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Influence of *Eucalyptus* Agroforestry on Crop Yields, Soil Properties, and System Economics in Southern Regions of India

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Abstract: Agroforestry benefits farmers, making it a sustainable alternative to monoculture. To create a viable *Eucalyptus* clone-based agroforestry system, a field experiment was carried out in Tamil Nadu, India. The economics and changes in the soil qualities were evaluated by growing agricultural and horticultural crops, namely pearl millet, sorghum, maize, sesame, small onions, green gram, and red gram, as intercrops under eight-month-old eucalyptus clone trees using a randomised block design in three replications at a spacing of 3 m × 1.5 m. The plots for the intercrops and the eucalyptus clones were kept apart for comparison. Maize showed the greatest drop in plant height during all the phases, including 30 DAS, 60 DAS, and harvest, while small onions showed the least reduction in plant height. Sesame and small onions showed the greatest drop in dry matter production, whereas sorghum showed the least. In terms of the intercrop yield reduction, maize had the biggest reduction and green gram had the lowest. Red gram had the largest crop equivalent yield, whereas maize had the lowest. The volume of the trees was generally increased more favourably by red gram than by green gram. The intercrops had some effects on the nutrients in the soil. Red gram intercropping had the highest levels of EC, soil organic carbon, available soil nitrogen, available soil phosphorus, and available soil potassium, while the sole tree treatment had the lowest levels. Small onions, red gram, and sesame were the crops; tree + small onion, tree + red gram, and tree + sesame were the intercrop combinations with the highest gross income, net income, and B:C in the intercropping treatment alone. Tree + green gram had the highest land equivalent ratio (LER) and the red gram, sesame, and small onion intercrops were shown to be the most profitable. Although the present study supports a complementary relationship, the lack of awareness among farmers of *Eucalyptus* allelopathy formed the major limitation.

Keywords: intercrops; *Eucalyptus*; agroforestry system; economics; soil properties

1. Introduction

Eucalyptus is the second most dominant hardwood species planted after pines, occupying an area of 10 to 15 million ha throughout the world [1]. It is a native of Australia, and it was introduced into India during the early 19th century. *Eucalyptus* has emerged as one of the most favoured fast-growing tree species due to its unique adaptability to a wide range of sites and suitability for varied environmental conditions. Almost all industries in the country are in the process of establishing industrial wood plantations [2]. *Eucalyptus* is one of the most promising tree species for pulp wood production. In India, the current production of raw materials for pulp and paper is 2.76 million tonnes against a demand of 5.04 million tonnes, which shows a shortfall of 45%. The projected demand by 2020 is 13.2 million tonnes, which is still more staggering. The demand for wood-based products in Tamil Nadu is 8 to 10 lakh tonnes of wood pulp per year, which is greater than the 4 lakh tonnes that are currently available [3].

Eucalyptus is the main fast-growing tree for biomass production in the tropics, providing resources for the pulp and paper industries and bioenergy [4]. *Eucalyptus* is the most popular choice to be planted along the edges or bunds of agricultural fields, and it appears to be well incorporated and accepted in agroforestry in India [5]. However, an increase in demographic pressure has resulted in the overexploitation of resources, which has created a vast gap between the demand and supply of wood products. A shortage of industrial round wood has hampered the modernisation, growth and expansion of wood-based industries in India, resulting in increasing imports of timber, paper and wood-based products. In such circumstances, agroforestry has once again emerged as the most appropriate land use option. An agroforestry system will be more profitable than tree monoculture since the advantages of biological and economic integration are felt either immediately or after some time among its individual components. Agroforestry allows for the efficient use and management of natural resources, as it follows the principles of sustained yield. It permits increases in the total production (of preferred commodities) and productivity (of the land), reducing the risks and diversifying the cultivation by using management practices that are compatible with the cultural patterns of the local population [6].

Agroforestry systems for pulpwood production involve the growing of commercial timber species for the wood industry in an agricultural field with irrigation, fertilisers, plant management technology, etc., in a harvest cycle of 4–7 years. Agroforestry not only takes into account the use of land for forestry and agriculture but can also improve the efficacy of the utilised above- and belowground resources, which have always garnered widespread attention [7]. The combination of agricultural crops and *Eucalyptus* trees for pulpwood production can bring higher profit than pure plantings of either. The profitability of *Eucalyptus* planting by individual farmers varies with the farm gate prices and yields of the trees, which in turn depend on the quality of the site and the technology of production. In an intercropping system, the most suitable crops that could be raised profitably under clonal plantations of trees, thereby effecting the productivity of the tree crop and the associated changes in the soil fertility status, are to be thoroughly investigated for higher productivity. Intercropping boosts the soil water environment, improves the soil aggregate structure, and enhances the soil organic matter status. It changes the root exudates, improves soil nutrients, promotes soil microbes, and regulates soil diversity by controlling soil-borne diseases and restoring the ecological balance. The changes in the soil optimise resource use, reduce carbon footprints, and contribute to crop yield stability under stressful conditions. Combining trees with multiple crops further improves the soil's physical and chemical properties by bringing nutrients from deeper layers to the topsoil. The tree crop intercrops thus promote growth and development, leading to the enhanced yields and productivity of all the associated plants in a dynamic integrated system and ensuring the sustainability of multiple products, viz. food, wood, fodder, fruits, etc. The multiple production achieved through intercropping can help to reduce the score of the hunger index in India, as projected by Global Hunger Index 2022. However, detailed studies of the *Eucalyptus*-based intercropping system are very few for promotion or adoption. Hence, intensive research is needed to recommend suitable *Eucalyptus*-based tree-crop combinations for the benefit of tree-growing farmers. This study has been carried out under the hypothesis that *Eucalyptus* has a negative impact on the soil as well as intercrops due to its allelopathic nature. Therefore, the present study was undertaken to explore the prospects of successfully growing intercrops with *Eucalyptus* clones to boost the income of farmers and improve the long-term productivity, sustainability and profitability of the system in southern regions of India.

2. Materials and Methods

A field experiment was carried out with the objective of developing a suitable *Eucalyptus* clone-based agroforestry system for higher productivity.

2.1. Experimental Site

This experiment was conducted at Tamil Nadu Newsprint and Papers Limited, Kagithapuram, Karur District, Tamil Nadu, India. The field is located inside the factory premises. The factory is situated in Kagithapuram, lying at 11°02″ N latitude and 77°59″ E longitude, at an altitude of 125 m above the mean sea level. The prevailing climate in Karur is known as a hot semi-arid climate with a mean annual rainfall between 400 mm and 1300 mm. Most of the rainfall (about 70%) in the region occurs during July to September. The average temperature is 28.7 °C, ranging from a maximum of 39 °C to a minimum of 17 °C. Karur experiences significant seasonal variation in the perceived humidity. The soil in the area is red sandy loam. The vegetation in the area includes kharif and rabi crops in agricultural land; the forests comprise deciduous, evergreen and degraded forest, with the wasteland having scrub vegetation.

2.2. Experimental Design and Layout

The experiment was laid out in a randomised block design (RBD) with three replications. The size of the plot was 9 m × 9 m. The design of the experiment is given in Figure 1A,B.

Block 1							
T6	T8	T1	T4	T5	T2	T3	T7
Block 2							
T4	T8	T6	T2	T7	T3	T1	T5
Block 3							
T2	T4	T8	T3	T7	T1	T5	T6

Treatment details:			
T1	Eucalyptus + *Pennisetum glaucum* (*CO 9)	T5	Eucalyptus + *Allium cepa* (*Local)
T2	Eucalyptus + *Sorghum bicolor* (*CO(S) 28)	T6	Eucalyptus + *Vigna radiata* (*CO 6)
T3	Eucalyptus + *Zeamayz* (*COH(M) 5)	T7	Eucalyptus + *Cajanus cajan* (*CO 7)
T4	Eucalyptus + *Sesamum indicum* (*CO 1)	T8	Control (Eucalyptus)
*** Name of Variety used**			

(**A**)

Figure 1. *Cont.*

T1

***Eucalyptus* + *Pennisetum glaucum* (*CO 9)**

T2

***Eucalyptus* + *Sorghum bicolor* (*CO (S) 28)**

T3

***Eucalyptus* + *Zeamayz* (*COH (M) 5)**

T4

***Eucalyptus* + *Sesamum indicum* (*CO 1)**

T5

***Eucalyptus* + *Allium cepa* (*Local)**

T6

***Eucalyptus* + *Vigna radiata* (*CO 6)**

T7

***Eucalyptus* + *Cajanus cajan* (*CO 7)**

T8

Control (*Eucalyptus* alone)

(**B**)

Figure 1. (**A**) Experimental design layout. (**B**) Treatment details of the study (* Name of the variety used).

All the intercrops were raised under open conditions as a sole crop for comparison purposes. There were separate control plots for the trees alone too.

2.3. Agronomic Practices Adopted

When the trees were eight months old, the horticultural and agricultural crops of millets, pulses, oilseeds, and vegetables were grown as intercrops beneath the *Eucalyptus* clones. In the experiment, different types of crops were used, such as millet crops (pearl millet, sorghum, and maize); pulse crops (green gram and red gram); oilseed crops (sesame); and horticultural crops (small onion) (Figure 1B). These are traditional crops, fetch good returns, provide staple food to small and marginal farmers, form part of the indigenous food habits, and are suitable for the climatic requirements of the region. Moreover, these crops have compatible complimentary interaction with short-rotation tree crops.

The tree crop (*Eucalyptus* clones) was coppiced, and it was 8 months old when it was sown. With an iron plough attached to a tractor, the inter-tree space was ploughed and harrowed. There were ridges, furrows, and channels carved into the levelled field. For both the crop and soil, the recommended amount of fertilisers (nitrogen, phosphorus, and potash) was applied as urea, super phosphate, and muriate of potash. The intercrop seeds were sown at a rate of two seeds per hill, using the recommended spacing for each crop, i.e., pearl millet and sorghum were sown at a spacing of 45 cm × 15 cm, maize at a spacing of 45 cm × 20 cm, green gram at a spacing of 30 cm × 15 cm, red gram at a spacing of 45 cm × 60 cm, sesame at a spacing of 45 cm × 15 cm and small onion at a spacing of 30 cm × 10 cm. Since there was no rain after the intercrops were sown, the experimental plots were irrigated right away. Channel irrigation was then administered. To maintain a consistent population of intercrops and ensure that the crop plants were distributed evenly throughout the plots, any gaps were filled seven days after sowing. Twenty days following sowing, weeding was manually done. A hoeing and earthing-up operation was completed to give the pants more anchoring. At 30 DAS, Roger (2 mL L^{-1}) was sprayed. Monocrotophos (3 mL L^{-1}) and neem oil (10 mL L^{-1}) were mixed together and sprayed at 60 DAS. The harvesting procedures were followed, and after drying, threshing was completed.

2.4. Tree Management

The clone ITC 3, which has proved to be one of the most promising clones of *Eucalyptus tereticornis* in Tamil Nadu, was used for this study. The tree crop (*Eucalyptus* clones), was coppiced, and it was 8 months old when it was intercropped for this study.

2.5. Growth and Yield Measurement

The growth and yield parameters, tree height and tree volume of the *Eucalyptus* were measured. The tree height and diameter at breast height (DBH) were measured before sowing and after harvesting of the intercrops. The measurement of the tree height was done (in metres) using a graduated bamboo pole. It is expressed in metres. The dbh of the trees was measured using digital callipers and expressed in centimetres. The volume of the standing trees was estimated using formula as per reference [8] and expressed in cubic metres (m^3). The growth and yield parameters of the intercrops, such as the plant height, dry matter production, yield of intercrops crop equivalent yield and light availability, were measured. The height was measured using a scale from ground level to the uppermost leaf tip. Representative plant samples from each treatment were pulled out carefully, washed, cleaned and their fresh weight was recorded. The dry weight was recorded after air drying the samples and expressed in kg ha^{-1}. The seed/pod/bulb yields of all the intercrops were recorded after harvesting from each plot and expressed in terms of kg ha^{-1}. The crop equivalent yield was calculated using the ratio of the net return of crop and cost of red gram.

The light intensity was recorded under the *Eucalyptus* clone intercropping plots using a Digital Lux meter. The light availability in the morning was recorded between 8 am and 9 am, and the mid-day light intensity was measured between 12.00 and 13.00 h. The Lux meter readings were taken just over the crop but under the canopy (between planting lines), and then again also over the crop but in the absence of a tree canopy.

2.6. Soil Fertility Status

The initial and post-harvest soil samples were analysed for the pH, EC, organic carbon, available nitrogen, available phosphorus and available potassium.

2.7. Economic Analysis

Economic analyses are applied to evaluate the performance of a system based on the returns derived from the inputs used in the system. This helps to determine the economic returns that can be derived from the use of various crop combinations in an agroforestry system. Different functions have been used to analyse the economics of the systems based on the market prices of the inputs used, output produced and returns derived after meeting the costs of various inputs to assess the viability and adoption of specific intercrops. The following were the methods used in the present study.

Gross return and Net return: The Gross and Net returns of the *Eucalyptus*-based agroforestry system were evaluated as a measure to assess the economic performance of the intercrop combinations.

Benefit Cost Ratio: The Benefit Cost Ratio (BCR) was worked out and defined using the following formula:

$$BCR = \frac{Gross\ Return}{Total\ cost\ of\ cultivation}$$

Land equivalent ratio:

The land equivalent ratio (LER) was used to evaluate the productivity and land use efficiency of the mixed cropping system [9]. The LER is a measure of the degree to which intercropping gives higher returns to the land area than monocropping. It was calculated using the following formula:

$$LER = \frac{\text{Crop A (Tree) yield in mixture}}{\text{Crop A (Tree) yield in monoculture}} + \frac{\text{Crop B yield in mixture}}{\text{Crop B yield inmonoculture}}$$

where

LER < 1 = Yield disadvantage for intercropping (system suffers from competition)
LER = 1 = Intercropping has no advantage over monocropping
LER > 1 = Yield advantage for intercropping (intercropping is better than monocropping)

2.8. Statistical Analysis

The experimental data were subjected to statistical analysis using the Excel program, Windows 2007 and the ICAR software Web Agri Stat Package (WASP). The mean, standard deviation, standard error, co-efficient of variation and confidence interval were found using descriptive statistics [10].

3. Results

The results of this study deal with the effects of trees on the growth and yield of seven intercrops, the effects of the intercrops on the trees' growth and productivity, and soil fertility changes. In addition, the economic aspects of the agroforestry systems are discussed below.

3.1. Effect on Intercrop

The data presented in Table 1 revealed that of the seven intercrops tested, maize had the biggest drop in plant height during all the phases, including 30 DAS, 60 DAS, and harvest, with reductions of 13%, 16%, and 18%, respectively, and sorghum at 30 DAS (13%). Small onions recorded the lowest drop in plant height throughout all the stages, with reductions of 7%, 7%, and 8%, respectively. The statistical analysis ($p < 0.05\%$) indicated a significant difference in the dry weight of the treatment in intercropping. The highest dry weight was recorded in the red gram (2995 ± 56.18 kg per ha.), followed by the sesame, pear millet, and maize. The lowest dry weight was recorded in the small onions

(1225 ± 11.49 kg per ha.). In pure cropping, among the treatments highest dry weight was recorded in the red gram (3975 + 76.63 kg per ha) followed by sesame, sorghum, and pearl millet. The lowest dry weight was recorded in the small onions (1750 + 10.94 kg per ha). Figure 2 shows that a higher yield was observed in the pure cropping compared to the intercropping. Among the pure cropping, the maximum yield was observed in the small onions (4250 kg per ha), followed by maize, pearl millet and sorghum. The minimum yield was observed in the sesame. In the intercropping, the maximum yield was observed in the small onions (2890 kg per ha), followed by sorghum, pearl millet and maize. The minimum yield was observed in the sesame (420 kg per ha). Among the pulses, a higher crop yield was reported in the red gram in both types of cropping. Among the cereals, a higher yield was reported in the maize (pure cropping) and sorghum (intercropping), i.e., 1960 kg per ha. and 1330 kg per ha., respectively, and the lowest yield was reported in the sorghum (pure cropping) and maize (intercropping). The average amount of light that the intercrops received in the morning and the afternoon under both open conditions and tree cover was measured. The percentage of light that the intercrops received in the morning, according to the results, ranged from 50% to 57% and the afternoon's light between 79% and 84% (Figure 3).

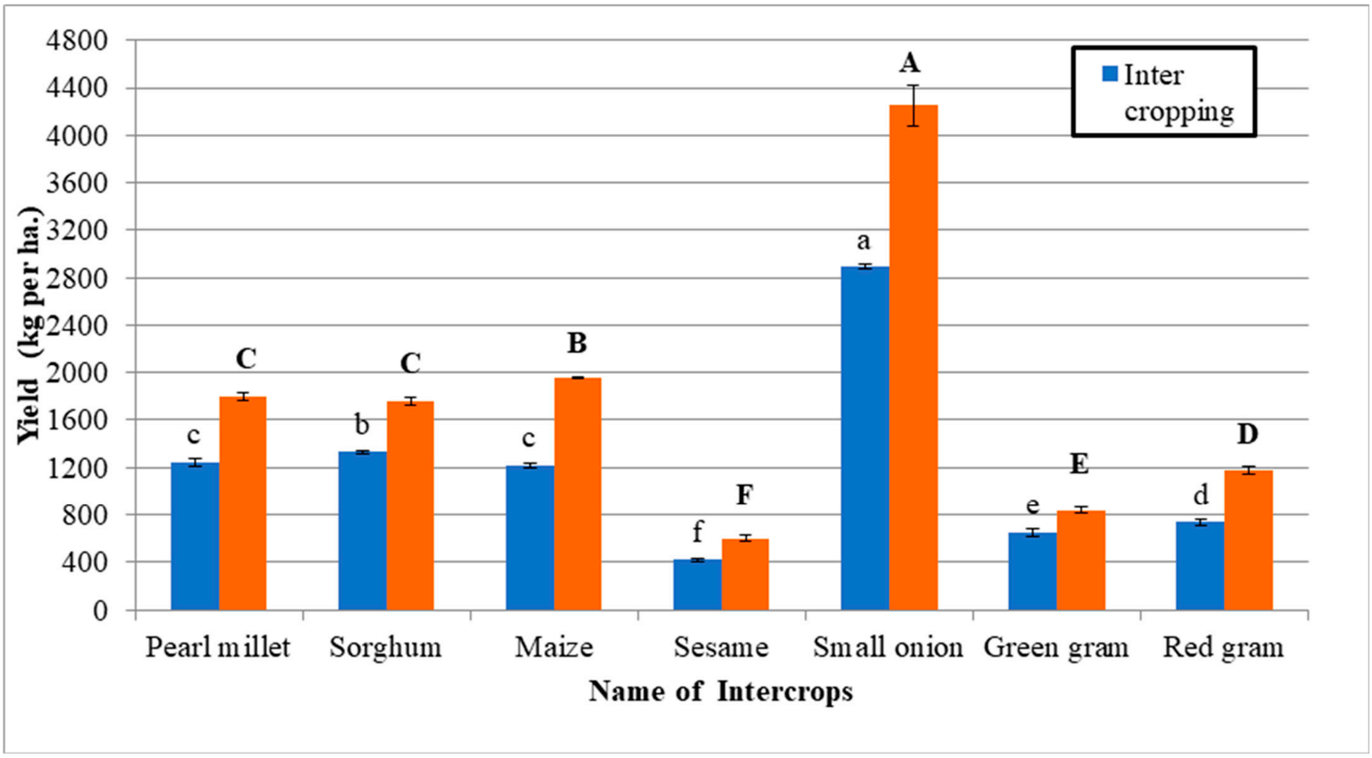

Figure 2. Effect of intercropping with *Eucalyptus* clones on the yield of intercrops (kg per ha.). Letters (a–f) and (A–F) indicates the level of significance ($p < 0.05$) for intercropping and pure cropping, respectively.

Table 1. Effect of intercropping with *Eucalyptus* clones on the plant height (cm) and dry weight (kg ha^{-1}) of intercrops.

S. No	Intercrops	30 DAS		60 DAS		At Harvest		Dry Weight	
		Intercropping	Pure Cropping	Intercropping	Pure Cropping	Intercropping	Pure Cropping	Intercropping	Pure Cropping
1	Pearl millet	22.4 ± 0.37^{c}	25.5 ± 0.60^{c}	98.9 ± 2.52^{a}	116.4 ± 1.95^{a}	145.6 ± 0.99^{b}	175.4 ± 3.97^{b}	2148 ± 11.86^{c}	2685 ± 59.32^{d}
2	Sorghum	20.7 ± 0.51^{d}	23.8 ± 0.07^{d}	76.2 ± 1.40^{d}	88.6 ± 2.09^{c}	138.3 ± 3.04^{c}	166.7 ± 3.67^{c}	2430 ± 56.98^{b}	3000 ± 17.19^{c}
3	Maize	17.8 ± 0.20^{e}	20.5 ± 0.17^{e}	81.8 ± 1.54^{c}	97.4 ± 2.14^{b}	123.2 ± 1.61^{d}	150.3 ± 2.13^{d}	1860 ± 15.51^{d}	2555 ± 5.32^{e}
4	Sesame	27.4 ± 0.20^{b}	29.8 ± 0.73^{b}	89.6 ± 2.25^{b}	98.5 ± 1.39^{b}	116.5 ± 2.32^{e}	132.4 ± 1.11^{e}	2450 ± 22.98^{b}	3500 ± 43.77^{b}
5	Small onions	18.2 ± 0.29^{e}	19.6 ± 0.47^{e}	26.4 ± 0.07^{f}	28.4 ± 0.40^{e}	30.0 ± 0.44^{g}	32.7 ± 0.05^{g}	1225 ± 11.49^{e}	1750 ± 10.94^{f}
6	Green gram	22.1 ± 0.20^{c}	24.6 ± 0.03^{cd}	43.6 ± 0.73^{e}	48.4 ± 0.99^{d}	53.6 ± 1.26^{f}	60.3 ± 1.20^{f}	1240 ± 30.37^{e}	1590 ± 1.66^{g}
7	Red gram	28.5 ± 0.18^{a}	31.4 ± 0.41^{a}	80.3 ± 1.47^{cd}	90.2 ± 0.95^{c}	164.1 ± 1.38^{a}	188.6 ± 1.19^{a}	2995 ± 56.18^{a}	3975 ± 76.63^{a}

Letters in the same column indicate significant differences at a 5% level of significance ($p < 0.05$). Value followed by mean is the standard error of the mean.

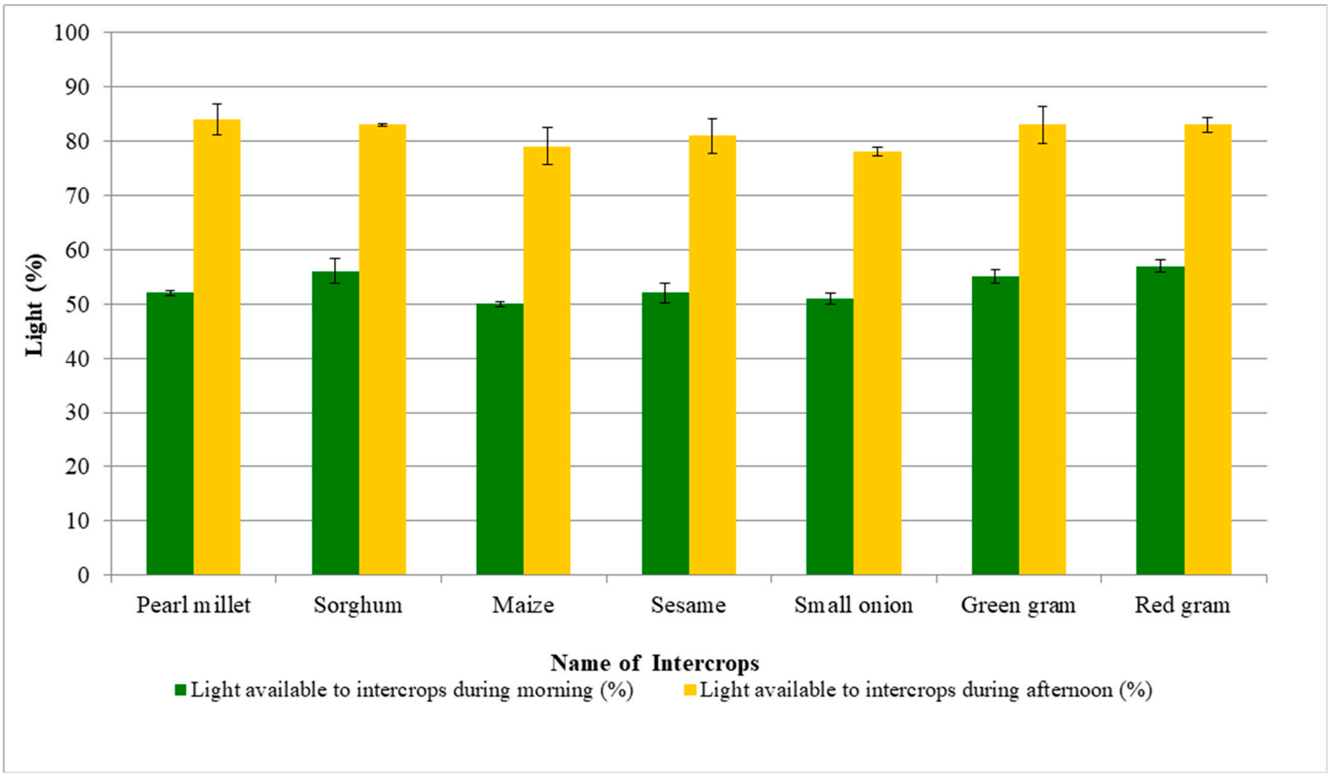

Figure 3. Light transmission ratio (%) under *Eucalyptus* clone-based agroforestry system.

3.2. Effect on Tree Growth

The data concerning the effect of the intercrops on tree growth are presented in Table 2. The findings showed that the tree height ranged between 4.42 and 4.48 metres before sowing and between 6.23 and 6.62 metres after harvesting the intercrops. The findings demonstrated that growing trees with intercrops differed from growing trees alone in terms of the height increment. The highest height increment in a tree was recorded under red gram (2.17 m), while the lowest increment was reported under sesame, among the various tree-crop combinations (1.98 m). The control (tree alone) treatment's height increment (1.8 m) was smaller than that of the other treatments. Before sowing and after harvesting the intercrops, the diameter at breast height (dbh) ranged from 3.76 cm to 3.93 cm and from 5.65 cm to 5.86 cm, respectively. The results showed that after harvesting the intercrops, there was a difference in the dbh between the treatments. The highest dbh increment in the tree crop was observed under red gram (1.93 cm), while the lowest was discovered under sesame, among the various tree-crop combinations (1.88 cm). The control (tree alone) had a lower dbh increment (1.75 cm) than all the other treatments. According to the findings, the tree volume before sowing and after harvesting the intercrops changed from 6.57 m^3 ha^{-1} to 7.19 m^3 ha^{-1} and from 20.30 m^3 ha^{-1} to 23.79 m^3 ha^{-1}, respectively. The findings revealed a substantial variation in the volume increment in the trees following the intercrop harvest. Among the various tree-crop combinations, red gram (16.60 m^3 ha^{-1}) had the highest volume growth in the trees, while maize had the lowest volume increment (14.91 m^3 ha^{-1}). In comparison to all the other treatments, the volume increment in the control (tree alone) was lower (13.50 m^3 ha^{-1}) (Tables 2 and 3).

Table 2. Effect of the intercrops on the tree height and diameter at breast height of the *Eucalyptus* clones.

Sl. No.	Treatments	Height (m)			Diameter at Breast Height (cm)		
		Before Sowing of Intercrops	After Harvesting of Intercrops	Increment	Before Sowing of Intercrops	After Harvesting of Intercrops	Increment
1	Pearl millet	4.46 ± 0.032	6.51 ± 0.026	2.05	3.84 ± 0.092	5.75 ± 0.170	1.91
2	Sorghum	4.48 ± 0.04	6.47 ± 0.190	1.99	3.79 ± 0.028	5.68 ± 0.130	1.89
3	Maize	4.44 ± 0.131	6.43 ± 0.038	1.99	3.76 ± 0.028	5.65 ± 0.029	1.89
4	Sesame	4.48 ± 0.132	6.46 ± 0.190	1.98	3.85 ± 0.028	5.73 ± 0.029	1.88
5	Small onions	4.42 ± 0.101	6.52 ± 0.043	2.10	3.88 ± 0.017	5.79 ± 0.097	1.91
6	Green gram	4.42 ± 0.098	6.58 ± 0.063	2.16	3.91 ± 0.109	5.83 ± 0.038	1.92
7	Red gram	4.45 ± 0.105	6.62 ± 0.019	2.17	3.93 ± 0.026	5.86 ± 0.137	1.93
8	Tree alone	4.43 ± 0.020	6.23 ± 0.119	1.80	3.83 ± 0.079	5.58 ± 0.078	1.75
	SEd			0.03			0.026

Value followed by mean is the standard deviation.

Table 3. Effect of the intercrops on the volume growth of the *Eucalyptus* clones.

Sl. No.	Treatments	Volume (m^3 ha^{-1})		
		Before Sowing of Intercrops	After Harvesting of Intercrops	Increment
1	Pearl millet	6.88 ± 0.21	22.53 ± 0.80	15.64 ^{abc}
2	Sorghum	6.73 ± 0.19	21.85 ± 0.56	15.11 ^{c}
3	Maize	6.57 ± 0.24	21.48 ± 0.14	14.91 ^{c}
4	Sesame	6.95 ± 0.11	22.20 ± 0.02	15.25 ^{bc}
5	Small onions	6.96 ± 0.18	22.88 ± 0.47	15.91 ^{abc}
6	Green gram	7.07 ± 0.10	23.41 ± 0.83	16.33 ^{ab}
7	Red gram	7.19 ± 0.29	23.79 ± 0.18	16.60 ^{a}
8	Tree alone	6.80 ± 0.04	20.30 ± 0.07	13.50 ^{d}

Value followed by mean is the standard error of the mean; the form factor for the *Eucalyptus* clones is 0.6. Letters (a–d) indicate significant differences at a 5% level of significance ($p < 0.05$).

3.3. Effect on Soil

The results of the post-harvest soil samples were also assessed. After the intercrops were harvested, the soil pH values under the intercrops and the tree alone treatments both slightly declined from the initial soil samples, although the variations between the treatments were minimal. The lowest values were reported under the green gram and red gram treatments, and the highest pH value was observed under the tree alone treatment (8.20), followed by the sorghum and maize treatments (8.19 and 8.16, respectively). The intercrops somewhat increased the soil EC, and the values under the tree alone treatment also marginally increased, although the differences between the treatments were minimal. However, the red gram had the greatest EC value (0.24 dSm^{-1}), which was followed by the green gram (0.23 dSm^{-1}) and the small onions (0.21 dSm^{-1}). Under the tree alone treatment, the lowest EC value was observed (0.14 dSm^{-1}). When compared to the starting value, the data showed that there had been a slight build-up of organic carbon in the soil following the intercropping under all of the treatments, including the tree alone treatment. After the intercrops were harvested, the original soil organic carbon content of 6.20 g C kg^1 increased to 7.00 g C kg^1. The red gram treatment had the largest amount of

OC (7.00 g C kg^{1}), followed by the green gram treatment (6.90 g C kg^{1}), while the tree alone treatment (6.6 g C kg^{1}) had the lowest amount. The experiment field's initial available N concentration was 231 kg ha^{-1}. Under all of the treatments, including the tree alone treatment, an upward trend in the available nitrogen was seen. The increase from the starting point ranged from 3.0 to 17.0 kg ha^{-1}. The fact that cropping and fertiliser N addition had priming effects, which would have caused the concurrent release of N from the entire N reserve in the soil, was clearly demonstrated by the built-up of accessible N during the post-harvest stage. The red gram intercrop had the highest amount of accessible nitrogen (248 kg ha^{-1}), followed by the green gram intercrop (243 kg ha^{-1}), and the lowest amount was seen in the tree alone treatment (234 kg ha^{-1}). The findings indicated that all the intercrops, including the tree alone treatment, showed a slight increase in the available phosphorus content relative to the original value. However, the red and green gram treatments had the highest levels of accessible phosphorus (18.5 kg ha^{-1}), while the pearl millet, sorghum, maize, and tree alone treatments had the lowest levels (17.5 kg ha^{-1}). In the post-harvest soil samples, an increase over the baseline soil accessible potassium level (192 kg ha^{-1}) was seen in all the treatments, including the pure tree crop. Between 4.0 and 12.0 kg ha^{-1} were added to the initial value. The treatments with the highest accessible K content were the red gram intercropping (204 kg ha^{-1}) and green gram (201 kg ha^{-1}). The treatment with the lowest available K was the tree alone treatment (196 kg ha^{-1}) (Table 4).

Table 4. Effect of intercropping with *Eucalyptus* clones on the soil properties.

Sl. No.	Treatments	P^{H}	EC (dSm^{-1})	OC (g C kg^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
1	Tree + Pearl millet	8.18 ± 0.18	0.19 ± 0.006 ^{cd}	6.70 ± 0.05	237 ± 8.30	17.5 ± 0.39	198 ± 3.38
2	Tree + Sorghum	8.19 ± 0.09	0.18 ± 0.006 ^{de}	6.70 ± 0.18	235 ± 5.36	17.5 ± 0.30	197 ± 5.80
3	Tree + Maize	8.19 ± 0.10	0.17 ± 0.003^{e}	6.70 ± 0.11	236 ± 2.08	17.5 ± 0.63	198 ± 1.60
4	Tree + Sesame	8.17 ± 0.05	0.20 ± 0.002 ^{bc}	6.80 ± 0.06	239 ± 6.68	18.0 ± 0.09	200 ± 5.15
5	Tree + Small onions	8.17 ± 0.14	0.21 ± 0.006 ^{b}	6.80 ± 0.13	238 ± 3.85	18.0 ± 0.26	199 ± 7.03
6	Tree + Green gram	8.16 ± 0.23	0.23 ± 0.003 ^{a}	6.90 ± 0.02	243 ± 2.50	18.5 ± 0.38	201 ± 4.73
7	Tree + Red gram	8.16 ± 0.05	0.24 ± 0.001 ^{a}	7.00 ± 0.19	248 ± 0.91	18.5 ± 0.82	204 ± 5.55
8	Tree alone	8.20 ± 0.15	0.14 ± 0.005 ^{f}	6.60 ± 0.17	234 ± 1.55	17.5 ± 0.52	196 ± 0.14

Letters in the same column indicate significant differences at a 5% level of significance ($p < 0.05$). Value followed by the mean is the standard deviation.

3.4. System Economics

Since farmers are frequently interested in the advantages and disadvantages of a technology, an economic analysis of the intercropping system is crucial to understanding the outcomes from their perspective. For this reason, a comprehensive budget was created for each treatment to assess the associated costs and advantages. In order to determine the budgets for the various treatments, the economic analysis in the current study employed the prices of inputs and outputs that were prevalent in the local market. The benefit cost ratio, land equivalent ratio, net returns, and gross returns were all included in the economic analysis. Small onions had the highest recorded intercrop gross income (Rs. 34,680 ha^{-1}), while maize had the lowest (Rs. 18,300 ha^{-1}). Tree + small onions had the highest reported gross income in the intercrop category (Rs. 62,140 ha^{-1}), while tree + maize had the lowest (Rs. 44,080 ha^{-1}). The final economic criterion for assessing the viability and adaptation of a specific intercropping system is the net income. This outcome revealed that red gram (Rs. 18,150 ha^{-1}) reported the highest net income in the intercrop alone, while maize reported the lowest (Rs. 8050 ha^{-1}). Tree + red gram had the highest reported net revenue in the intercrop (Rs. 41,690 ha^{-1}), whereas tree + maize had the lowest (Rs. 28,830 ha^{-1}). According to the results, sesame had the greatest BC ratio in the intercrop alone (3.00), whereas small onions had the lowest (1.65). Sesame had the highest reported BC ratio in the tree + intercrop (3.97) and small onions had the lowest (2.39) (Table 5). The combination of trees and intercrops with the highest LER was tree + green gram (1.92), and the one with the lowest LER was tree + maize (1.68). Every tree-crop combination displayed LER >1, demonstrating the superiority of intercropping over monocropping (Table 6).

Table 5. Economics of the intercrops under the *Eucalyptus* clones.

Sl. No.	Treatments	Gross Income (Rs.)	Net Income (Rs.)	B:C Ratio
1	Pearl millet	18,504	10,754	2.39
2	Sorghum	18,627	10,877	2.40
3	Maize	18,300	8050	1.79
4	Sesame	21,000	14,000	3.00
5	Small onions	34,680	13,680	1.65
6	Green gram	22,750	12,000	2.12
7	Red gram	29,400	18,150	2.61

Data are not analysed statistically.

Table 6. Land equivalent ratio of the *Eucalyptus* clone-based agroforestry system.

Sl. No.	Treatments	Land Equivalent Ratio		
		Intercrop	Tree	Total
1	Pearl millet	0.69	1.11	1.80
2	Sorghum	0.76	1.08	1.84
3	Maize	0.62	1.06	1.68
4	Sesame	0.70	1.09	1.79
5	Small onions	0.68	1.13	1.81
6	Green gram	0.77	1.15	1.92
7	Red gram	0.63	1.17	1.80

Data are not analysed statistically.

4. Discussion

This part encompasses the discussion concerning the results of the experiment to study the effects of trees and the effects of intercrops on the growth and productivity, changes on soil fertility and also the economic system aspects of agroforestry systems.

4.1. Effect of Intercrops

The results showed that among the seven intercrops tried, the highest reductions in the plant height at all the stages (i.e., 30 DAS, 60 DAS and at harvest) were observed in maize, with reductions of 13%, 16% and 18%, respectively, and in the sorghum at 30 DAS (13%). The lowest reductions in the plant height at all the stages were reported in the small onions, with reductions of 7%, 7% and 8%, respectively (Table 1). The rivalry for resources such as light, moisture, and nutrients may be to blame for the decrease in the plant height of the intercrops in the current study. Cowpea was revealed to be the least impacted and most suitable intercrop with *Acacia nilotica* among the four. With an increasing distance from *Eucalyptus tereticornis*, the growth of wheat and mustard plants reduced linearly [11]. According to Narwal and Sarmah [12], plants such as pearl millet, maize, castor, pigeon pea, sesbania, and sunhemp gradually grow taller as their distance from *Eucalyptus tereticornis* increases. Brahmam et al. reported on the reduction in the intercrop plant height caused by a steady rise in shade [13]. They discovered that the pigeon pea's height, number of branches and pods, seeds per plant, and grain output all gradually decreased as a result of the rubber tree's gradual increase in shade.

The results showed that there was a marked difference in the DMP between the pure crop and intercrop. The results revealed that among the seven intercrops, the highest DMP in the intercrops was recorded in the red gram (2995 kg ha^{-1}) and the lowest in the small onions (1225 kg ha^{-1}). With respect to the percentage reduction in dry matter production in the intercrops, the highest reduction was recorded in the sesame and small onions (30% each) and lowest reduction was noticed in the sorghum, with a reduction of 19% over the pure crop (Table 1). Where moisture, space, and nutrients are not constraints, the rate of dry matter production by a crop is primarily a function of the amount of solar radiation intercepted by its foliage [14]. In the current study, the dry matter production of all the seven intercrops was lower under intercropping when compared to sole cropping. The lack of adequate light for photosynthesis and the accumulation of dry matter may be the causes of the lower production of dry matter under intercropping. Jamaludheen [15], who also noted that the intercrops under one-year-old Casuarina produced less dry matter than the sole crops, validated the findings of the present study.

The results revealed that there was a significant reduction in the yield of the intercrops when compared to the pure crops. Among the millets tried, the sorghum (1330 kg ha^{-1}) recorded the highest yield, followed by the pearl millet (1245 kg ha^{-1}), and the lowest yield was recorded in the maize (1220 kg ha^{-1}). Among the pulses, the red gram recorded a higher yield (735 kg ha^{-1}) than the green gram (650 kg ha^{-1}). Under intercropping, yields of 420 kg ha^{-1} and 2890 kg ha^{-1} were observed in the sesame and small onions, respectively. Among the seven intercrops, the highest reduction in the yield when compared to the pure crop was observed in the maize (38%) and the lowest reduction was noticed in the green gram (23%) (Table 1).

The red gram had the largest crop equivalent yield (454 kg ha^{-1}), whereas the maize had the lowest (201 kg ha^{-1}). According to the study's findings, the yield of the intercrops was lower than the yield of the solitary crops. Maheta et al. [16] also showed that there was a decrease in the grain production of the intercrops when compared to the solo crops, which is consistent with the findings of the present study. The yield of groundnut, cassava, and maize under *Eucalyptus camaldulensis* [17] was lower than that of the pure crops, as were the yields of green gram, sesame, sorghum, and maize, pearl millet, and red gram, and sorghum with the increasing age of *Eucalyptus mellicdora*. According to Osman et al. [18], for trimmed and unpruned trees, respectively, the two-year mean sorghum grain yields were 76% and 39% of the pure crop yield (1553 kg ha^{-1}). According to Lott et al. [19], *Grevillea robusta* caused a 50% reduction in the maize yields. Based on the comparative growth and yield, Shanmughavel and Francis [20] suggested intercropping pigeon pea, soybean, and turmeric in bamboo (*Bambusa bambos*) plantations. Close to the tree rows of *G. robusta*, the maize output was lowered by 36%, according to Muthuri et al. [21]. Under a one-year-old *Jatropha curcas*-based agroforestry system, it was also discovered that groundnut produced the highest groundnut equivalent yield, followed by cowpea and green gram [22]. According to Osman et al. [23], the pearl millet output was decreased by up to 67% under trees, while the cowpea yield was decreased under trees by up to 21% when compared to outside.

The mean light availability to the intercrops during morning and afternoon under the tree canopy as well as open conditions was recorded. The results reported that the percentage of light available to the intercrops during the morning varied from 50% to 57%. The percentage of light available to the intercrops during the afternoon ranged from 79% to 84% (Figure 3). The photosynthetically active radiation (PAR), which varies greatly among tree species, is often a result of understorey productivity [24,25]. The stand density, canopy structure, row orientation, leaf area index, site, latitude, season, and spectral quality of incoming light are the main factors that affect the amount of solar radiation that enters the sub-canopy, although it is still variable [26]. The yield of the intercrops in the current study was also lower under the tree canopy than in the open condition. The rate of dry matter production by a crop is primarily a function of the amount of solar radiation intercepted by its foliage, where moisture and nutrients are not limiting factors [14]. This may be caused by the decreased light interception ratio obtained in the intercropping plots. Between the rows of trees, the amount of light was less than in the open. The canopy of the *Eucalyptus* clones may be blocking light, which could be the cause. The competition for light in intercropping systems has a greater impact than the competition for moisture or nutrients [27,28]. This is also true in an irrigated poplar-based agro-ecosystem. The average drop in the wheat grain yield under a one-year-old poplar plantation was 20%, and that reduction increased to 54% in a four-year-old plantation. In order to maximise the yield, it is crucial to choose suitable types that can withstand shadow [29].

4.2. Effect of Tree Growth

The results revealed that the tree height varied from 4.42 m to 4.48 m and from 6.23 m to 6.62 m before sowing and after harvesting the intercrops, respectively. The results showed that there was a difference in the height increment in the trees when grown along with the intercrops than the trees when grown alone. Among the different tree-crop combinations, the maximum height increment in the trees was recorded under the red gram (2.17 m) and the lowest increment was reported under the sesame (1.98 m). The height increment (1.8 m) in the control (tree alone) was lower than all the other treatments (Table 2). According to Khistaria et al. [30], the intercrops boosted the height and robust growth of *B. vulgaris* in an agroforestry system, which is consistent with the aforementioned findings. When cultivated with black gram, *Eucalyptus* trees grew more effectively than when grown alone [31]. The positive impact on tree growth is justified by the improved nitrogen nutrition. According to Jamaludheen [15], cowpea and black gram were the most advantageous intercrops, favouring the height growth of trees (by 31% and 32% in the first; 24% and 18% in the second; and 21% and 18% in the third intercropping) throughout the growth of trees up to 18 MAP.

The diameter at breast height varied from 3.76 cm to 3.93 cm and from 5.65 cm and 5.86 cm before sowing and after harvesting the intercrops, respectively. From the findings, it was noticed that a difference in the dbh among the treatments after harvesting the intercrops was observed. Among the different tree-crop combinations, the maximum dbh increment in the tree crop was recorded under the red gram (1.93 cm) and the minimum was found under the sesame (1.88 cm). The dbh increment in the control (tree alone) was lower than all the other treatments (1.75 cm) (Table 6). Samraj et al. [32], who reported that when crops such as potatoes, scented geraniums, and grass-legume mixture were raised in the interspaces of *Eucalyptus globulus*, compared to monoculture, the trees in the potato plots recorded an increase of 28% in the diameter at breast height, which provides support for the present findings.

The results indicated that the tree volume varied from 6.57 m^3 ha^{-1} to 7.19 m^3 ha^{-1} and from 20.30 m^3 ha^{-1} to 23.79 m^3 ha^{-1} before sowing and after harvesting the intercrops, respectively. The results showed that there was a significant difference in the volume increment in the trees after harvesting the intercrops. Among the different tree-crop combinations, the maximum volume increment in the trees was recorded under the red gram (16.60 m^3 ha^{-1}) and the minimum volume increment was reported under the maize (14.91 m^3 ha^{-1}). The volume increment (13.50 m^3 ha^{-1}) in the control (tree alone) was lower than all the other treatments (Table 3). The findings of the current investigation are consistent with those of Chaudhry et al. [33], who found that the wood yield in the intercropped stand was 29.4% higher than it was in the pure poplar stand. According to Jamaludheen [15], sesame intercropping had the lowest tree volume, while cowpea, small onions, and black gram intercropping had the highest mean volume in *Casuarina junghuhniana*.

4.3. Effect of Soil

One of the key factors in agro-forestry methods is nutrient cycling. The combined impact of trees and agricultural crops on soil fertility is given reasonable weight in this context. Discussions were held regarding the post-harvest soil sample results.

The soil pH values under the intercrops and tree alone treatment after harvesting the intercrops were slightly decreased from the initial soil samples, although the differences among the treatments were meagre. However, the highest pH value was recorded under the tree alone treatment (8.20), followed by the sorghum and maize (8.19), and the lowest values were recorded under the green gram and red gram treatments (8.16) (Table 4). This might be because the pH is a constant characteristic that cannot be changed in a short amount of time. It is unlikely that the pH will change significantly unless the soil is chemically augmented. Such a circumstance of no change in the soil pH under *Dalbergia sissoo* and *Derris indica* was also reported by Chandrasekhariah [34].

The intercrops had slightly increased the soil EC, and slight increases in the values were also observed under tree alone treatment, although the differences among the treatments were meagre. However, the highest EC value was recorded under the red gram (0.24 dSm^{-1}), followed by the green gram (0.23 dSm^{-1}) and small onions (0.21 dSm^{-1}). The lowest EC value was noticed under the tree alone treatment (0.14 dSm^{-1}) (Table 4). As the intercrops and tree components share nutrients in an irrigated, high input system such as an industrial agroforestry plantation, the intercropped plots may have a somewhat greater soluble salt content than the control. The addition of fertilisers throughout the cropping period may have caused the increase in the EC. According to Nithiya Kalyani [35], significant changes in the soil pH and EC cannot be observed after just one season of intercropping.

The results revealed that there was a little build-up of organic carbon in the soil after intercropping under all the treatments, including the tree alone treatment, when compared to the initial value. The initial soil organic carbon content of 6.20 g C k^{-1} was increased up to 7.00 g C kg^{-1} after harvesting the intercrops. The highest amount of OC was observed under the red gram (7.00 g C kg^{-1}), followed by the green gram (6.90 g C kg^{1}), and the lowest organic carbon content was observed under the tree alone treatment (6.6 g C k^{-1}) (Table 4). Given that they are left in the field after harvesting, the higher OC in the red gram and green gram plots may be the result of more biomass being added to the soil. These results are consistent with those of Jamaludheen [20], who noted that among the seven intercrops tested, cowpea intercropping had the highest soil organic carbon (0.975%), followed by groundnut intercropping (0.952%), while gingelly intercropping (0.714%) and tomato intercropping had the lowest (0.836%). In comparison to all the other tree crop combinations, the tree alone treatment had the lowest organic carbon content (0.685). According to Nithiya Kalyani [35], of the seven intercrops tested, the green gram and black gram had the highest soil organic carbon content (0.66%), cowpea intercropping came in second (0.65%), and okra and brinjal had the lowest (0.61%).

The initial available N content of the experiment field was 231 kg ha^{-1}. An increasing trend in the available nitrogen was observed under all the treatments, including the tree alone treatment. The increase over the initial value varied between 3.0 and 17.0 kg ha^{-1}. The build-up of available N at the post-harvest stage clearly brought forth the fact that cropping and fertiliser N addition had a priming effect, which would have caused the concurrent release of N from the total N reserve in the soil. Among the intercrops tried, the higher available N was found in the red gram (248 kg ha^{-1}), followed by the green gram (243 kg ha^{-1}), and lowest was in the tree alone treatment (234 kg ha^{-1}) (Table 4). Leguminous intercrops and soil microorganisms may have a symbiotic relationship that allows them to fix atmospheric nitrogen that would otherwise be inaccessible in the soil. This is consistent with the research by Thiyageshwari et al. [36], who found that intercropping hybrid Napier grass with teak increased the nitrogen availability by 25%. According to Jamaludheen [15], the intercrops had a significant impact on the amount of nitrogen that was available in the soil. Of the seven intercrops that were tried, the cowpea had the highest amount of available nitrogen (335 kg ha^{-1}), followed by the groundnut intercropping (327 kg ha^{-1}), while the small onions (295 kg ha^{-1}) and gingelly intercropping had the lowest amounts.

The results showed that a little increase in the available phosphorus content was observed over the initial value in all the intercrops, including the tree alone treatment.

However, the highest available phosphorus (18.5 kg ha^{-1}) was reported under the red gram and green gram, while a lower amount of available phosphorus (17.5 kg ha^{-1}) was noticed under the pearl millet, sorghum, maize and tree alone treatments (Table 4). The addition of fertiliser to the intercrops may be the cause of the rise in the soil accessible phosphorous following intercropping over the starting value. According to Mohan Raj [37], who discovered that the soil P increased with the inclusion of intercrop cowpea with Simaruba, intercrops may have contributed to the increase in the soil P. According to Jamaludheen [15], among the seven intercrops tested, the groundnut intercropping had the highest P content (28.0 kg ha^{-1}), while the gingelly and small onion intercropping had the lowest soil P (17.4 kg ha^{-1} and 17.6 kg ha^{-1}, respectively). The tree alone treatment continued to have the lowest P content that was currently accessible (13.7 kg ha^{-1}). An increase over the initial soil available potassium content (192 kg ha^{-1}) was observed in all the treatments, including the pure tree crop, in the post-harvest soil samples. The increase over the initial value varied between 4.0 and 12.0 kg ha^{-1}.

Among the treatments, the red gram intercropping registered the highest available K content of 204 kg ha^{-1}, followed by the green gram (201 kg ha^{-1}), and the lowest available K was observed under the tree alone treatment (196 kg ha^{-1}) (Table 4). After cropping, there may have been a minor increase in the amount of K that was accessible due to the release of K from unavailable forms into available forms as a result of the dynamic equilibrium that exists among the various soil K forms. This is consistent with the findings of Kathirvel [38], who also said that the teak-based agroforestry system increased the soil's availability of potassium. According to Jamaludheen [15], among the seven intercrops tested, the groundnut intercropping (163.9 kg ha^{-1}) had the highest available K content, followed by the cowpea intercropping, while the gingelly intercropping had the lowest (119.1 kg ha^{-1}). In the current study, which assessed the soil fertility changes under irrigated, intensively managed, and short rotation clonal *Eucalyptus* plantations for the promotion of industrial agroforestry, the improvement in the soil available K content was also in line with the improvement in the organic matter, nitrogen, and phosphorus. The tree-based approach improves livelihoods, yields, resilience, and food security, in addition to soil fertility [39]. One of the sustainable agricultural models is intercropping systems because they help to preserve soil fertility, make optimal use of resources, maintain consistent yields, and lessen the impacts of diseases and pests on crops.

4.4. System Economics

An economic analysis of the intercropping system is essential to look at the results from the farmers' point of view, as they are often interested in the benefits and costs of a technology. For this purpose, a complete budget was constructed for each treatment to evaluate the costs and benefits associated with it. In the economic analysis in the present study, the prices of inputs and outputs prevailing in the local market were used to calculate the budgets for the different treatments. The economic analysis included the gross returns, net returns, benefit cost ratio and land equivalent ratio.

The maximum gross income in the intercrop alone was reported in the small onions (Rs. 34,680 ha^{-1}) and the minimum was reported in the maize (Rs. 18,300 ha^{-1}). The maximum gross income in the tree + intercrop was reported in the tree + small onions (Rs. 62,140 ha^{-1}) and the minimum was reported in the tree + maize (Rs. 44,080 ha^{-1}) (Table 5). According to Nithiya Kalyani [35], in an agroforestry system based on *Bambusa vulgaris* with seven intercrops, the brinjal generated the highest gross income (Rs. 113,590 ha^{-1}) and the cowpea generated the lowest (Rs. 23,250 ha^{-1}). The net income is the final economic criterion for evaluating the feasibility and adaptability of a particular intercropping system. The results showed that the maximum net income in the intercrop alone was reported in the red gram (Rs. 18,150 ha^{-1}) and the minimum was reported in the maize (Rs. 8050 ha^{-1}). The maximum net income in the tree + intercrop was reported in the tree + red gram (Rs. 41,690 ha^{-1}) and the minimum was reported in the tree + maize (Rs. 28,830 ha^{-1}) (Table 5). According to Dey et al. [40], bamboo production using agroforestry techniques has a high rate of return. They calculated the NPV, BCR, and IRR to be Rs. 72,550, 2.93, and 47.85, respectively, using a 10% discount rate. According to Nithiya Kalyani [35], of the seven intercrops tried, the brinjal and black gram had the highest net returns. According to Jamaludheen [15], among the seven intercrops tested, the tomato had the lowest net returns, followed by the cowpea, groundnut, and bhendi. The net return values demonstrated that compared to a single *C. junghuhniana* tree planting, all the intercropping schemes provided significantly higher net revenue per hectare.

The maximum net return of Rs. 39800 ha^{-1} was produced by the cowpea + casuarina trees at a density of 2 m × 2 m (2500 trees ha^{-1}). When compared to Casuarina grown as a monoculture, the return from the groundnut intercropped with Casuarina was greater [41]. According to Doharey et al. [42], the intercropping of urd + toria in an NA-7 cultivar of aonla at Dehradun resulted in the maximum net profit of Rs. 86822.0 ha^{-1}. Due to their lesser yield declines and ability to grow kharif and rabi crops in rotation, agroforestry plantations are becoming more and more popular among farmers.

The results revealed that the highest BC ratio in the intercrop alone was reported in the sesame (3.00) and the lowest was noticed in the small onions (1.65). The highest BC ratio in the tree + intercrop was reported in the sesame (3.97) and the lowest was noticed in the small onions (2.39) (Table 5). According to Nithiya Kalyani [35], brinjal intercropped with *B. vulgaris* had the greatest BCR of 7.5 and gingelly had the lowest BCR (2.6). According to Jamaludheen [15], of the seven intercrops, the tomato and small onions recorded the lowest BCR, whereas the cowpea, groundnut, bhendi, and black gram showed the highest BCR (except for in 1.5 m × 1.5 m spacing). Agroforestry land management systems provided the highest B/C ratio (2.28) when compared to pure agriculture or pure silviculture according to case studies carried out in Rajasthan, Gujarat, and Uttar Pradesh in India [43].

Additionally, according to Kondas [42], cowpea had a higher BCR when grown in conjunction with trees (*Faidherbia albida*, *Albizia lebbeck*, and *Acacia ferruginea*), while the lowest returns were obtained by growing only annual crops, and cowpea also had a higher BCR than sorghum. Early intercropping enables better cash flow during periods of rapid growth when tree revenue is not expected. Additionally, compared to the tree alone treatment in the current set of tests, the intercrops' synergistic effect on the development and productivity of the *Eucalyptus* clones was noticeable.

When any of the fodder crops were planted in succession in combination with khejri (*Prosopis cineraria*) rather than monocropping, higher returns were produced, according to the economic analysis of this type of agroforestry system. Under khejri trees, the highest net returns (Rs. 15,197 ha^{-1}) and benefit cost ratio (3.73) were attained when todia (*Brassica tournefortii*) was planted in rabi after pearl millet in kharif [44]. According to Singh et al. [45], agri-silviculture models showed higher benefit cost ratios than agri-silvi-hoticulture models. Agroforestry systems must advance land use development due to constrained agricultural land areas and rising food demand. Alternative methods of producing food in forested environments include intercropping root crops with trees.

Among the tree + intercrop combinations, the highest LER was found in the tree + green gram (1.92) and the lowest in the tree + maize (1.68). All the tree-crop combinations showed an LER >1, which showed that intercropping has advantages over monocropping (Table 6). The productivity and land use effectiveness of the mixed cropping system were assessed using the land equivalent ratio (LER) [9]. According to Jamaludheen [15], there was a noticeable change in the LER with respect to the intercrops. The combinations of trees and intercrops that displayed the highest LER were the tree and cowpea, tree and black gram, and tree and groundnut. The treatment with trees and gingelly had the lowest LER. He claimed that the overall LER was higher than the one in all of the *C. junghuhniana*-based agroforestry combinations, highlighting the fact that intercropping is preferable to growing *Casuarina junghuhniana* as a monoculture. In an agroforestry system, the peanut (*Arachis hypogea*), sesame (*Sesamum indicum*), and roselle (*Hibiscus sabdariffa*) performance and yield were reported to be impacted by *Acacia senegal* by Fadl and Sheikh [46]. All of the treatments produced land equivalent ratios (LER) greater than 1, which showed that cultivating field crops as intercrops is preferable to monoculturing trees.

5. Implications of the Present Study

In this study, *Eucalyptus*-based agroforestry systems were used to simulate the impacts of trees and intercrops on growth and production, changes in soil fertility, and system economics. When compared to the pure crops, the intercrops had a significantly different plant height, dry matter output, and yield. The findings demonstrated that the intercrops caused a difference in the trees' height increment and DBH increment. The intercrops had some effects on the nutrients in the soil. The red gram intercropping had the highest levels of EC, soil organic carbon, available soil nitrogen, available soil phosphorus, and available soil potassium, while the sole tree treatment had the lowest levels. The small onions, red gram, and sesame were the intercropping crops with the highest gross income, net income, and B:C ratios, respectively. The tree + green gram had the highest land equivalent ratio (LER), and the tree + maize had the lowest. Based on this result, red gram emerged as the most lucrative intercrop, followed by sesame and small onion. Of the seven intercrops tested, maize was the least effective. When compared to monoculture, intercropping had a significant complimentary impact on the development and productivity of the *Eucalyptus* clones. The soil fertility status in the intercropped plots was somewhat higher than when the trees were grown alone. The economic factors showed that intercropping with *Eucalyptus* clones was more profitable than *Eucalyptus* clone monoculture. The present study concerning the influence of *Eucalyptus*-based agroforestry systems helped in understanding the agro-ecology of farms with different traditionally cultivated crops, thereby identifying the best crop combinations for more income per unit area of land. This study also revealed the suitable crop combination model for the sustainability of the farm. The economic benefits from the farmers' point of view were the prime criteria for the adoption of any agroforestry model. Based on the benefit and cost ratio values of the evaluated crop combinations, the most profitable model was *Eucalyptus* + sesame, which had the highest B:C ratio (i.e., 3), followed by *Eucalyptus* + red gram and *Eucalyptus* + Sorghum.

6. Conclusions

In agroforestry systems, the LER is a useful method for expressing productivity advantages. The results concerning the LER indicated that all the intercropping treatments had higher productivity advantages than the monocropping. The most beneficial crop combination was *Eucalyptus* + green gram. In production-oriented systems, sustainability can be considered the maintenance of production over time, without the degradation of the soil, on which production is dependent. In the present scenario, the adverse effects of fertilisers are well known. Thus, the adoption of a nature-based solution is the best option for sustainable production. Legumes are the best farming solutions to combat the bad effects of fertilisers. Based on the present study, *Eucalyptus* + green gram and *Eucalyptus* + red gram improved the soil fertility by enhancing soil nutrients such as nitrogen, phosphorus, potassium and organic carbon. Overall, this study will be helpful for farmers, industries and policymakers seeking to make the right decision concerning the selection of a *Eucalyptus*-based agroforestry model. Farmers can successfully adopt *Eucalyptus*-based agroforestry with small onions, red gram, sesame, and sorghum in areas that are adaptable to grow these combinations depending on the climatic and edaphic requirements instead of growing *Eucalyptus* in monocultures in order to gain the maximum benefits. This will allow the long-term maintenance of soil fertility without much use of chemical fertilisers and also reduce the dependence on chemical control over pests and diseases, thereby keeping the plant combinations healthier, which will lead to lots of health benefits for local communities. Such practices can be applied not only at the local/regional level but also globally to similar locations wherever such crops can be grown. Further field studies can be taken up using specific biofortified varieties of these crops with *Eucalyptus* and other trees, depending on the social acceptability and requirements of the communities in specific locations, as part of multilocational trials in order to develop suitable agroforestry models. Such combinations could go a long way in contributing to the nutritional requirements of small and marginal farmers and help in compensating for the food hunger that pertains to certain areas globally, thereby meeting the United Nations Sustainable Development Goals.

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References

1. Neilson, D. The global *Eucalyptus* resource and some solidwood-panel product development issues. In Proceedings of the IUFRO Conference, Launceston, Australia, 19–24 March 2000.
2. Lal, P. National forest policy and raw material supplies for Wood Based Industries in India. *Indian For.* **2000**, *126*, 351–366.
3. Parthiban, K.T.; Rao, M.G. Pulpwood based industrial agroforestry in Tamil Nadu—A case study. *Indian For.* **2008**, *134*, 155–163.
4. Cavalli, J.P.; Frank de Araújo, E.; Reichert, J.M. Eucalyptus Growth Responses to Soil Water Storage Capacity in Arenosols and Acrisols Soils: Wood and Biomass Stock Modelling. *Sustainability* **2022**, *14*, 12215. [CrossRef]
5. Tejwani, K.G. *Agroforestry in India*; Oxford and IBH: New Delhi, India, 1994; pp. 10–47.
6. Nair, P.K.R. *An Introduction to Agroforestry*; Kluwer: Dordrecht, The Nederland, 1993; 499 p.
7. Huang, C.; Wang, Z.; Ren, X.; Ma, X.; Zhou, M.; Ge, X.; Liu, H.; Fu, S. Evaluation of Soil Quality in a Composite Pecan Orchard Agroforestry System Based on the Smallest Data Set. *Sustainability* **2022**, *14*, 10665. [CrossRef]
8. Chaturvedi, A.N.; Khanna, L.S. *Forest Mensuration*; International Book Distributors: Dehradun, India, 1982; p. 408.
9. Willey, R. Intercropping—Its importance and research needs. Competition and yield advantages. *Field Crop Abstr.* **1979**, *32*, 1–10.
10. Kumar, R.; Pandey, R.; Pal, M. Statistics of biomass structure of *Dendrocalamus strictus* Roxb. Neem seedlings. *Indian For.* **2000**, *126*, 993–1001.
11. Malik, R.S.; Sharma, S.M. Moisture extraction and crop yield as a function of distance from a row of *Eucalyptus tereticornis*. *Agrofor. Syst.* **1990**, *12*, 187–195. [CrossRef]
12. Narwal, S.S.; Sarmah, M.K. Suppression effect of *Eucalyptus tereticornis* on the field crops. In Proceedings of the First National Symposium on Alleleopathy in Agroecosystems (agriculture and forestry), Hisar, India, 12–24 February 1992; pp. 111–113.
13. Brahmam, M.; Pillai, S.S.K.; Patil, U.K. Influence of rubber (*Hevea brasiliensis)* tree shade on growth performance and seed yield of pigeon pea (*Cajanus cajan*) intercrop. *Indian J. For.* **1997**, *20*, 181–182.
14. Monteith, J.L. Climate and efficiency of crop production in Britain. *Phil. Trans. R. Soc. Lond. B.* **1977**, *281*, 277–294.
15. Jamaludheen, V. Studies on Intercropping with *Casuarina junghuhniana* at Different Stand Densities in Western Zone of Tamil Nadu. Ph.D. Thesis, Tamil Nadu Agricultural University, Coimbatore, India, 2010.
16. Maheta, K.B.; Kukadia, M.U.; Vashi, B.G.; Jadeja, D.B. Effect of forest tree species on the yield potential of intercrops. *Indian For.* **1996**, *122*, 651–653.
17. Kananji, B. Prospects for using *Eucalyptus camaldulensis* Dehn. in mixture with agricultural crops. *South Afr. For. J.* **1992**, *162*, 49–57.
18. Osman, M.; Emminhgam, W.H.; Sharrow, S.H. Growth and yield of sorghum or cowpea in an agrisilviculture system in semiarid India. *Agrofor. Syst.* **1998**, *42*, 91–105. [CrossRef]
19. Lott, J.E.; Howard, S.B.; Ong, C.K.; Black, C.R. Long-term productivity of a *Grevillea robusta*-based overstorey agroforestry system in semi-arid Kenya. *For. Ecol. Manag.* **2000**, *139*, 187–201. [CrossRef]
20. Shanmughavel, P.; Francis, K. Intercropping trials of four crops in bamboo plantations. *J. Bamboo Ratt.* **2001**, *1*, 3–9. [CrossRef]
21. Muthuri, C.W.; Ong, C.K.; Black, C.R.; Ngumi, V.W.; Mati, B.M. Tree and crop productivity in Grevillea, Alnus and Paulownia-based agroforestry systems in semi-arid Kenya. *For. Ecol. Manag.* **2005**, *212*, 23–39. [CrossRef]
22. Basha, M. Evaluation of Suitable Intercrops under Different Geometry of *Jatropha curcas*. . Master's Thesis, Tamil Nadu Agricultural University, Coimbatore, India, 2006.
23. Osman, A.N.; Reabild, A.; Christiansen, J.L.; Bayala, J. Performance of cowpea (*Vigna unguiculata*) and pearl millet (*Pennisetum glaucum*) intercropped under *Parkia biglobosa* in an agroforestry system in Burkina Faso. *Afr. J. Agric. Res.* **2011**, *6*, 882–891.

24. Hazra, C.R.; Tripathi, S.B. Soil properties, micro-meteorological parameters, forage yield and phosphorus uptake of berseem as influenced by phosphate application under agroforestry system of production. *J. Agron. Crop Sci.* **1986**, *156*, 145–152. [CrossRef]
25. Yirdaw, E.; Luukkanen, O. Photosynthetically active radiation transmittance of forest plantation canopies in the Ethiopian highlands. *For. Ecol. Manag.* **2004**, *188*, 17–24. [CrossRef]
26. Jackson, J.E.; Reifsnyder, W.S.; Darnhofer, T.O. Tree and crop selection and management to optimize overall system productivity, especially light utilization, in agroforestry. In Proceedings of the An International Workshop on the Application of Meteorology to Agroforestry Systems Planning and Management, Nairobi, Kenya, 9–13 February 1987.
27. Vinaya Rai, R.S.; Swaminathan, C.; Surendran, C. Studies on intercropping with coppice shoots of *Eucalyptus tereticornis* sm. *J. Trop. For. Sci.* **1990**, *3*, 97–100.
28. Roy, R.D.; Gill, A.S. Tree growth and crop production under agri-silviculture system. *Range Manag. Agrofor.* **1991**, *12*, 69–78.
29. Gill, R.I.S.; Singh, B.; Kaur, N. Productivity and nutrient uptake of newly released wheat varieties at different sowing times under poplar plantation in North-Western India. *Agrofor. Syst.* **2009**, *76*, 579–590. [CrossRef]
30. Khistaria, M.K.; Padmani, D.R.; Khokhani, M.G.; Kalaria, K.K. Production potential and compatibility of arable crops with subabul (*Leucaena leucocephala*) and perennial pigeon pea (*Cajanus cajan*) under alley cropping. *Indian J. Agron.* **1998**, *43*, 704–708.
31. Pal, S.; Hansda, S.K.; Maiti, S. Growth of trees and grain production of crops under agroforestry system in the lateritic tracts of West Bengal. *J. Inter Acad.* **2000**, *4*, 17–22.
32. Samraj, P.; Haldoral, B.; Henry, C. Potato intercropping with blue gum and black wattle, soil conservation. *News Lett.* **1982**, *1*, 7.
33. Chaudhry, A.K.; Khan, G.S.; Siddiqui, M.T.; Akhtar, M.; Aslam, Z. Effect of arable crops on the growth of poplar (*Populus deltoides)* tree in agroforestry system Pak. *J. Agri. Sci.* **2003**, *40*, 82–85.
34. Chandrasekhariah, A.M. Some Investigation on Agroforestry in Black Soils of Transitional Belt. Ph.D. Thesis, Univ. Agrl. Sciences, Bangalore, India, 1987.
35. Nithiya Kalyani, M. Evolving Suitable *Bambusa vulgaris* Based Agroforestry Model for Higher Productivity. Master's Thesis, Tamil Nadu Agricultural University, Coimbatore, India, 2010.
36. Thiyageshwari, S.; Dasthagir, M.G.; Yassin, M.M. Nutrient dynamics in *Gmelina arborea* based silvipastoral system. In *National Seminar on Integration of Livestock and Agroforestry Systems in Wasteland Development*; Tamil Nadu Veterinary Research Institute: Chennai, India, 1998; pp. 50–51.
37. Mohanraj, T. Studies on Compatibility of Agricultural Crops with *Simaruba glauca* DC. Master's Thesis, Tamil Nadu Agricultural University, Coimbatore, India, 2004.
38. Kathirvel, P. Studies on Compatibility of Forage Crops under Established Teak (*Tectona grandis* Linn.) Plantation. Master's Thesis, Tamil Nadu Agricultural University, Coimbatore, India, 2003.
39. Fahad, S.; Chavan, S.B.; Chichaghare, A.R.; Uthappa, A.R.; Kumar, M.; Kakade, V.; Pradhan, A.; Jinger, D.; Rawale, G.; Yadav, D.K.; et al. Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability* **2022**, *14*, 14877. [CrossRef]
40. Dey, A.N.; Mohanty, T.L.; Patra, S.N. Economic analysis of Bamboo based agroforestry system in Eastern and south eastern central plains of Orissa. Department of Forestry, Uttar Banga, Krishi Viswavidhalaya, Punidiburi, Cooch Behar (West Bengal). *Indian J. For.* **2007**, *30*, 279–282.
41. Kondas, S. *Casuarina equisetifolia*–A multipurpose tree cash crop in India. In *Casuarina–Ecology, Management and UtilizationI*; Midgley, S.J., Turnbull, J.W., Johnston, R.D., Eds.; Commonwealth Scientific and Industrial Research Organization: Canberra, Australia, 1983; pp. 66–76.
42. Doharey, V.K.; Rathore, A.C.; Jayaprakash, J.; Singh, C. Evaluation of *Emblica officinalis* cultivars for agroforestry system in north-western Himalayas. *Indian For.* **2011**, *137*, 447–452.
43. Mathur, R.S.; Sharma, K.K.; Ansari, M.Y. Economics of *Eucalyptus* plantation under agroforestry. *Indian For.* **1984**, *110*, 71–201.
44. Kaushik, N.; Kumar, V. Khejri (*Prosopis cineraria*)-based agroforestry system for arid Haryana, India. *J. Arid Environ.* **2003**, *55*, 433–440. [CrossRef]
45. Singh, P.K.; Das, P.K.; Quli, S.M.S. Economic analysis of agroforestry model adopted by tribal of Orissa, India. *Indian For.* **2011**, *137*, 535–543.
46. Fadl, K.E.M.; Sheikh, S.E.E. Effect of *Acacia senegal* on growth and yield of groundnut, sesame and roselle in agroforestry system in North Kordofan, Sudan. *Agrofor. Syst.* **2010**, *78*, 243–252. [CrossRef]