping. It also contributes to improved soil health, greater pest and disease resistance, and reduced reliance on external inputs. In dryland agriculture, where water scarcity and poor soil fertility prevail, selecting complementary crop combinations is essential for sustainable productivity (Kumar *et al*., 2024) [11]. One effective example is the intercropping of castor (*Ricinus communis* L.) with finger millet (*Eleusine coracana*), which demonstrates the potential of such systems to enhance resilience and resource efficiency in marginal environments.

Castor is a drought-resilient, non-edible oilseed crop valued for its high-quality oil, with India being the largest producer, particularly in states like Gujarat and Andhra Pradesh.

It is having deep rooted system allows it to access moisture from deeper soil layers, while finger millet primarily utilizes surface moisture, thereby reducing competition between the two crops (Vinay *et al*., 2021) [22]. Castor also offers partial shade, which helps lower heat stress on finger millet, while the millet suppresses weed growth and enhances ground cover. This complementary interaction enhances soil organic matter, minimizes erosion and provides diversified income sources for farmers in dryland regions. Despite these benefits, adoption among smallholders remains low due to the limited food and fodder utility of castor (Kumar and Yamanura, 2019) [12].

In Karnataka, the rainfed alfisols regions receive rainfall in two distinct periods, offering a good opportunity to grow both *kharif* and *rabi* crops. However, this potential is not fully utilized due to a lack of technical knowledge among farmers. One way to make better use of the rainfall is through relay cropping is a method where the next crop is sown before the first one is harvested. This technique helps make full use of the soil moisture and rainfall. Legumes are especially suitable for relay cropping because they improve soil fertility by fixing nitrogen, help control weeds and make the best use of land. When short-duration legumes are grown during the late *kharif* season, they can increase the overall productivity of the system by providing both grains for food and fodder for livestock, which are essential for smallholding farmers.

Combining cropping geometry and relay intercropping cropping practices offers a low-cost, eco-friendly solution that improves farm sustainability and resilience. To explore the effectiveness of this approach, a study titled “studies on feasibility of castor-based relay intercropping system under rainfed alfisols” was carried out at the Zonal Agricultural Research Station (ZARS), GKVK, Bangalore during 2022-2024 under rainfed conditions.

Materials and Methods

The field experiment was carried out at the castor research unit (K_7) located within the Zonal Agricultural Research Station (ZARS) of the University of Agricultural Sciences (UAS), at GKVK, Bengaluru. This area falls under the Eastern Dry Zone (Zone V) of Karnataka and is situated at 12°58' N latitude, 77°35' E longitude and 930 meters above sea level. During the crop growing periods, the experimental site has received 1013.6 mm of rainfall in 2022-23 cropping season and 557.8 mm in 2023-24 cropping season. The soil at the experimental site is red sandy loam, classified under the alfisols group. It was slightly acidic (pH 6.25), had low organic carbon content (0.33%), and an electrical conductivity of 0.33 dS m^{-1}, indicating non-saline conditions. The initial fertility of the soil was low in nitrogen (256.72 kg ha^{-1}), medium in phosphorus (42.69 kg ha^{-1}), and medium in potassium (284.53 kg ha^{-1}).

This study aimed to assess the practicality and performance of castor-based relay intercropping systems under rainfed conditions in Alfisols of Karnataka, conducted during both the kharif and rabi seasons of 2022-23 and 2023-24. The experiment was conducted using a split-plot design to study different cropping systems. It includes four main treatments based on different cropping geometry of castor and intercropping it with fingermillet *i.e*., G_1: Paired row planting (60-240 cm x 45 cm) + fingermillet intercropping, G_2: Paired row planting (45-240 cm x 30 cm) + fingermillet intercropping, G_3: Skipped row planting (120 cm x 60 cm) + fingermillet intercropping and G_4: Skipped row planting (90 cm x 60 cm) + fingermillet intercropping and each of these main treatments was combined with four types of relay intercrops *i.e*., I_1: Fieldbean, I_2: Horse gram, I_3: Cowpea and I_4: Sorghum, this resulted in 16 combinations of relay intercropping systems. Additionally, for comparison and to calculate the benefits of relay intercropping system, the following sole crops were also grown *i.e*., C_1: Sole castor (90 cm x 60 cm), C_2: Sole castor (120 cm x 60 cm), C_3: Sole fingermillet, C_4: Sole fieldbean, C_5: Sole horse gram, C_6: Sole cowpea and C_7: Sole sorghum, however, G_4 treatment is the recommended package of practice for castor by UAS, Bengaluru.

The castor hybrid ICH 66 was planted using specific crop spacing methods followed in geometry treatments, with a seed rate of 5 kg per hectare and a sowing depth of 4 to 5 cm. At the same time, fingermillet (variety GPU-66) was intercropped between the castor rows at a spacing of 30 cm x 10 cm, also using 5 kg of seed per hectare. After harvesting the fingermillet, four different relay intercrops (Fieldbean: Hebbal avare-4; Horsegram: CRIDA-18R; Cowpea: C-152 and Sorghum: Nirmal NSRR-259) were sown with minimal soil disturbance. Fertilizers were applied according to each crop's requirement using urea, single super phosphate, and muriate of potash to supply nitrogen (N), phosphorus (P) and potassium (K), respectively. Half of the required nitrogen and the full dose of phosphorus and potassium were applied at sowing, while the remaining nitrogen was split into two equal doses and applied later at 30 and 60 days after sowing (DAS). Recommended dose of fertilizers used for castor: 45:45:25, fingermillet: 50:40:25, fieldbean: 25:50:25, horsegram: 25:50:25, cowpea: 25:50:25 and sorghum: 50:25:25 kg ha^{-1} NPK. Regular field management practices such as thinning, gap filling, weeding, pest and disease control were carried out as needed to ensure healthy crop growth.

Biometric observations on growth and yield attributes parameters were recorded from five plants of each net plot on randomly selected plants. The dry matter production per plant was recorded at harvest, where five plants from each plot as per the treatments was uprooted from the net plot area and shade dried for three days. After shade drying the plant was oven dried at 60-65° C to achieve a constant weight, after the 14 hours drying period. After cooling, the plant samples were weighed and total dry matter production was expressed as g per plant. Data related to yield was recorded at the time of harvest of the crop. The plants from the net plot were harvested and threshed separately and the grain and straw yield were recorded and expressed on hectare basis. For the assessment of castor equivalent yield (CEY), the yield of intercrop was converted into castor seed yield on the basis of prevailing market prices (₹ ha^{-1}) with below formula.

$$\text{Castor equivalent yield} = \frac{\text{Yab x Pa}}{\text{Pa}} + \frac{\text{Yba x Pb}}{\text{Pb}}$$

Where,

Y_{ab} and Y_{ba} = The yields of castor and intercrop, respectively in intercropping system

P_a and P_b = Market value of castor and intercrop yield, respectively

Land equivalent ratio quantifies the relative land area required for sole cropping system to produce the same yield as that obtained from a given area of intercropping system. The LER was worked out by using the following formula given by Willey and Osiru (1972) [23] is given below.

LER = La + Lb

$$\text{LER} = \frac{\text{Yab}}{\text{Yaa}} + \frac{\text{Yab}}{\text{Ybb}}$$

Where,
L_a and L_b = Land equivalent ratio of castor and intercrop, respectively
Y_{aa} and Y_{ab} are yields of the main crop in sole stand and intercropping, respectively
Y_{bb} and Y_{ba} are the yield of intercrop in sole stand and intercropping, respectively

Rain water use efficiency is the amount of dry matter that can be produced from a rainfall received during cropping season. It was worked out by the ratio of the yield of individual crop and total rainfall received. RWUE is expressed in kg ha-mm^{-1}.

$$\text{RWUE} = \frac{\text{System yield (kg ha}^{-1})}{\text{Total amount of rainfall (mm) received during cropping season}}$$

System profitability calculates the average daily profit generated per hectare of land for the entire duration of the cropping system. System profitability was calculated based on below formula and it is expressed in terms of ₹ ha-day^{-1}.

$$\text{System profitability (SP)} = \frac{\text{Net returns (₹ ha}^{-1})}{\text{Duration of cropping system (Days)}}$$

Net returns per rupee invested is an essentially economic indices to calculates the return on investment for the treatment. It tells you how much net profit you get for every rupee invested in that particular treatment. It is expressed in terms of ₹ Rupee^{-1}.

$$\text{Net returns per rupee invested (NRRI)} = \frac{\text{Net profit (₹)}}{\text{Cost of cultivation (Rupee)}}$$

The statistical analysis of the data generated for various parameters during the investigation was carried out following the procedure of split-plot design described by Panse and Sukhatme (1985) [15]. The variances of different sources of variation in ANOVA were tested by the 'F' test and compared with the value of table 'F' at a 5 percent (P=0.05) level of significance. The mean values of main plot, sub-plot and highest order interaction effects were separately subjected to Duncan's Multiple Range Test (DMRT) using the corresponding error mean sum of squares and degrees of freedom values under OPSTAT program.

Results and Discussion

Dry matter accumulation

The effect of different cropping geometries on dry matter accumulation at harvest showed significant variation in castor but was less pronounced in fingermillet and relay intercrops. Among the treatments, G_1 recorded the highest dry matter accumulation in castor (145.26 g plant^{-1}), followed closely by G_4 (137.09 g plant^{-1}) and G_2 (133.70 g plant^{-1}), while G_3 recorded the lowest (117.95 g plant^{-1}). For fingermillet, the values were relatively similar across geometries, ranging from 44.85 to 46.33 g plant^{-1}, with no significant differences. In the case of relay intercrops, all treatments had comparable values, though G_3 (25.14 g plant^{-1}) and G_4 (25.08 g plant^{-1}) showed slightly higher dry matter accumulation than G_1 and G_2. Overall, G_1 proved to be the most beneficial for castor biomass accumulation.
The influence of relay cropping systems on dry matter accumulation was not statistically significant for castor and fingermillet but showed noticeable variation among relay intercrops. Castor dry matter ranged narrowly between 132.81 and 134.26 g plant^{-1} across all intercropping systems (I_1 to I_4), and fingermillet also exhibited uniform accumulation (45.36 to 45.78 g plant^{-1}). However, for relay intercrops, I_1 recorded the highest dry matter (26.41 g plant^{-1}), significantly outperforming I_3 (22.58 g plant^{-1}) and I_4 (25.40 g plant^{-1}), while I_2 (24.16 g plant^{-1}) was intermediate. Thus, I_1 was more favorable for relay intercrop growth.
Interaction effects between cropping geometry and intercropping systems revealed noticeable variations in dry matter accumulation, particularly in castor and relay intercrops. The combination G_1 fb I_3 (150.05 g plant^{-1}) and G_1 fb I_1 (149.89 g plant^{-1}) showed the highest dry matter in castor, indicating a strong positive interaction. Conversely, G_3 combinations resulted in the lowest castor dry matter, particularly G_3 fb I_2 and G_3 fb I_3, both around 114-115 g plant^{-1}. For relay intercrops, the maximum dry matter was observed in G_3 fb I_1 (29.02 g plant^{-1}) and G_4 fb I_2 (28.74 g plant^{-1}), while the lowest was recorded under G_3 fb I_4 (20.16 g plant^{-1}). Despite consistent fingermillet values across treatments, this interaction clearly influenced castor and intercrop biomass.
Sole cropping treatments showed distinctly higher dry matter accumulation compared to intercropped systems. Castor under sole cropping (C_1 and C_2) recorded the highest values, with C_2 (171.65 g plant^{-1}) significantly surpassing all other treatments, followed by C_1 (160.32 g plant^{-1}). For fingermillet, sole cropping (C_3) resulted in 47.90 g plant^{-1}, slightly higher than the intercropped treatments. Among the relay intercrops, C_4 through C_7 displayed dry matter values ranging from 27.28 to 30.07 g plant^{-1}, all were higher than most intercropping treatments. This indicates that while intercropping supports crop diversity, sole cropping provides superior dry matter accumulation for individual crops, especially castor.
Increase in dry matter production of castor (Table 1) was with increased spacing. This might be due to availability of more feeding area per plant, reduced inter and intra plant competition for space and nutrients, reduced mutual shading thereby increasing plant spread, number of leaves plant^{-1} and its photosynthetic surface area ultimately adding to the dry matter of an individual plant. These results are in accordance with the findings of Parmar *et al*., 2018 [16]. The significantly higher dry matter production was found with sole cropping of castor compared to intercropping system. The less accumulation of dry matter in intercropping systems might be due to suppression in the castor growth because of poor nutrient availability and competition with component crops which might have smothered the castor growth in intercropping. These results were supporting by the research finding of Veeramani *et al*. (2024) [21] and Desai *et al*. (2022) [3]. The dry matter accumulation per hill of fingermillet (Table 1) was found to be non-significant on

cropping geometry and relay intercropping system. This might be due to fingermillet crop was sown at same spacing in all four cropping geometries and the relay crops were sown after harvest of the fingermillet. Hence both cropping geometry and relay intercropping has no significant influence on the growth and development of finger millet. These results also corroborate the earlier finding of Vaghasia *et al*. (2016) [19] and Ghilotia *et al*. (2019) [8]. Significantly higher dry matter accumulation (Table 1) was noticed in sole cropping system compared to intercropping system. This indicates that there was less intra-specific competition, more availability of nutrients and better utilization of sun light in the sole cropping system. Among intercropping treatments, competition from its neighboring crops at all growth stages of crop was observed for all resources. The results are in conformity with the findings in castor based intercropping systems Gangadhar *et al*. (2023) [5].

Yield of castor and component crops

Cropping geometry had a significant influence on both the economic and biological yields of castor and fingermillet. Among the four geometries tested, G_1 (Paired row 60-240 cm x 45 cm) recorded the highest castor seed yield (1442 kg ha^{-1}) and stalk yield (2628 kg ha^{-1}), though it had the lowest fingermillet grain (2408 kg ha^{-1}) and straw yield (4160 kg ha^{-1}). In contrast, G_3 (Skipped row 120 cm x 60 cm) and G_4 (Skipped row 90 cm x 60 cm) produced the highest grain yields (2641 and 2640 kg ha^{-1}, respectively) and straw yields (4582 and 4694 kg ha^{-1}, respectively), indicating their advantage for fingermillet. However, these skipped row geometries had significantly lower castor seed and stalk yields compared to paired row geometries. Overall, G_1 was superior for castor, while G_3 and G_4 favored fingermillet productivity.

Relay intercropping with different legume and cereal species showed no significant differences among treatments for either castor or fingermillet yield. All intercropping treatments (I_1-Fieldbean, I_2-Horsegram, I_3-Cowpea and I_4-Sorghum) yielded comparable castor seed yields (ranging from 1331 to 1341 kg ha^{-1}) and fingermillet grain yields (2538 to 2542 kg ha^{-1}). Similarly, the stalk and straw yields followed the same trend, with no statistically significant variation. These results suggest that the choice of relay crop among the tested species did not significantly influence yield performance in this intercropping setup.

The interaction between crop geometry and relay cropping systems showed notable differences in yield outcomes. The highest castor seed yield within the interaction was recorded in G_1 with I_1 (Fieldbean), G_1 with I_2 (Horsegram) and G_1 with I_4 (Sorghum), all producing over 1440 kg ha^{-1}. Conversely, the lowest yields were recorded in G_3-based combinations, such as G_3 with I_2 (1237 kg ha^{-1}). Fingermillet grain yield was consistently higher in skipped row systems (G_3 and G_4), with G_4 with I_2 (2650 kg ha^{-1}) and G_3 with I_3 (2646 kg ha^{-1}) were performed better than all other combinations. However, the higher straw yield was observed under G_4 with I_1 and I_2 combinations, yields exceeding 4700 kg ha^{-1}. The interaction data highlight that specific combinations of geometry and relay crops can optimize either castor or fingermillet yield, depending on the target crop.

In the control plots, sole castor planted at 90 cm x 60 cm (C_1) recorded the highest castor seed yield (1477 kg ha^{-1}) and stalk yield (2777 kg ha^{-1}), outperforming both intercropped castor and the 120 cm x 60 cm sole castor geometry (C_2). In contrast, sole fingermillet (C_3) recorded the highest grain (2671 kg ha^{-1}) and straw yield (4790 kg ha^{-1}), surpassing all intercropped treatments. These findings confirm that sole cropping maximized the productivity of each crop individually, though intercropping offers potential benefits in terms of land-use efficiency and system productivity.

Castor grown under paired row planting (60-240 cm x 45cm) has recorded significantly higher seed and stalk (Table 2) compared to other planting geometries. This might be due to reflection of high yield attributing characters usually achieved well under optimum availability of space, light, nutrients and moisture, where competition within the crop plants was minimum. Closer plant geometry might have increased competition within the crop plant which resulted in poor growth *i.e*. dry matter accumulation per plant that decreased the seed, stalk and biological yield. Current results are strongly supported by the earlier findings of the scientists Gangadhar *et al*. (2022) and Aruna and Chandrika *et al*. (2023) [1]. Maximum seed, stalk and biological yield was observed with sole castor compared to castor based intercropping system, may be due to production of more dry matter, yield attributes and effective translocation of photosynthates from source to sink resulting in maximum yield. These results corroborate with the findings of Mudalagiriyappa *et al*. (2011) [13] and Veeramani *et al*. (2024) [21]. Fingermillet yield (grain and straw) presented in Table 2 was significantly influenced by different cropping geometry and relay intercropping system of castor. Sole cultivation of fingermillet outperformed over intercropping system. This might be due to less competition which was observed for all resources (space, water, light and nutrients) compared to intercropping system. Among different cropping geometry, skipped row planting of castor produced significantly higher fingermillet yield over paired row planting of castor, this was due to higher plant population of fingermillet, which reflects in the higher grain yield production per area compared to paired row planting due to less plant population. The results are in accordance with the findings of Gangadhar *et al*. (2023) and Ikeh *et al*. (2024) [5, 9].

System productivity

The influence of crop geometry on castor equivalent yield, land equivalent ratio (LER) and rain water use efficiency (RWUE) showed significant variation among the treatments. Paired row geometry (G_1: 60-240 cm x 45 cm) resulted in the highest castor equivalent yield of 2868 kg ha^{-1}, the highest LER of 1.88 and the highest RWUE of 3.97 kg ha-mm^{-1}, all statistically superior to other geometries. G_2 (45-240 cm x 30 cm) and G_4 (Skipped row 90 cm x 60 cm) showed moderate performance, while G_3 (Skipped row 120 cm x 60 cm) had the lowest castor equivalent yield (2805 kg ha^{-1}), LER (1.83) and RWUE (3.88). However, despite some numerical differences, LER values across all geometries remained statistically similar, indicating efficient land use regardless of geometry. Overall, paired row geometry (G_1) was superior in optimizing yield and resource use.

The relay intercropping systems (I_1: Fieldbean, I_2: Horsegram, I_3: Cowpea, I_4: Sorghum) demonstrated very similar results in terms of castor equivalent yield, LER and RWUE. All relay crops recorded nearly equal castor equivalent yields (~2836 to 2845 kg ha^{-1}), identical LER values of 1.85 to 1.86 and RWUE of about 3.93 kg ha-mm^{-1}. There were no significant differences among the relay crops for any of the parameters, suggesting that all four relay crops were equally effective when intercropped with castor under the given conditions.

The interaction between crop geometry and relay cropping revealed that the combination of paired row geometry with fieldbean (G_1 fb I_1) produced the highest castor equivalent yield (2881 kg ha^{-1}), LER (1.89) and RWUE (3.98), indicating a synergistic effect. Other interactions involving G_1 with different relay crops also showed relatively higher values compared to other geometry fb relay crop combinations. Conversely, the skipped row geometry (G_3) with any relay crop recorded the lowest yields, LER and RWUE values. Although variations existed among interaction treatments, LER values remained statistically similar, reflecting consistent land-use efficiency. These results highlight that geometry and relay cropping combinations can influence yield and resource use efficiency, with paired rows and fieldbean being the most beneficial combination.

Sole castor cropping treatments (C_1: 90 cm x 60 cm and C_2: 120 cm x 60 cm) recorded the lowest castor equivalent yields (1477 and 1404 kg ha^{-1}, respectively), with LER fixed at 1.00 as expected for sole crops and the lowest RWUE values (2.00 and 1.91 kg ha-mm^{-1}, respectively). These values were significantly lower than those observed in intercropping systems, emphasizing the advantages of relay intercropping and optimized crop geometry in enhancing productivity, land use efficiency and water use efficiency in castor cultivation.

The castor equivalent yield, land equivalent ratio and rain water use efficiency showed significantly difference due to different relay intercropping systems and varied cropping geometry of castor. Apart from the competitive effects, prevailing prices of economic produce become an additional factor in choosing the intercropping system and yield of intercrops were converted to equivalent yield and added to castor yield. Castor equivalent yield, land equivalent ratio and rain water use efficiency was significantly higher in paired row planting (60-240 cm x 45 cm) with fingermillet intercropping followedby fieldbean relay intercropping system over sole castor and other intercropping systems which due to higher biomass production and efficient use of available resources under paired row planting system and also high price along with higher yield of intercrops as well as less reduction of castor seed yield in this intercropping system. Similar results were also reported in castor intercropping systems under rainfed condition (Ramachandrappa *et al*., 2016 [17] and Thanunathan *et al*., 2008) [18]. Veeramani *et al*. (2024) [21] revealed that castor equivalent yield was significantly greater in castor + groundnut (1:3) than in sole castor system.

Economics: The effect of different crop geometries on system profitability and net returns per rupee invested showed significant variation. Among the cropping geometries tested, G_1 (Paired Row 60-240 cm x 45 cm) recorded the highest system profitability of ₹ 452.25 ha-day^{-1} and the highest net returns of ₹ 2.08 per rupee invested. This was followed by G_3 (Skipped Row 120 cm x 60 cm) and G_4 (Skipped Row 90 cm x 60 cm), with profitability values of ₹430.98 and ₹429.76 ha-day^{-1}, respectively and returns of ₹1.93 and ₹1.85 per rupee invested, respectively. G_2 (Paired Row 45-240 cm x 30 cm) exhibited the lowest profitability (₹ 417.85 ha-day^{-1}) and net returns (₹ 1.70 per rupee). The differences in profitability among geometries were statistically significant, indicating that the spatial arrangement of castor rows influences economic outcomes.

Relay cropping systems (I_1: Fieldbean, I_2: Horsegram, I_3: Cowpea and I_4: Sorghum) showed relatively similar system profitability and net returns. Fieldbean (I_1) had the highest profitability at ₹ 437.32 ha-day^{-1} and the best net returns of ₹ 1.95 per rupee invested, closely followed by Horsegram (I_2) and Sorghum (I_4), which showed profitability values of ₹ 434.69 and ₹ 433.22 ha-day^{-1}, respectively, and net returns around ₹ 1.88 to ₹ 1.91 per rupee, respectively. Cowpea (I_3) had the lowest profitability at ₹ 425.62 ha-day^{-1} and net returns of ₹ 1.81 per rupee. However, these differences were not statistically significant, suggesting that the choice of relay crop has a limited impact on profitability compared to cropping geometry.

The interaction effects between cropping geometry and relay crops revealed that the combination of G_1 (Paired Row 60-240 cm x 45 cm) with Fieldbean (I_1) resulted in the highest system profitability (₹ 459.98 ha-day^{-1}) and net returns (₹ 2.17 per rupee invested). Other combinations involving G_1 with relay crops also performed well, with profitability exceeding ₹ 446 ha-day^{-1} and net returns above ₹ 2.00 per rupee. In contrast, the combinations involving G_2 generally showed the lowest profitability and returns, with values ranging from ₹ 411.49 to ₹ 421.24 ha-day^{-1} and net returns between ₹ 1.64 to ₹ 1.74 per rupee. Combinations with G_3 and G_4 had intermediate profitability and returns. These interaction results underscore that the most profitable system is the paired row geometry combined with fieldbean relay cropping.

Sole castor cropping systems (C_1: 90 cm x 60 cm and C_2: 120 cm x 60 cm) recorded the lowest system profitability and net returns. C_1 and C_2 yielded profitability of ₹ 186.15 and ₹ 180.99 ha-day^{-1}, respectively and net returns per rupee invested of ₹ 1.17 and ₹ 1.23, respectively. These values were significantly lower than all intercropping treatments, indicating that relay intercropping and optimized crop geometry substantially improve economic returns compared to sole cropping of castor.

The system profitability and net returns per rupee invested (Table 4) were significantly influenced by cropping geometry and relay intercropping over castor sole cropping system. Paired row planting (60-240 cm x 45 cm) of castor + fingermillet intercropping followedby fieldbean relay intercropping system found significantly higher system profitability over sole and other intercropping systems. The higher net returns incurred due to increase production of economic yield by both component and castor crops with higher market price resulted in higher system profitability. The results are in conformity with those of Veeramani *et al*. (2022), Nalini *et al*. (2023) and Gangadhar *et al*. (2024) [4, 14, 20].

Table 1: Effect of cropping geometry and relay intercropping on pooled dry matter accumulation at harvest (g plant^{-1}) of castor, fingermillet and relay intercrops

Treatments	Castor	Fingermillet	Relay intercrop
Main plot: Cropping geometry (G) + fingermillet intercropping			
G_1: Paired Row (60-240 cm x 45 cm)	145.26^{a}	46.01^{a}	24.26^{a}
G_2: Paired Row (45-240 cm x 30 cm)	133.70^{b}	46.33^{a}	24.07^{a}
G_3: Skipped Row (120 cm x 60 cm)	117.95^{c}	44.85^{a}	25.14^{a}
G_4: Skipped Row (90 cm x 60cm)	137.09^{a}	45.31^{a}	25.08^{a}
S.Em±	3.88	1.52	1.03
Sub plot: Relay cropping (I)			
I_1: Fieldbean	133.96^{a}	45.36^{a}	26.41^{a}
I_2: Horsegram	132.81^{a}	45.78^{a}	24.16^{ab}
I_3: Cowpea	134.26^{a}	45.78^{a}	22.58^{b}
I_4: Sorghum	132.97^{a}	45.59^{a}	25.40^{b}
S.Em±	4.74	1.13	1.19
Interaction: (GxI)			
G_1 fb I_1	149.89^{c}	45.50^{a}	23.81^{b-d}
G_1 fb I_2	144.34^{d}	46.82^{a}	24.81^{a-d}
G_1 fb I_3	150.05^{c}	45.52^{a}	25.65^{a-d}
G_1 fb I_4	136.77^{ef}	46.19^{a}	22.03^{cd}
G_2 fb I_1	135.49^{ef}	46.00^{a}	27.45^{a-c}
G_2 fb I_2	133.14^{f}	47.06^{a}	23.76^{b-d}
G_2 fb I_3	132.22^{f}	46.76^{a}	23.57^{b-d}
G_2 fb I_4	133.93^{f}	45.52^{a}	25.76^{a-d}
G_3 fb I_1	117.68^{h}	44.71^{a}	29.02^{ab}
G_3 fb I_2	113.99^{h}	44.21^{a}	24.29^{b-d}
G_3 fb I_3	115.42^{h}	45.07^{a}	23.57^{b-d}
G_3 fb I_4	124.70^{g}	45.42^{a}	20.16^{d}
G_4 fb I_1	132.78^{f}	45.23^{a}	25.34^{a-d}
G_4 fb I_2	139.75^{de}	45.02^{a}	28.74^{ab}
G_4 fb I_3	139.34^{de}	45.76^{a}	23.85^{b-d}
G_4 fb I_4	136.48^{ef}	45.24^{a}	22.39^{cd}
S.Em±	9.48	2.27	2.38
Control plots: (C)			
C_1: Sole castor (90 cm x 60 cm)	160.32^{b}		2777^{a}
C_2: Sole castor (120 cm x 60 cm)	171.65^{a}		2632^{cd}
C_3: Sole fingermillet		47.90^{a}	
C_4: Sole fieldbean			30.07^{a}
C_5: Sole horsegram			27.28^{a-c}
C_6: Sole cowpea			28.49^{ab}
C_7: Sole sorghum			28.04^{ab}
S.Em±	8.61	2.38	7.9

Table 2: Effect of castor and fingermillet pooled economic and biological yield on cropping geometry and relay intercropping Systems

Treatments	Economic yield (kg ha^{-1})		Biological yield (kg ha^{-1})	
	Seed yield	**Grain yield**	**Stalk yield**	**Straw yield**
Main plot: Cropping geometry (G) + fingermillet intercropping				
G_1: Paired Row (60-240 cm x 45 cm)	1442^{a}	2408^{c}	2628^{a}	4160^{d}
G_2: Paired Row (45-240 cm x 30 cm)	1381^{b}	2469^{b}	2517^{b}	4237^{c}
G_3: Skipped Row (120 cm x 60 cm)	1241^{d}	2641^{a}	2204^{d}	4582^{b}
G_4: Skipped Row (90 cm x 60cm)	1276^{c}	2640^{a}	2307^{c}	4694^{a}
S.Em±	10	59	24	40
Sub plot: Relay cropping (I)				
I_1: Fieldbean	1333^{a}	2539^{a}	2408^{a}	4428^{a}
I_2: Horsegram	1337^{a}	2538^{a}	2432^{a}	4437^{a}
I_3: Cowpea	1331^{a}	2542^{a}	2405^{a}	4363^{a}
I_4: Sorghum	1341^{a}	2540^{a}	2411^{a}	4444^{a}
S.Em±	25	48	76	35
Interaction: (GxI)				
G_1 fb I_1	1446^{b}	2422^{f}	2636^{c}	4221^{h}
G_1 fb I_2	1445^{b}	2391^{g}	2663^{b}	4111^{l}
G_1 fb I_3	1435^{b}	2412^{f}	2615de	4184^{k}
G_1 fb I_4	1443^{b}	2406^{fg}	2599^{e}	4124^{l}
G_2 fb I_1	1372^{e}	2462^{e}	2484^{h}	4213^{hi}
G_2 fb I_2	1391^{d}	2467de	2536^{g}	4201^{ij}
G_2 fb I_3	1375^{e}	2466de	2485^{h}	4192^{jk}
G_2 fb I_4	1388^{d}	2483^{d}	2564^{f}	4342^{g}
G_3 fb I_1	1248^{h}	2642^{bc}	2248^{l}	4488^{f}
G_3 fb I_2	1237^{h}	2643^{bc}	2210^{m}	4712^{b}
G_3 fb I_3	1241^{h}	2646^{bc}	2163^{n}	4502^{f}
G_3 fb I_4	1240^{h}	2635^{bc}	2194^{m}	4625^{d}
G_4 fb I_1	1267^{g}	2630^{c}	2265^{l}	4792^{a}
G_4 fb I_2	1273^{g}	2650^{b}	2318^{j}	4725^{b}
G_4 fb I_3	1273^{g}	2646^{bc}	2357^{i}	4576^{e}
G_4 fb I_4	1292^{f}	2635^{bc}	2287^{k}	4685^{c}
S.Em±	51	96	152	71
Control plots: (C)				
C_1: Sole castor (90 cm x 60 cm)	1477^{a}	-	2777^{a}	-
C_2: Sole castor (120 cm x 60 cm)	1404^{c}	-	2632^{cd}	-
C_3: Sole fingermillet	-	2671^{a}	-	4790^{a}
S.Em±	43	98	130	71

Table 3: Influence of crop geometry and relay intercropping on pooled castor equivalent ratio (kg ha^{-1}), land equivalent ratio and rain water use efficiency (kg ha-mm^{-1})

Treatments	Castor equivalent yield	Land equivalent ratio	Rain water use efficiency
Main plot: Cropping geometry (G) + fingermillet intercropping			
G_1: Paired Row (60-240 cm x 45 cm)	2868^{a}	1.88^{a}	3.97^{a}
G_2: Paired Row (45-240 cm x 30 cm)	2844^{b}	1.86^{a}	3.94^{a}
G_3: Skipped Row (120 cm x 60 cm)	2805^{c}	1.83^{a}	3.88^{a}
G_4: Skipped Row (90 cm x 60cm)	2840^{b}	1.85^{a}	3.93^{a}
S.Em±	29	0.02	0.04
Sub plot: Relay cropping (I)			
I_1: Fieldbean	2837^{a}	1.85^{a}	3.93^{a}
I_2: Horsegram	2839^{a}	1.85^{a}	3.93^{a}
I_3: Cowpea	2836^{a}	1.85^{a}	3.93^{a}
I_4: Sorghum	2845^{a}	1.86^{a}	3.93^{a}
S.Em±	31	0.02	0.05
Interaction: (GxI)			
G_1 fb I_1	2881^{a}	1.89^{a}	3.98^{a}
G_1 fb I_2	2861^{bc}	1.87^{a}	3.95^{a}
G_1 fb I_3	2863^{bc}	1.87^{a}	3.96^{a}
G_1 fb I_4	2868^{b}	1.88^{a}	3.96^{a}
G_2 fb I_1	2831^{fg}	1.85^{a}	3.93^{a}
G_2 fb I_2	2852^{c-e}	1.87^{a}	3.94^{a}
G_2 fb I_3	2835^{fg}	1.85^{a}	3.94^{a}
G_2 fb I_4	2858^{bc}	1.87^{a}	3.95^{a}
G_3 fb I_1	2812^{hi}	1.83^{a}	3.89^{a}
G_3 fb I_2	2801^{i}	1.83^{a}	3.87^{a}
G_3 fb I_3	2807^{i}	1.83^{a}	3.88^{a}
G_3 fb I_4	2800^{i}	1.83^{a}	3.87^{a}
G_4 fb I_1	2824^{gh}	1.84^{a}	3.92^{a}
G_4 fb I_2	2842^{d-f}	1.85^{a}	3.93^{a}
G_4 fb I_3	2839^{ef}	1.85^{a}	3.93^{a}
G_4 fb I_4	2853^{cd}	1.86^{a}	3.95^{a}
S.Em±	63	0.04	0.09
Control plots: (C)			
C_1: Sole castor (90 cm x 60 cm)	1477^{j}	1.00^{b}	2.00^{b}
C_2: Sole castor (120 cm x 60 cm)	1404^{k}	1.00^{b}	1.91^{b}
S.Em±	58	0.04	0.08

Table 4: Effect of pooled system profitability and net returns per rupee invested of different crop geometry and relay intercropping systems

Treatments	System profitability (₹ ha-day^{-1})	Net returns per rupee invested (₹ Re^{-1})
Main plot: Cropping geometry (G) + fingermillet intercropping		
G_1: Paired Row (60-240 cm x 45 cm)	452.25^{a}	2.08^{a}
G_2: Paired Row (45-240 cm x 30 cm)	417.85^{c}	1.70^{a}
G_3: Skipped Row (120 cm x 60 cm)	430.98^{b}	1.93^{a}
G_4: Skipped Row (90 cm x 60cm)	429.76^{b}	1.85^{a}
S.Em±	6.8	0.03
Sub plot: Relay cropping (I)		
I_1: Fieldbean	437.32^{a}	1.95^{a}
I_2: Horsegram	434.69^{a}	1.91^{a}
I_3: Cowpea	425.62^{a}	1.81^{a}
I_4: Sorghum	433.22^{a}	1.88^{a}
S.Em±	7.33	0.05
Interaction: (GxI)		
G_1 fb I_1	459.98^{a}	2.17^{a}
G_1 fb I_2	452.19^{b}	2.10^{a}
G_1 fb I_3	446.32^{b}	2.01^{a}
G_1 fb I_4	450.52^{b}	2.06^{a}
G_2 fb I_1	419.19^{g}	1.74^{ab}
G_2 fb I_2	421.24^{fg}	1.72^{a-c}
G_2 fb I_3	411.49^{h}	1.64^{a-c}
G_2 fb I_4	419.50^{g}	1.69^{a-c}
G_3 fb I_1	437.20^{c}	1.99^{a}
G_3 fb I_2	431.43^{c-e}	1.94^{a}
G_3 fb I_3	426.59^{ef}	1.87^{a}
G_3 fb I_4	428.71^{de}	1.91^{a}
G_4 fb I_1	432.90^{c-e}	1.91^{a}
G_4 fb I_2	433.89^{cd}	1.89^{a}
G_4 fb I_3	418.09^{g}	1.71^{a-c}
G_4 fb I_4	434.17^{cd}	1.87^{a}
S.Em±	14.66	0.1
Control plots: (C)		
C_1: Sole castor (90 cm x 60 cm)	186.15^{i}	1.17^{c}
C_2: Sole castor (120 cm x 60 cm)	180.99^{i}	1.23^{bc}
S.Em±	13.58	0.08

Conclusion

1. Castor sown under wider paired row planting (60-240 cm x 45 cm) with fingermillet intercropping was recorded significantly higher dry matter accumulation, castor yield, castor equivalent yield, land equivalent ratio, water use efficiency, system profitability and net returns obtained compared to other geometries.
2. Fingermillet sown under skipped row panting of castor with fingermillet intercropping has found significantly higher grain and straw yield compared to paired row cultivation of castor.
3. Fieldbean cultivation as relay intercropping with wider paired row planting of castor (60-240 cm x 45 cm) with fingermillet intercropping has significantly improved dry matter accumulation of all crops (castor, fingermillet and fieldbean), castor yield, fingermillet yield, castor equivalent yield, land equivalent ratio, water use efficiency, system profitability and net returns obtained compared to other geometries.

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