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Response of short-rotation *Melia dubia* Cav. agroforestry plantation to mineral fertilization in a semiarid Alfisol

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Abstract
A field experiment was conducted to optimize the mineral fertilizer application dose to a short-rotation *Melia dubia* plantation raised in semiarid alfisol. Four fertilizer treatments consisting of absolute control, 100:50:100 kg NPK ha^{-1}, 150:75:150 kg NPK ha^{-1} and 200:100:200 kg NPK ha^{-1}, applied in 24 monthly equal splits, were studied for their effect on mean annual increments in tree height, GBH, stand volume and total biomass production in 36-month-old stand. Results confirmed the positive role of mineral fertilizers on mean annual growth increments in parameters such as tree girth (p =. 001), stand volume (p =. 012), total biomass production (p =. 034) and carbon sequestration (p =. 049) in short-rotation *M. dubia* plantations, with the application rate of 200:100:200 kg NPK ha^{-1} recording the highest values. However, the residual standardized regression analysis showed that application of mineral fertilizers are non-significant in increasing tree height (F = 1.561; p =. 216) and total biomass production (F = 4.774; p =. 34) due to a short-rotation of 3 years, a less fertilizer-responsive duration. In contrast, the mean annual increment in tree GBH (F = 6.433; p =. 015) and stand volume (F = 6.546; p =. 014) was found to be statistically significant. This study recommends application of 200:100:200 kg NPK ha^{-1} to short-rotation *M. dubia* plantations for higher wood productivity and to extend the rotational period for a higher fertilizer response, with increased wood and biomass production as well as the farm income.

Keywords: *Melia dubia*, mineral fertilizer recommendations, mean annual growth increment, fertilizer response, carbon sequestration

Introduction

The National Forest Policy (2014) emphasizes production of woody raw materials on farmers' fields, which has led to organized agroforestry for the production of wood-based raw materials. It also paved the way for increased participation of industries in using the agroforestry products at appropriate prices without disturbing the forest ecosystem. In India, the industrially important exotic tree species such as *Eucalyptus*, *Casuarina*, *Leucaena*, and *Populus* require specific climatic conditions and grow well in certain agro-climatic areas. On the other hand, *Melia dubia* is one of the indigenous fast-growing alternate pulpwood species that are adaptive to wide agro-climatic conditions (Thakur *et al*., 2017) [1] and the inclusion of *Melia dubia* in agroforestry has been found to be superior to many exotic tree plantations in terms of economic returns and ecosystem services like enhancing soil fertility and atmospheric carbon sequestration (Jayakumar *et al*., 2025) [2]. Furthermore, *M. dubia* is being advocated as an amenable tree species for agro-forestry without any deleterious effects on under-storied agricultural crops (Kumar *et al*., 2017 and Parmer *et al*., 2018) [3, 4]. The industrial and ecological importance of *M. dubia* has encouraged farmers to take large-scale plantations with various intercrops. Under commercial exploitation, knowledge of nutrient management needs to be clarified to the small and marginal farmers, who have been practicing traditional methods. The available information on the growth response of *M. dubia* to mineral fertilization is not sufficient for making suitable decisions on the use of fertilizers and the time of applications.

The application of mineral fertilizers, particularly the nitrogen (N), phosphorus (P), and potassium (K) has been seen as a means to enhance the productivity of short-rotation renewable forest plantations (Pukkala, 2017) [5]. The deficiency of any of these nutrients will negatively affect the growth and development of the plantations (Khalofah *et al*., 2022) [6]. N is essential for chlorophyll synthesis and vegetative growth and therefore should remain available during vegetative growth. P stimulates cell division and promotes root development and its deficiency delays growth increments. K plays a vital role in plant protection by maintaining cell turgidity throughout the lifecycle. However, excess or deficient nutrition will negatively impact the growth and targeted yield of the plantations (Alem, 2024) [7]. Furthermore, mineral fertilizers have not been widely used in agroforestry mainly due to a lack of knowledge about the quantities of fertilizer needed for different species and specific soil types. Information on optimum dosages of inorganic nutrients for better growth of *Melia dubia* is lacking or very limited under Indian conditions. Generation of such information will be helpful in standardizing the most favorable dosage of nutrients for *Melia dubia* plantations to obtain maximum wood productivity.

Even though this study was principally aimed at optimizing the mineral fertilizer dose for a commercial agroforestry *M. dubia* plantation grown under semiarid conditions, we studied the annual growth increment and the effect of different doses of mineral fertilization on the GBH, height, stand volume, and carbon sequestration through a residual standardized regression model. This study will provide insight into mineral fertilizer application to short-rotation *M. dubia* plantations.

Materials and Methods

Field experiment

A field experiment for optimizing mineral nutrition for the short-rotation *M. dubia* clone GK-10 was conducted at plantation research block of TNPL, situated under semiarid conditions. The sandy loam alfisol soil was neutral in pH with non-saline nature, having 182 kg ha^{-1} of N, 16 kg ha^{-1} of P and 396 kg ha^{-1} of K, respectively. The experiment was laid out in a randomized block design in three replications with the mineral fertilizer treatments as depicted in Table 1:

Table 1: Doses of mineral fertilizers applied to short-rotation *Melia dubia* plantation

Treatment	Treatment code	Fertigation details
1	F1	Control - No Fertilizer application
2	F2	100:50:100 NPK kg ha^{-1}
3	F3	150:75:150 NPK kg ha^{-1}
4	F4	200:100:200 NPK kg ha^{-1}

Planting was established at a spacing of 3.0 m × 1.5 m with a population of 2,222 plants ha^{-1}. Each treatment plot had a gross plot area and a net plot area of 144 m^2 and 54 m^2, respectively. After the necessary land preparations, the *M. dubia* clone GK-10 plants were planted in all the plots during the first week of January 2018. The entire fertilizer doses were applied through drip irrigation according to the treatments using commercial grade water soluble fertilizers in 24 equal monthly splits.

Biometric observations

The biometric observations were made in 12-, 24-, and 36-month-old plantations. The total height of the trees (m) was measured using a Haga altimeter. All the trees were marked at 1.37 m from ground level, and GBH (cm) was measured using tailor's tape. The volume of standing trees (m3) was estimated using the formula of Chaturvedi and Khanna (1982) [8]: $V = \pi r^2 h \times$ Form Factor (0.58), where V is the volume of the tree; r is the radius at breast height and h is the height of the tree.

The measurement of total biomass, including the above ground (AGB) and below ground (BGB) was done using destructive sampling method in triplicate. The representative trees were felled at ground level and the fresh weights of the above ground tree components (stem, twigs and leaves) and below ground tree components (coarse and fine roots) were measured immediately. The dry matter production (DMP) of AGB and BGB was calculated after drying them to a constant weight and converted into fixed carbon by multiplying the DMP by 0.50 (Brown and Lugo, 1982) [9] and expanded to t ha^{-1}, which is considered the carbon sequestration potential of *M. dubia* plantation. From the biometric recordings, annual growth increments in growth parameters, *viz*., GBH, tree height, stand volume, total biomass and C sequestration were calculated for the 2nd year and 3rd year and the mean annual increments were presented.

Statistical analysis

Data were subjected to univariate analysis of variance (ANOVA) to find the effect of different doses of mineral fertilization on mean annual increments in growth parameters. A post hoc test of Duncan's multiple range test (DMRT) was employed to find the significant difference in wood yield and carbon sequestration. With the observed growth data, a residual standardized regression analysis was performed to predict the significant effect of fertilizer application on the dependent growth variables and carbon sequestration of *M. dubia* plantations. All statistical analyses were conducted using SPSS ver. 30 (SPSS Inc., Chicago, USA).

Results and Discussion

In general, it was observed that the fertilized trees were found to be significantly superior in mean annual growth increments compared to the trees in control plots, confirming the important role of mineral fertilizers in short-rotation agroforestry plantations. The highest wood yield was obtained with the fertilizer application at the rate of 200:150:200 kg ha^{-1} of NPK throughout the growth period (Fig 1). This was followed by the application of 150:75:150 kg of NPK ha^{-1}. The minimal dose of fertilizer application (100:50:100 kg NPK ha^{-1}) had no significant effect in this regard, as the yield was statistically comparable with the control treatment. However, the treatments F4 and F3, which received a higher dose of fertilizers, were found to be statistically on par and superior in sequestering atmospheric carbon at 36 months after planting (MAP). During the first year, the response of *M. dubia* plantation to different doses of inorganic fertilizer was minimal in increasing the growth rate and carbon sequestration, which was likely because of underdeveloped root system and limited exploitation of the rhizospheric zone (Fig 1). However, from the second year onwards, a clear trend was noted among the fertilizer doses.

Studies revealed that mineral fertilization increases the GBH of early wood by thickening the cell wall. However, the magnitude of this effect is mainly dependent on the frequency and cumulative quantity of fertilizer application (Shmulsky and Jones 2019) [10]. In the present study, a cumulative application of 200:100:200 kg NPK ha^{-1} at a monthly frequency for two years recorded significantly higher GBH ($F = 9.974$; $p = .001$; Table 2). The application of 150:75:150 kg NPK ha^{-1} followed this treatment in increasing the tree GBH. The lowest fertilizer rate of application (100:50:100 kg NPK ha^{-1}; F2) showed no statistical advantage over control treatment in increasing the GBH. Although the p-value of this parameter was higher than 0.05, indicating that it did not reach statistical significance, the regression analysis showed a generalized significant effect of fertilizer application on the GBH increments in *M. dubia* plantation ($F = 6.433$; $p = .015$; Fig. 2a). Therefore, it is worth considering even a small quantity of fertilizer application over no fertilization for increasing the GBH in *M. dubia* plantations.

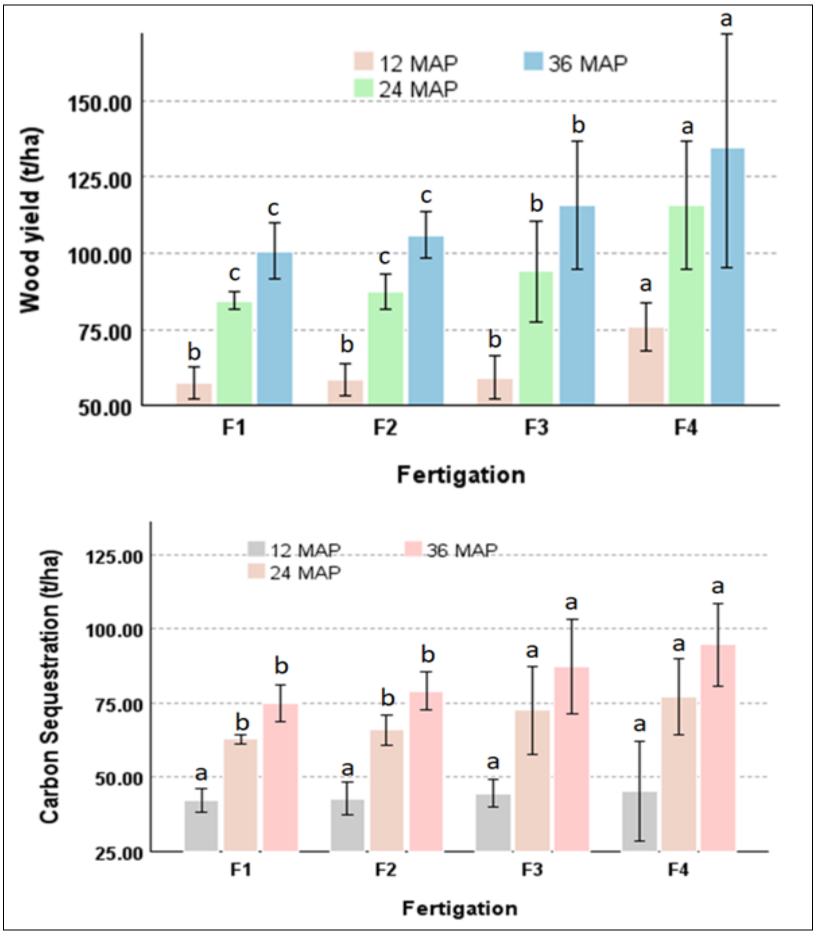

Fig 1: Wood yield and carbon sequestration obtained from different mineral fertilizer doses for the *M. dubia* plantation. Error bars indicate 95% confidence intervals. Different letters in the corresponding parameters are significantly different according to DMRT at $p < 0.05$.

Table 2: Effect of doses of mineral fertilizers on the mean annual increment in growth parameters of the *Melia dubia* agroforestry plantation

Treatment	Fertigation dose	Mean annual girth increment (cm year^{-1})	Mean annual height increment (m year^{-1})	Mean annual volume increment (m^3 year^{-1})	Mean annual total biomass increment (t ha^{-1} year^{-1})	Mean annual increment in carbon sequestration (t ha^{-1} year^{-1})
F1	Control - No Fertilizers	3.41 ±0.12	0.94±0.05	31.3±0.84	32.44±0.11	16.36±1.60
F2	100:50:100 NPK kg ha^{-1}	3.40±0.14	1.00±0.05	34.89±0.74	36.32±0.14	18.16±1.71
F3	150:75:150 NPK kg ha^{-1}	3.60±0.19	1.07±0.04	40.85±1.28	42.37±0.14	21.43±1.93
F4	200:100:200 NPK kg ha^{-1}	5.14±0.28	1.06±0.07	45.10±1.22	42.33±0.12	21.17±1.56
Error mean square		2.826	.013	150.692	94.844	23.950
F value		9.974	.840	5.634	4.012	3.509
P value		.001	.498	.012	.034	.049

The doses of fertilizer application showed no significant difference in increasing the height of *M. dubia* trees (F =. 840; p =. 498; Table 2), which was confirmed in regression analysis (F = 1.561; p =. 218; Fig. 2b). In many of the earlier studies, the height potential of *M. dubia* traits was reported to be between 10 m and 12 m only (Goswami *et al*., 2020; Sharma *et al*., 2021; Jayakumar *et al*., 2025) [11, 12, 2]. Since the height parameter in *M. dubia* is more of a genetic character, rather than an environmental influence, the exogenous fertilizer application had a minor effect in increasing the height of the trees.
The statistical analyses, *viz*., ANOVA as well as residual standardized regression showed a significant effect of mineral fertilization on increasing the volume of *M. dubia* plantation (p =. 012 in ANOVA-Table 2 and p =. 014 in regression analysis-Fig. 2c), indicating that stand volume in *M. dubia* plantations can be increased through mineral fertilizers from the first year onwards, even though the height of the trees remains unalterable. This can be explained by the fact that the increment in stand volume was mainly attributed to the increment in GBH of individual trees (Prasad *et al*., 2011) [13]. Further, the lower quantity and greater frequency of fertilizer application through the drip irrigation system provided effective utilization of mineral nutrition by individual trees and resulted in an increase in the volume of the plantation (Neupane *et al*., 2024) [14].
The positive effect of mineral fertilization extended to total biomass increment and C sequestration as well. Though the ANOVA in Table 2 showed a significance of F = 4.012 and p =. 034, the residual standardized regression in Fig. 2d recorded a relatively less significant F value of 4.774 at p = 0.34 for biomass production. While applying mineral nutrition to short-term agroforestry plantations, the duration of the fertilizer effect should also be considered for effective plantation management. In contrast to agricultural crops, agroforestry plantations exhibit a long duration response to mineral fertilizers. Even though N is associated with short-term response, the effect persists for a mid-term rotation of 8-10 years (Akello *et al*., 2024) [15]. Some research points out an even higher response period of 15 years after the last application of N (Smolander *et al*., 2022) [16]. The

response of P application to tree plantations was found to be longer than that of N and K, due to its effective retention in agroforestry systems, with the potential to improve tree growth even in subsequent rotations of 20 years (Everett and Palm-Leis, 2009; Akello *et al*., 2024) [17, 15]. The application of K nutrient to tree crops could be a reserve for the present as well as subsequent short and mid-term rotations, as the applied K is fixed in the soil system and released gradually with the progress of rhizo-acidification (Crous *et al*., 2009) [18]. With the addition of mineral NPK fertilizers, the availability of these nutrients is further enhanced in the soil, as about 70-80% of the nutrients are recycled in agroforestry plantations (Patil *et al*., 2017) [19].

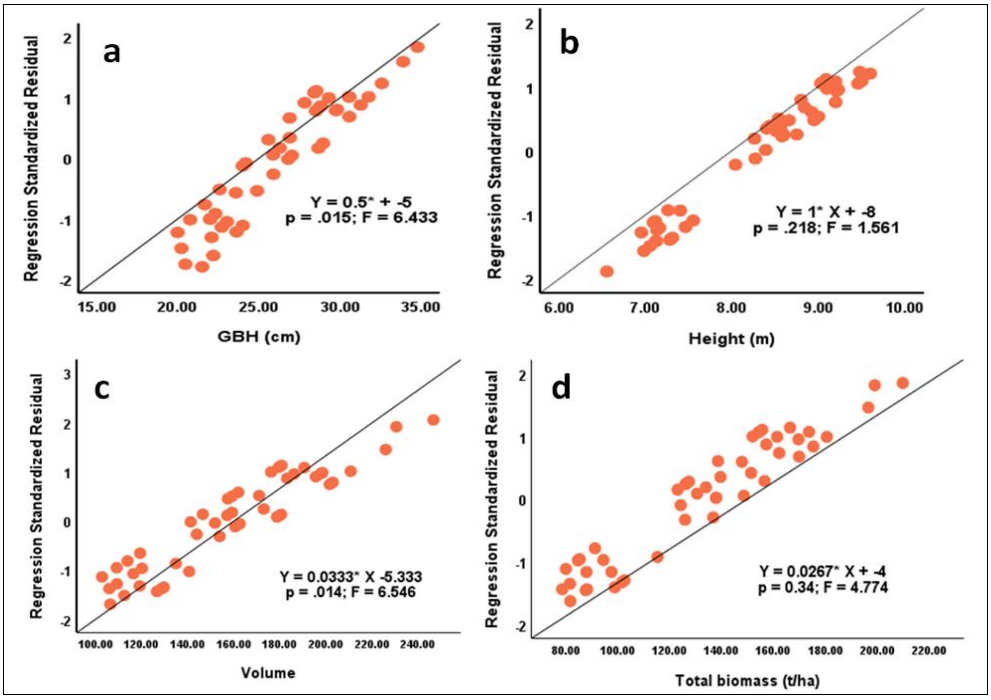

Fig 2: Standardized residuals (observed and predicted in regression analysis) of mineral fertilizer application against the growth and productivity of a short rotation *Melia dubia* agroforestry plantation: a) effect on GBH; b) effect on tree height; c) effect on tree volume; d) effect on total biomass production.

From ANOVA, it is apparent that mineral fertilizer application increased the mean annual growth increments (Table 2). However, the results of the regression analysis (Fig. 2) suggest that the biomass production and subsequent C sequestration in short-rotation *M. dubia* plantations are governed by other factors as well, in addition to mineral nutrition. For instance, Deng *et al*. (2024) [20] noted that the fertilizer response of perennial trees is influenced by factors such as the genetic nature of the species, soil fertility level, and prevailing climatic conditions.

Conclusion

This study found that a mineral fertilizer application of 200:100:200 kg NPK ha^{-1} to *M. dubia* plantations at a monthly interval of 24 months was found to be better in relation to commercial wood production at 36 month of age, with a potential of further improving the yield in subsequent years. It is, however, the regression analysis that clearly indicated that the fertilizer application for total biomass production in the *M. dubia* plantation has a non-significant effect, likely due to the short responsive growth period of 3 years. Therefore, this fertilizer recommendation cannot be generalized without considering the similarities in soil (alfisol) and climatic (semiarid) conditions, and the purpose for which *M. dubia* plantations are raised: for wood production or total biomass production. From the results of this study, it is possible to conclude that a mineral fertilizer dose of 200:100:200 kg NPK ha^{-1} can be applied to short-rotation *M. dubia* plantations for higher wood productivity. In addition, extending the rotational period will result in a higher fertilizer response, with increased wood and biomass productivity and farm income. Future studies should focus on the residual effects of applied mineral fertilizers in subsequent rotations.

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