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Research Article

Stand Density Influences Pulpwood Yield, Soil Fertility and Carbon Sequestration in Semiarid *Melia dubia* cav. Plantation

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Abstract

Melia dubia is one of the promising farm forestry tree species in semiarid regions to provide raw materials for industries and to restore the soil fertility, besides contributing to regional carbon budget. An optimal stand density will result in higher pulpwood productivity and ecological restoration. This study aimed to optimize the stand density of *Melia dubia* plantation in a semiarid region by studying four stand densities, viz., 4444 trees ha^{-1}, 2500 trees ha^{-1}, 2000 trees ha^{-1}, and 2222 trees ha^{-1}, for obtaining higher pulpwood yield and to find their effect on soil fertility. Pulpwood yield in all the stand densities was measured in 3 year old plantations. Physico-chemical properties and available nutrients of the post-harvest soils were compared to the initial status. Carbon sequestration was estimated by the addition of C stocks in the biomass, litter and soil. Results showed that a significantly highest pulpwood yield was obtained with 2222 trees ha^{-1} ($P < 0.05$), while the highest carbon sequestration was recorded with 4444 trees ha^{-1}. The nutrient content the post-harvest soil was found to increase compared to the initial stage in all the stand densities. Principal component analysis revealed a positive correlation between stand density and soil parameters like EC, SOC, nutrient contents, and exchangeable cations ($P < 0.05$). This study concluded that a stand density of 2222 trees ha^{-1} is optimal for obtaining significantly higher pulpwood yield with *Melia dubia* plantations ($P < 0.05$), besides improving soil fertility and carbon sequestration in semiarid regions.

Keywords

Melia dubia, Stand Density Optimization, Pulpwood Yield, Post-Harvest Soil Quality, Plantation Carbon Dynamics, Semiarid Region

1. Introduction

In India, a number of exotic pulpwood tree species such as *Eucalyptus*, *Casuarina*, *Leucaena*, and *Populus* are currently promoted by industrial sectors that require specific agro-climatic conditions for better growth and targeted yield [1]. By contrast, *Dalbergia sissoo*, *Gmelina arborea*, *Melia dubia* and *Neolamarkia cadamba* are some of the indigenous, relatively fast- growing alternative pulpwood species that could be adaptable to a wide range of agro-climatic conditions [2].

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Among these indigenous tree species, *Melia dubia*, due to its amenable nature in agroforestry systems and without causing any deleterious effects on under storied agricultural crops, is often advocated for inclusion in agroforestry [3]. From an industrial point of view, *Melia dubia* is one of the highly suitable raw materials for the pulp and paper industry, considering its high pulp recovery and fibre strength [4]. Further, the inclusion of *Melia dubia* in agroforestry has been found to be superior to exotic plantations in terms of economic returns and ecological restoration [5].

Spatial arrangement of plantations plays an important role in increasing the growth and yield of trees. The choice of planting density is the primary silvicultural decision, which influences the total stand volume, quality, and quantity of wood products throughout the rotation, as they compete for above-ground factors like sunlight, aeration and below-ground factors like space, water, and nutrients [6]. Furthermore, the influence of stand density on above and below ground biomass of *Melia dubia* is associated with many uncertainties, which prevent clear management recommendations for small landholders. Economically, however, the production optimization should be based on the value of the products, particularly wood assortments. While *Melia dubia* has a coppicing nature, more economic benefits will be pronounced in the second harvest, as around 60% of the plantation establishment cost is spent on plantation establishment such as land development, cost of planting material, and planting expenses. An optimal stand density will considerably reduce the establishment cost.

Therefore, to improve land utilization in semiarid zones under small and marginal land-holding patterns, spatial arrangement is to be optimized based on the purpose for which plantations are grown. For example, the timber and plywood industry needs attention to individual tree size rather than the total volume of plantations with 8-year rotational period. On the other hand, industries like pulp and paper concerned with the volume of wood rather than the size of individual trees with a rotational period of 3 to 5 years. However, studies on the influence of different stand densities on the pulpwood production of *Melia dubia* are rare so far, necessitating a comprehensive investigation in this regard.

Tree plantations also play a key role in restoring the fertility of soils, especially under semiarid conditions [7]. For semiarid conditions, tree growth and biomass production are often controlled by factors such as climate and soil quality. The soils of semiarid regions usually contain low organic carbon, thus providing a great opportunity to sequester the atmospheric CO_2, and thereby restore soil fertility. *Melia dubia*-based forest system has the potential to improve soil fertility *i.e.* stabilizing soil physico-chemical properties and increasing nutrient contents by recycling available natural resources [7-9]. Planted forests are the widely accepted means of carbon sequestration, and for that reason, they offer a unique opportunity to combine the dual goals of climate change adaptation and mitigation [10].

The present study is based on the hypotheses that (1) higher stand densities increase competition among trees, reducing pulpwood yield, but maximizing carbon sequestration, (2) under lower stand densities, the pulpwood yield will increase due to the utilization of full natural resources while maintaining positive impacts on soil fertility (3) harvesting trees with larger diameters under low stand densities will increase productivity, reduce cost and save time, as fewer trees are required to harvest. The objectives of this study were to optimize tree density for *Melia dubia* pulpwood plantation, to find the effect of various stand densities (ranging from 2000 to 4444 trees per hectare) on pulpwood yield, improving soil fertility, and to assess carbon sequestration in a semiarid region.

2. Materials and Methods

2.1. Experimental Location and Soil Properties

Precision silvicultural experiment on *Melia dubia* was carried out during January 2018 to December 2020 in the Plantation Research Block of Tamil Nadu Newsprint and Papers Limited (TNPL; N11°03.448’, E 077° 59.444’). The study location is classified as a semiarid region based on the prevailing temperature and annual rainfall [11]. The mean monthly rainfall and temperatures are shown in Figure 1, indicating high to moderate temperatures throughout the year, with maximum rainfall occurs in the month of November. The physico-chemical and chemical properties of the experimental soil are depicted in Table 1. The pH indicates slight alkalinity (7.59), and EC (0.17 dS m^{-1}) shows non-salinity nature of the soil. Total soil cations (TC) of 14.92 C mol (P^{+})/ kg are considered low in status. The soil organic carbon content and available nutrients denote a low fertility level. The particle size distribution reveals a sandy loam texture, and the soil taxonomic classification was keyed out as *typic Ustorthents*.

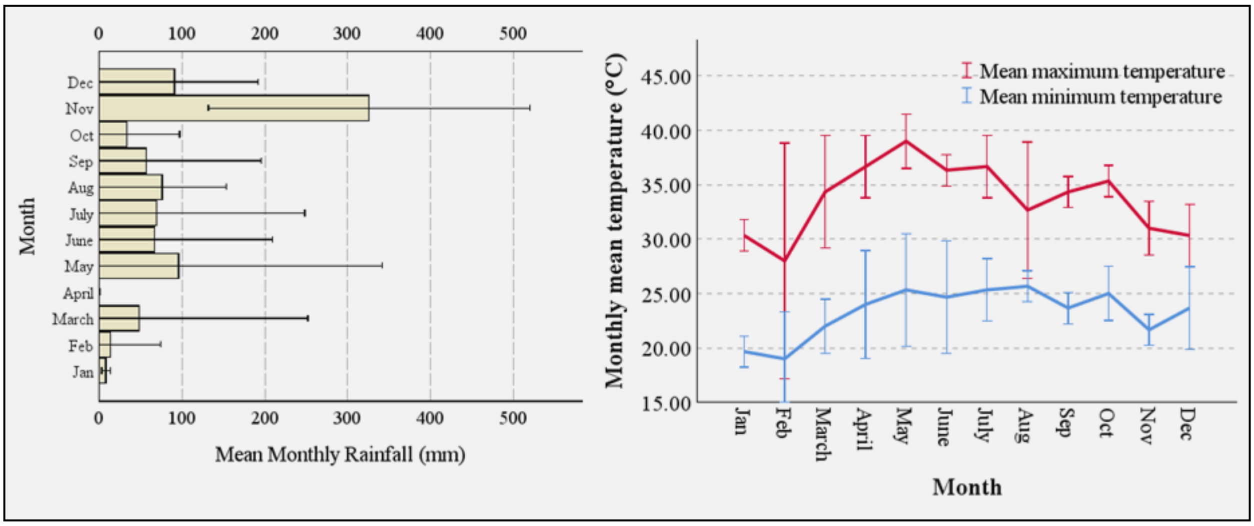

Figure 1. *Mean annual rainfall and maximum and minimum temperatures recorded at the experimental site during the years 2018-2020. Error bars indicate standard deviations.*

2.2. Experimental Details

Meliadubia clone GK-10, which has superior genetic features, is fast-growing and high-yielding was used in our experiment. The experiment was laid out in a randomized block design (RBD) and replicated three times. The details of different spacing adopted (which are the stocking levels widely practiced in commercial plantations of *Melia dubia* in South India), plot area for each spacing treatment, number of trees per plot and tree density at different spacing are shown in Table 2. Planting was carried out during January 2018 as per the spacing treatments, and after the establishment of plants, a fertigation dose of 150: 75: 150 NPK kg ha^{-1} was applied in six equal splits to all the plots, irrespective of the spacings adopted. Necessary silvicultural operations were carried out throughout the experimental period. The pulpwood was harvested in January 2021 i.e. in 36 month- old plantation.

Table 1. *Soil characteristics of the study location.*

Parameters	Symbol	Units	Value
Textural class	-	-	Sandy loam
Bulk density	BD	Mg m^3	1.52 ±0.04
pH	pH	-	7.59 ±0.14
Electrical Conductivity	EC	dS m^{-1}	0.17 ±0.02
Organic Carbon	SOC	mg kg^{-1}	0.35 ±0.06
Total Cations	TC	C mol (P$^+$) kg^{-1}	14.92 ±0.28
$KMnO_4$- N	Av-N	ppm	79.46 ±1.79
Olsen- P	Av-P	ppm	6.02 ±1.12
NH_4OAc- K	Av-P	ppm	172.62 ±4.24
Available Zn	Av-Zn	ppm	9.57 ±1.07
Available Cu	Av-Cu	ppm	4.27 ±0.41
Available Mn	Av-Mn	ppm	7.26 ±0.36
Available Fe	Av-Fe	ppm	7.92 ±0.27

Note: Data represented as mean of three replications (± Standard Error)

Table 2. Spacing treatments / stand density evaluated in the Melia dubia plantation.

Treatment	Spacing	Plot area (m^2)	Number of trees/ plot	Stand density (trees/ ha)
S1	1.5 m × 1.5 m	243	108	4444
S2	2.0 m × 2.0 m	192	48	2500
S3	2.0 m × 2.5 m	168	34	2000
S4	3.0 m × 1.5 m	162	36	2222

2.3. Biometric Observations

The biometric observations, *viz*. tree height and girth at breast height (GBH) at 36 months after planting, were measured to estimate the tree volume. All the trees were marked at 1.37 m from ground level, and the GBH was measured using a tailor's tape and expressed in cm. The volume of standing trees was estimated using the formula according to Chaturvedi and Khanna [12] and expressed in cubic meters (m^3):

$$V = \pi r^2 h \times \text{Form factor (0.58)}$$

Where V= volume of standing trees; r = radius at breast height; h=total height of the tree.

The monthly litter fall biomass (LFB) of the stand was collected starting from January 2019 to December 2020, from the subplots measuring 1m × 1m, demarcated within the treatment plots, and sorted into leaves, twigs and bark. The collected litter components were homogenized as per the treatment plots, and dried to a constant weight, weighed with the help of a weighing balance, and converted into kg ha^{-1} dry matter production (DMP).

Pulpwood yield, above-ground biomass (AGB) and below-ground biomass (BGB) estimation were done using the destructive sampling method in triplicate. Three representative trees in each plot were felled at ground level using a mechanical chainsaw (STIHL, India). The pulpwood yield was measured by weighing the harvested trees with the desired wood dimension (> 8 cm diameter) and converted into t ha^{-1} for all stand densities. Fresh weights (FW) of the above-ground tree components were recorded immediately after felling, which are considered AGB. After felling, the root portion of the trees was excavated and weighed as BGB. The AGB and BGB were converted into DMP after drying to a constant weight and expressed in t ha^{-1}.

2.4. Soil Analysis

Soil samples collected at the standard depth of 0–45 cm were composited for each stand density. The bulk density of the soil samples was determined by the gravimetric method, which involves the division of total soil volume by the mass of oven dry soil, as suggested by Gupta and Dakshinamoorthy [13]. Soil pH and EC (1: 2.5 soil: water ratio) were measured by the potentiometric method (LI120, ELICO pH meter, India) and a conductivity meter (611, Deep Vision, India) respectively, as advocated by Jackson [14]. Soil organic carbon concentration was estimated by digesting 1 g of soil with 10 ml of 1N $K_2Cr_2O_7$, 20 ml of H_2SO_4, 10 ml of H_3PO_4, 10 ml of NaF, and titrating with 0.5N $Fe(NH_4)_2(SO_4)_2.6H_2O$ [15]. Available nitrogen was estimated by the alkaline KMnO4-Kjeldahl distillation method, in which 20 g of soil was distilled with 100 ml each of 0.32% $KMnO_4$ + 2.5% NaOH, the liberated ammonia was trapped in a boric acid-double indicator solution, and ammonia was quantified by titrating with 0.02N H_2SO_4 [16]. The available phosphorus in 1.0 g of soil was extracted with 0.5 M $NaHCO_3$ (Olsen's extract; Olsen et al., 1954) and measured using a spectrophotometer (Visican 167, Systronics, India) at 882 nm after the blue color developed with reagent A (12 g of $[(NH_4)_6Mo_7O_{24}.4H_2O]$ and 0.2908 g of $[K(SbO)C_4H_4O_6.1/2H_2O]$ in 2000 ml of 2.5 M H_2SO_4) and reagent B (1.056 g of $C_6H_8O_6$ dissolved in reagent A) [17]. The available K was extracted by centrifuging 5 g of soil with 25 ml of neutral normal NH_4OAc at 2000 rpm for 10 minutes, and the K content was measured using a flame photometer (Model 1385, Deep Vision, India) as per the procedure by Tandon [18]. For the estimation of soil exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) and available micronutrients (Zn^{2+}, Cu^{2+}, Mn^{2+}, and Fe^{2+}), 0.5 g of soil was digested with 20 ml of HNO_3 + 3 ml of H_2O_2 at 180 ± 5 ℃ for 15 minutes in a microwave digestion unit (Ethos Easy, Milestone, Italy). The digested solutions were filtered, made up to a volume of 50 ml with ultrapure water and measured for exchangeable cations and available micronutrients using microwave plasma-Atomic Emission Spectrometry (MP 4200, Agilent Technologies, USA). The exchangeable cations and available micronutrients in the soil were expressed in C mol (P^+) kg^{-1} of soil and mg kg^{-1} of soil, respectively.

2.5. Estimation of C Sequestration Potential

The planted forests are considered C sinks as they directly sequester through photosynthesis and indirectly through biochemical reactions in the soil. For that reason, this study included the investigation of the C sequestration in different stand densities. The AGB, BGB and LFB were converted into fixed carbon by multiplying them by 0.50 [19], and expanded to tha^{-1}. The carbon stock in the soil (Cs) was estimated using the formula of Post and Kwon [20]:

$$Cs = Cc \times D \times BD/10$$

Where Cs = soil organic carbon stock ($t\ ha^{-1}$); Cc = soil organic carbon concentration ($g\ kg^{-1}$); D = soil depth (cm); BD = bulk density ($g\ cm^{-3}$).

The carbon sequestration potential of *Melia dubia* plantation was calculated by adding the carbon stocks in AGB + BGB + LFB + Cs [21].

2.6. Statistical Analysis

The quantitative data were checked for normality and analyzed using univariate analysis of variance (ANOVA) to find the effect of different tree densities on tree growth parameters, pulpwood yield, above-ground and below-ground dry matter production and the carbon sequestration potential of *Melia dubia* plantation. Post hoc analysis was performed with Duncan's multiple range test ($P < 0.05$) when there was a significant difference among the variables. Results obtained from soil analysis in relation to different tree densities were subjected to principal component analysis (PCA) by performing the extraction in varimax rotation with Kaiser normalization, where the components were extracted for eigenvalues >1. All statistical analyses were conducted using SPSS version 29 (SPSS Inc., Chicago, USA).

3. Results and Discussion

3.1. Effect of Stand Density on Growth and Pulpwood Yield of *Melia dubia* Plantation

The influence of different stand densities on the growth parameters, stand volume, and pulpwood yield of *Melia dubia* plantation is shown in Table 3. The maximum height of individual trees was recorded at a tree density of 4444 trees per hectare (S1) with the spacing of 1.5 m × 1.5 m ($P < 0.05$). All other spacings were found statistically non-significant. It is because high stand density allows individual trees to have minimal branches with less crown density, which favors vertical growth of the trees rather than medial growth [22]. The wider spacing of 3.0 m × 1.5 m with 2222 trees per hectare recorded the significantly highest GBH ($P < 0.05$) as compared to other treatments. The treatments S2 (2500 trees ha^{-1}) and S3 (2000 trees ha^{-1}) were statistically similar in recording higher tree GBH ($P < 0.05$). It is obvious that the GBH of individual trees always has a strong negative correlation with stand density [23]. Generally, trees grow faster at lower stand density in terms of radial growth, and specific tree geometry primarily governs the uptake of water and nutrients from the soil and the capture of sunlight [6]. This may vary among genera and species within a genus under a particular climate. In the present study, *Melia dubia* with 2222 trees ha^{-1} produced more cumulative volume compared to the near tree densities of 2000 trees ha^{-1} (S3), and 2500 trees ha^{-1} (S2), suggesting an ideal stocking level under semiarid climate for pulpwood production. The increment in tree GBH with wider spacing was due to reduced competition among trees in above-ground factors like sunlight, aeration and below-ground factors like space for rooting, nutrient and water absorption [24, 25]. These associations of increased height with high stand density and increased GBH with low stand density plantations have been reported on various tree species: Nissan *et al*. [26] in *Paraserianthes falcataria*; Prasad *et al*. [27] in *Leucaena leucocephala* and Andrzej *et al*. [23] in *Pinus roxburghii*). The significantly highest stand volume was recorded with the stand density of 4444 trees per hectare ($P < 0.05$), implying that stand volume is higher with high- density plantations and *vice versa*. The increment in individual GBH is attributed to wider spacing, but the cumulative stand volume is attributed to the number of trees per unit area, suggesting a trade-off between individual tree growth and stand volume.

Table 3. *Effect of stand density on growth and pulpwood yield of Melia dubia plantation.*

Spacing	Individual tree height (m)	Individual tree GBH (cm)	Cumulative volume (m^3)	Pulpwood yield ($t\ ha^{-1}$)
S1	9.04±0.68a	22.99±0.84c	0.60±0.03c	89.04±3.54c
S2	8.68±0.52b	26.12±0.91b	0.71±0.02b	104.79±3.74b
S3	8.70±0.74b	26.89±0.54ab	0.69±0.03ab	103.42±4.54b
S4	8.72±0.80b	27.65±0.68a	0.76±0.02a	110.19±2.92a

Note: Data represented as mean ± SE and the different alphabet in the corresponding colomn are significantly different according to DMRT at $P < 0.05$.

The pulpwood yield with the specified wood dimension in different stand densities is recorded in the order of S4 > S2 > S3 > S1($P < 0.05$). From Table 2, it can also be observed that S2 with a tree density of 2500 trees per hectare is statistically on par with S3, with a tree density of 2000 trees ha^{-1}. The results of the present study support the hypothesis that site quality ultimately determines the productivity of tree species within certain stand densities and individual tree volumes [23], suggesting that a tree density ranging from 2000 to 2500 trees per hectare is optimal for raising *Melia dubia* plantations. A similar finding of increased wood productivity with stand density to a range of 2000 - 2500 trees per hectare in the *Melia dubia* plantation was reported by Prajapathi *et al*. [5], Patil *et al*. [6], and Syed *et al*. [25]. However, within this range, our results indicate that a stand density of 2222 trees ha^{-1} is ideal for *Melia dubia* pulpwood plantations in low-nutrient soil under semiarid conditions.

3.2. Effect of Stand Density on Post Harvest Soils of *Melia dubia* Plantation

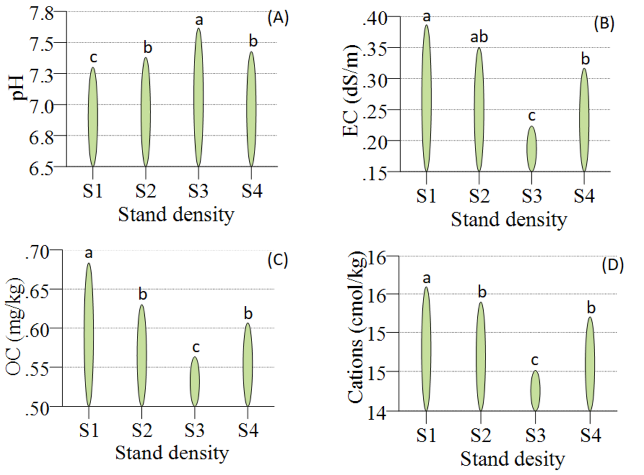

Figure 2. *Effect of stand density on the soil physico- chemical characteristics: a) soil pH; b) soil EC; c) soil organic carbon; d) total cations. Data are presented as mean ± SD (n = 3). Different alphabets in the corresponding parameters are significantly different according to DMRT at$P < 0.05$.*

The pH of the post- harvest *Melia dubia* planted soil in some stand densities was found to be reduced as compared to the initial soil pH of 7.76 (Figure 2). While the reduction ranged from 2.11% in S4 (2222 trees ha^{-1}) to 3.82% in S1 (4444 trees ha^{-1}), the soil pH remained unaltered with the stand density of 2000 trees per hectare (S3). Litter decomposition, soil respiration (CO_2 emission), microbial respiration, and root respiration resulted in a reduction in soil pH [8]. More reduction with high stand density may be ascribed to higher below-ground biomass production [28]. More than a twofold increase in soil EC was observed in the plots with higher stand densities of 4444 trees ha^{-1} and 2500 trees per hectare. An increase of about 88% was observed with 2222 trees ha^{-1} and the least increment of 29% with 2000 trees per hectare was recorded with regard to soil EC. This can be ascribed to the fact that our experimental soil was non-saline and no excess salts were present to leach out from the soil system in initial stages. In later stages, the release of salts by weathering the native minerals due to raised plantations (rhizo-acidification and solubilization) contributed to increasing the soil EC [11]. The significantly highest SOC of 0.70 mg kg^{-1} was recorded in the soil under the highest stand density (S1; 4444 trees per hectare), implying that a strong positive correlation exists between SOC and the number of trees per unit area (Figure 1). The growth increment of the *Melia dubia* plantation contributed to the buildup of soil organic carbon indirectly through increased root biomass [10, 21].

Likewise, the total cations consisting of Ca^{++}, Mg^{++}, Na^{+}, and K^{+} were also increased in the post harvest soil due to the planting of *Melia dubia*. Similarly, in the organic carbon content of the soil, the highest cationic increment in the soil was observed with S1 (4444 trees ha^{-1}), and the least increment was noticed with S3 (2000 trees ha^{-1}). Generally, tree plantations with a deep root system acidify the soil rhizosphere and solubilize/ release the fixed cations in the exchangeable sites, resulting in increased exchangeable cations [8]. The increase in the soil organic carbon content also enhances the exchangeable cations in the soil as the ion exchange capacity of the soil is very strongly related to soil organic matter content [29]. Further, the phenological behavior of *Melia dubia* being deciduous helps in the conservation of moisture in soil which aids in the weathering of minerals and mineralization of organic compounds [9]. All these reactions in the *Melia dubia* planted soil system resulted in more cationic ion release and made it in an exchangeable form.

As depicted in Table 4, the content of all the nutrients in post-harvest soils has increased when compared with their initial values. The highest soil N, P, and K contents were found in the plot with a low tree density of 2000 trees per hectare (S3; ($P < 0.05$). A spur in microbial activity because of the litter fall and root biomass facilitated nutrient recycling within the system, which contributed to increased soil N content [30]. This phenomenon was evidenced by a decrease in pH (acidification), an increase in EC (mineralization), and an increase in organic carbon content (decomposition) of the soil. The increased availability in *Melia dubia* plantation can be ascribed to the production of glucose in root exudates and the solubilization of fixed forms of phosphates [31]. The minimal loss of K ions through leaching and fixation of excess K ions in the exchangeable sites might be the reason for enhanced K availability in our experimental soil. In general, around 70- 80% of the applied K is retained on-site through belowground root biomass and litter fall in the plantation crops [6]. It can be observed that there is an increase in the available micronutrients of the post-harvest soil in all the plots as compared to their initial values. The increments ranged from 8.3 to 13.9% in Zn, 8.1 to 10.9% in Cu, 4.5 to 7.4% in Mn and 3.5 to 6.1% in Fe, respectively. However, differences between the various stand densities were not statistically significant ($P < 0.05$) in this regard. The stabilization of soil pH and increased SOC contributed to the increase in available micronutrients of the soil [32].

Table 4. *Effect of various stand densities on the available nutrients in the post-harvest soils of Melia dubia plantation.*

Stand density	$KMnO_4$-N (ppm)	Olsen-P (ppm)	NH_4OAc-K (ppm)	Av-Zn (ppm)	Av-Cu (ppm)	Av-Mn (ppm)	Av-Fe (ppm)
S1	79.38c	7.08c	171.00c	10.36a	4.62a	7.58a	8.20a
S2	84.81bc	8.05b	176.27bc	10.59a	4.66a	7.64a	8.29a
S3	92.94a	9.64a	187.48a	10.90a	4.73a	7.80a	8.40a
S4	86.07b	8.39b	180.80b	10.67a	4.69a	7.72a	8.36a

Note: All values represent the mean of three replications. Different alphabets in the corresponding column are significantly different according to DMRT at $P < 0.05$: n = 3.

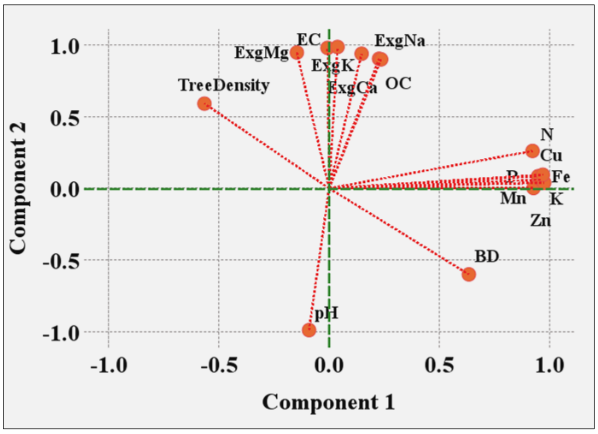

Figure 3. *Loading plots of principal component analysis (PCA). BD- bulk density; OC- organic carbon; EC- electrical conductivity; ExgCa- exchangeable Ca; ExgMg- Exchangeable Mg; ExgNa- exchangeable Na; ExgK- exchangeable K; all other plant nutrients denote their available forms in the soil.*

Principal component analysis (PCA) provides loading plots to assess the influence of different tree densities on soil fertility parameters (Figure 3). Accordingly, the soil pH and bulk density (BD) were negatively correlated with the number of trees per unit area. A substantial increase in soil electrical conductivity, organic carbon, and exchangeable cations (Ca^{++}, Mg^{++}, Na^{+} and K^{+}) was observed and positively correlated with the stand density of *Melia dubia* plantation. The available major (N, P, and K) and micro (Zn, Cu, Mn, and Fe) were also increased or stabilized with the plantation despite appreciable biomass production. As discussed earlier, the production of below ground root biomass and mineralization of organic matter including litter fall facilitated to the improvement of soil fertility parameters. The findings of our present study are in accordance with the results of Sumit *et al*. [7] in increasing the overall soil fertility (enhancing soil physico-chemical properties and available nutrients) under *Melia dubia* based agroforestry system in semiarid climate conditions.

3.3. Effect of Stand Density on Carbon Sequestration Potential of *Melia dubia* Plantation

Planted forests absorb atmospheric CO_2 through photosynthesis and primarily store it in the form of aboveground and belowground- biomass, in addition to fixing in the soil, making it a nature-based solution to mitigate global warming. Further, the optimization of stand density will provide climate-smart forestry, where carbon storage is enhanced further [33]. *Melia dubia* is one excellent tree species that could be adopted to trap atmospheric carbon, in addition to the economic benefits from biomass, particularly in semiarid regions [7].

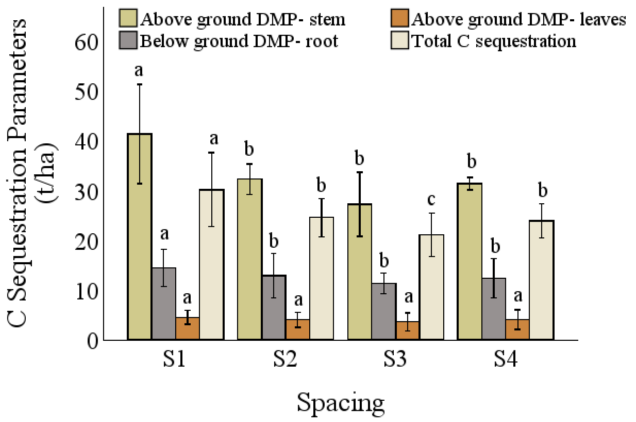

Figure 4. *Carbon sequestration in Melia dubia plantation at different stand densities. Error bars indicate standard deviations (n = 3). Different alphabets in the corresponding parameters are significantly different at P < 0.05 according to DMRT.*

In the present study, the highest above- and below- ground DMP were recorded in the stand density of 4444 trees per hectare at the pulpwood rotational period of three years. All other densities were statistically on par in producing stem and root DMP ($P < 0.05$; Figure 4). The highest leaf DMP was recorded with the treatment S1, but remained non-significant compared to all other spacings. This might be because, under semiarid irrigated conditions, *Melia dubia* trees effectively utilized the energy exerted through photosynthesis for the accumulation of above and below- ground biomass. The significantly highest total carbon sequestration (TCS) was found with S1, followed in the order of S2 > S4 > S3, suggesting that carbon sequestration in *Melia dubia*-based plantations has a strong positive correlation with stand density rather than individual tree growth. However, in the case of large-scale pulpwood plantations, the economic returns and associated environmental benefits such as carbon sequestration will be more pronounced by adopting the desired tree density level. Such carbon stock assimilation can have additional benefits in carbon offset programs and climate mitigation mechanisms [34].

4. Conclusion

This study aimed to optimize the stand density of *Melia dubia* in relation to raw material production to pulp and paper industries, as well as to achieve additional environmental benefits. The results indicate that a planting density in the range of 2000-2500 trees per hectare performed better in terms of producing salable pulpwood, with a spacing of 3.0 m × 1.5 m (2222 trees per hectare) achieving the highest yield. Although the higher planting density of 4444 trees per hectare offer more environmental benefits, the yield of merchantable pulpwood is relatively low. However, the wider spacing plantations also contributed to improving soil fertility and carbon sequestration under semiarid conditions. Adopting a density of 2222 trees per hectare could be highly suitable for pulpwood plantations, while also improving soil fertility and contributing to the carbon budget. One limitation of this study is that the experiments were conducted in a single semiarid location. Future studies should consider replicating the experiments under diverse climatic and soil conditions to validate the results. Subsequent research should focus on nutrient and water budgeting in *Melia dubia*-based pulpwood plantations to provide a more comprehensive understanding of sustainable management practices for this species.

Abbreviations

AGB	Above Ground Biomass
BD	Bulk Density
BGB	Below Ground Biomass
DMP	Dry Matter Production
DMRT	Duncan's Multiple Range Test
EC	Electrical Conductivity
GBH	Girth at Breast Height
LFB	Litter Fall Biomass
PCA	Principal Component Analysis
RBD	Randomized Block Design
SOC	Soil Organic Carbon
TC	Total Cations
TCS	Total Carbon Sequestration

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Author Contributions

Kuppusamy Jayakumar: Project administration, Supervision, Methodology, Writing – original draft

Vazram Prasath: Conceptualization, Methodology, Writing – review & editing

Perumal Sudhakar: Supervision, Writing – review & editing

Palanisamy Chezhian: Methodology

Thangavel Stalin: Methodology

Ramasamy Rajesh: Methodology

Conflicts of Interest

The authors declare no conflicts of interest.

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