Carbon Sequestration potential of *Melia dubia* progenies and plantations with varied spatial geometries at different age gradations in South Gujarat

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ABSTRACT: : *We evaluated Melia dubia for carbon sequestration potential under two different studies. First studies comprised of 17 open pollinated progenies planted at 3×3 m and the second one was plantations of same species at 2×2, 3×2, 3×3 and 4×2 m spatial geometries under randomized block design. The progeny evaluation study revealed that at the age of 5 years, progeny GJ09 produced maximum biomass (95.61 t/ha) with average maximum productivity of 19.12 t/ha/year, carbon stocks and carbon sequestration to tune of 48.76 t/ha and 178.95 t/ha, respectively. Further, progeny GJ09 showed carbon stock and carbon sequestration rate of 9.75 t/ha/year and 35.79 t/ha/year, respectively. The spatial geometry evaluation studies deduced that there was significant variation in biomass productivity, carbon stock and carbon sequestration among individuals under different spatial geometries. Although, at the age of 5-years, the individual tree biomass, carbon stock and carbon sequestration was maximum under 4×2 m spacing. However, at the 5-years of age, owing to the maximum tree per hectare 2×2 m spatial configuration provided highest biomass (20.29 t/ha/year), carbon stocks (10.35 t/ha/year) and carbon sequestration potential (24.94 t/ha/year). These studies revealed that M. dubia being fast growing species has great potential for carbon sequestration. The progenies with higher sequestration rate can be utilized for further planation programmes.*

1. INTRODUCTION

Carbon sequestration is the long-term storage or removal of that CO_2 in geological, biological, or ocean sinks. Climate change certainly is one of the most demanding environmental challenges being witnessed in world today. The speedy increase in atmospheric carbon dioxide (CO_2) and other greenhouse gases due to human activities such as industrialization, fossil fuel combustion, and deforestation has led to momentous changes in global climate systems. The increasing concentration of atmospheric carbon dioxide is a primary driver of global warming. Among the various strategies proposed to mitigate climate change, carbon sequestration has appeared as a vital natural answer. Manmade plantations, agroforests and forest ecosystems play a vital role in this process by acting as natural carbon sinks (Lal, 2008; Thakur *et al.,* 2011; Panwar *et al.,* 2022). This capacity to capture and store carbon helps offset emissions produced by human activities.

The Intergovernmental Panel on Climate Change (IPCC) has underlined the importance of forests and tree-based ecosystems in mitigating climate change by enhancing carbon sequestration (FAO, 2020; IPCC, 2022). Sustainable forest management, afforestation, and reforestation initiatives are therefore widely recommended as practical and cost-effective strategies to reduce atmospheric carbon levels. Urban forestry and agroforestry systems also contribute significantly to carbon sequestration. Agroforestry practices, which integrate trees with agricultural crops or livestock systems, enhance carbon storage while simultaneously improving soil productivity and agricultural sustainability (Bhusara *et al.,* 2016). These integrated systems are increasingly recognized as important strategies for climate-smart agriculture. Globally, governments and international organizations are promoting tree-based climate solutions through various environmental programs and policies. Initiatives such as afforestation, reforestation, and forest conservation are increasingly emphasized as part of climate mitigation strategies. Organizations such as the United Nations Environment Programme and the Food and Agriculture Organization advocate for sustainable forest management and restoration of degraded landscapes to increase carbon sequestration capacity (UNEP, 2021). These initiatives not only help mitigate climate change but also contribute to achieving

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sustainable development goals related to biodiversity conservation, poverty reduction, and environmental protection. Carbon sequestration by trees is a vital natural process that plays a key role in mitigating climate change and maintaining ecological balance (Luna *et al.,* 2016; UNEPA, 2023).

India's nationally determined contribution (NDC), to sequester an additional 2.5 to 3-billion-ton carbon dioxide (CO_2) equivalent by 2030 under the Paris Climate agreement, can be achieved by integrating trees in multiple land uses (Ruchika, 2019). In this direction, many industrially important fast growing species are already popular among the farmers and are integrated either under agroforestry or as sole plantations. These species provide a sustainable alternative to low-carbon land use systems, offering high yields of renewable woody biomass along with multiple ecosystem benefits (Luna *et al.,* 2009, 2011, 2014; Panwar *et al.,* 2022; Jinger *et al.,* 2024). Still we need to look for indigenous multipurpose tree species which could be utilized in wood based industries on one hand and have high carbon sequestration potential in shorter period leading to achieve NDC at national level sustainable development goals globally. One such species is *Melia dubia*. This species has already explored for its multipurpose potential (Sinha *et al.,* 2019; Sukhadiya *et al.,* 2021; Malek *et al.,* 2024) and is being cultivated as potential agroforestry ideotype (*Bhusara et al.,* 2018; Thakur *et al.,* 2018; Mohanty *et al.,* 2019). Its potential for carbon sequestration has not been explored much so far. Therefore, the present study intended to put forth the carbon sequestration potential different progenies and plantations done at varying spatial geometries in southern Gujarat.

2. MATERIALS AND METHODS

Edapho-climatic conditions of site

The investigation was carried out at the College of Forestry, Navsari Agricultural University, Navsari (20.95N latitude, 75.90E longitude with an altitude of 10 m amsl), Gujarat, India, during 2014-2019. Climate of area is characterized humid and warm with monsoon rainfall of around 1500 mm (June-September), moderately cold in winter (November-February) and fairly hot and humid in summer (March-May). Soils of experimental site is deep black originated from old alluvium of basaltic material, taxonomically placed under the group of *Ustochrepts*, sub group of *verti Ustochrepts*, sub order of *orchrepts* and order of *inceptisols*, characterized by clay, deep, moderately drained with good water holding capacity. The soil cracks heavily on drying and expands on wetting and predominant clay mineral found to be montmorillonite. Soil pH and average available nitrogen, phosphorus, potassium, and organic carbon of experimental site was 225.79 kg ha^{-1}, 32.81 kg ha^{-1}, 310.34 kg ha^{-1}, 7.67 and 0.87%, respectively.

Experimental details

The study-1 was conducted in randomized block design with 17 open pollinated *Melia dubia* Cav. progenies as treatments with three replications (three individuals in each replication). The seeds of 16 families were supplied by Division of Genetics and Tree Improvement, Forest Research Institute Dehradun, Uttarakhand, India and family named GJ09 was local source (collected from Northern most tip of Western Ghats), which were collected from South Gujarat, India. Planting was carried out in January, 2014 at 3x3 m spacing with boundary row to avoid edge effect.

The study-2 was comprised of *Melia dubia* plantations at with spatial geometries of 2×2, 3×2, 3×3 and 4×2 m. Both the experiments managed following normal tree management practices. No additional fertilizer (organic or inorganic) was applied throughout the period and trees were allowed to natural pruning after 2nd year onwards.

Above ground biomass

The tree height and diameter at breast height (DBH; at 1.37 cm above ground) were recorded (from 1st to 5th years of age) periodically following standard methods in each replication (3 tree/replication in progeny evaluation and 5 trees per replication in spatial geometry evaluation) of each family. Standing tree fresh biomass was calculated following regression equations B=0.0299(HD^2)+7.48 (Thakur *et al.,* 2021), Where, B =total tree fresh biomass, H=height (m) of the tree and D= DBH (cm). Estimated fresh biomass was converted to dry mass *i.e.* 50 per cent of the fresh biomass (Laxmai *et al.,* 2021).

Belowground Biomass

Below ground biomass (BGB) of the tree includes live root biomass, excluding fine roots and was calculated using 0.26 factor of root: shoot ratio (Ravindranath and Ostwald, 2008).

$$\text{BGB (t ha}^{-1}) = \text{AGB (t ha}^{-1}) \times 0.26$$

Total Biomass (TB)

Sum of AGB and BGB gives total biomass (TB) of the tree (Ravindranath and Ostwald, 2008).

$$\text{TB (t ha}^{-1}) = \text{AGB (t ha}^{-1}) + \text{BGB (t ha}^{-1})$$

Carbon stock and carbon sequestration

Then biomass was converted to total carbon stock by multiplying factor of 0.51 (Dury *et al.,* 2002) and carbon sequestration by multiplying the carbon stock by factor of 3.67 (Van-Kooten, 1999).

Statistical analysis

The data generated were subjected to the statistical analysis following randomized block design (RBD) and ANOVA was constructed. Further, Duncan's multiple range test (DMRT) was used to compare the sets of means of each treatment following Sheoran (n.d.). OPSTAT - Online Statistical Analysis Tools. CCS HAU, Hisar. http://14.139.232.173/opstat/default.asp.

3. RESULTS AND DISCUSSION

Carbon Sequestration potential of *Melia dubia* progenies

Biomass productivity

The results indicated that biomass production (kg/tree and ton/ha; dry weight basis) varied significantly (p<0.05) amongst the 17 progenies (Table 1). In the 1st, 2nd and 3rd year the maximum biomass production (9.05, 24.3 and 37.00 kg/tree and 10.05, 27.00 and 41.10 t/ha, respectively) was put up by progeny number 259. At the age of two years, biomass production (21.83 kg/tree and 24.25 t/ha) by progeny 260 was at par with that of 259. At the age of 4 years, highest biomass production (53.85 kg/tree and 59.83 t/ha) was of progeny GJ09, which however was statistically at par with progeny 260. However, at the age of 5 years (Table 1), GJ09 put up maximum biomass (86.06 kg/tree and 95.61 t/ha) with average maximum productivity of 17.21 kg/tree/year and 19.12 t/ha/year (Fig. 1a and b). The minimum biomass production and productivity was of progeny 270 at the age of 5 years.

Carbon stock and carbon sequestration

The results expressed that carbon stocks varied significantly among the progenies and the age gradations (Table 2). Among the 17 progenies, 259 progeny acquired maximum carbon stock amounting to 4.61, 12.39 and 18.87 kg/tree and 5.13, 13.77 and 20.96 t/ha from 1st to 3rd year of age. At 2nd year progeny 260 had at par carbon stock with 259. Progeny GJ09 showed highest carbon stock amounting to 27.47 and 43.89 kg/tree and 30.51 and 48.76 t/ha at 4th and 5th year, respectively. However, at 4th year progeny 260 was at par with GJ09 (Table 2). Minimum carbon stocks were of family 270 at 5 years of age.

Further, owing to maximum carbon stock, progeny 259 sequestered maximum carbon of 16.94, 45.49 and 69.25 kg/tree and 18.82, 50.53 and 76.94 t/ha at age of 1st, 2nd and 3rd year (Table 3). However, at 4th and 5th year, the maximum carbon sequestration (100.80 and 161.07 kg/tree and 111.99 and 178.95 t/ha) was of GJ09. Progeny 260 sequestered statistically at par carbon to that of GJ09. Progeny 270 sequestered minimum carbon at the age of 5 years.

Carbon stock and carbon sequestration potential

The results pinned out that the carbon stock and carbon sequestration potential of *M. dubia* progenies varied significantly at the age of 5 years (Fig. 2 and 3). Maximum carbon stock (8.78 kg/tree/year and 9.75 t/ha/year) and carbon sequestration (32.21

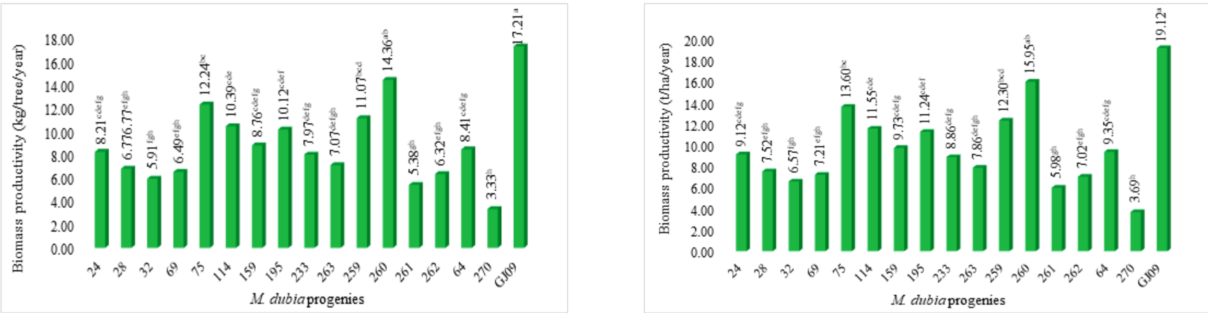

Figure 1. Variation in a) per tree [SE(m)±1.26] and b) per hectare biomass productivity [SE(m)±1.40] by *M. dubia* progenies in South Gujarat, means with different superscript letter in each bar indicate significant difference (p<0.05) according to Duncan's Multiple Range Test

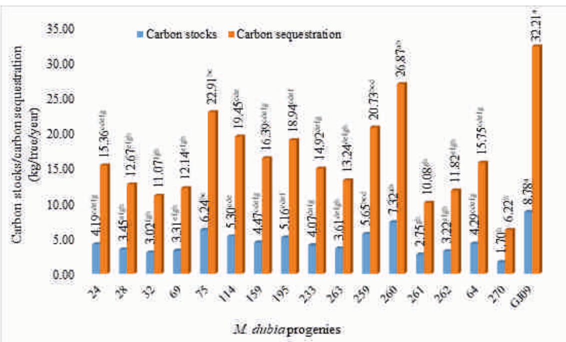

Figure 2. Variation in individual tree carbon stocks [SE(m)±0.64] and carbon sequestration [SE(m)±2.36] by *M. dubia* progenies in South Gujarat, means with different superscript letter in each bar indicate significant difference (p<0.05) according to Duncan's Multiple Range Test

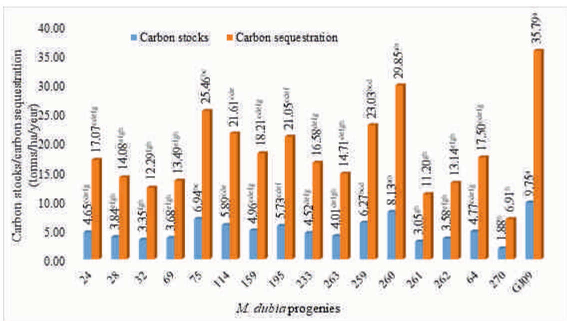

Figure 3. Variation in carbon stocks [SE(m)±0.72] and carbon sequestration [SE(m)±2.62] by *M. dubia* progenies in South Gujarat, means with different superscript letter in each bar indicate significant difference (p<0.05) according to Duncan's Multiple Range Test

Table 1. Variation in biomass production of *M. dubia* progenies in South Gujarat

Progeny	Dry biomass (kg/tree)					Dry biomass (t/ha)				
	Age (years)									
	1	2	3	4	5	1	2	3	4	5
24	6.94^{bc}	17.14^{b}	25.47^{bcd}	30.40^{bcde}	41.04^{cdefg}	7.71^{bc}	19.04^{b}	28.3^{bcd}	33.77^{bcde}	45.60^{cdefg}
28	5.64^{cd}	11.43^{de}	17.89^{def}	25.18^{def}	33.85^{efgh}	6.26^{cd}	12.7^{de}	19.88^{def}	27.98^{def}	37.6^{efgh}
32	5.12^{d}	10.17^{de}	15.71^{ef}	19.97^{ef}	29.56^{fgh}	5.68^{d}	11.3^{de}	17.45^{ef}	22.18^{ef}	32.84^{fgh}
69	5.57^{cd}	8.92^{de}	18.82^{de}	26.64^{cdef}	32.44^{efgh}	6.19^{cd}	9.91^{de}	20.91^{de}	29.6^{cdef}	36.04^{efgh}
75	7.44^{b}	16.44^{bc}	28.47^{bc}	37.41^{bcd}	61.21^{bc}	8.27^{b}	18.26^{bc}	31.63^{bc}	41.56^{bcd}	68.01^{bc}
114	5.02^{d}	8.55^{de}	24.84^{bcd}	42.27^{ab}	51.96^{cde}	5.58^{d}	9.5^{de}	27.6^{bcd}	46.96^{ab}	57.73^{cde}
159	5.67^{cd}	9.32^{de}	18.57^{de}	22.89^{def}	43.79^{cdefg}	6.29^{cd}	10.36^{de}	20.63^{de}	25.43^{def}	48.65^{cdefg}
195	7.29^{b}	20.68^{ab}	28.41^{bc}	40.73^{abc}	50.6^{cdef}	8.1^{b}	22.97^{ab}	31.56^{bc}	45.25^{abc}	56.22^{cdef}
233	4.91^{d}	7.82^{de}	11.42^{ef}	22.47^{def}	39.87^{defg}	5.45^{d}	8.69^{de}	12.69^{ef}	24.97^{def}	44.29^{defg}
263	5.99^{bcd}	12.14^{cd}	20.3^{cde}	28.19^{bcde}	35.37^{defgh}	6.66^{bcd}	13.49^{cd}	22.55^{cde}	31.31^{bcde}	39.29^{defgh}
259	9.05^{a}	24.3^{a}	37.00^{a}	41.67^{abc}	55.37^{bcd}	10.05^{a}	27.00^{a}	41.10^{a}	46.29^{abc}	61.52^{bcd}
260	6.46^{bcd}	21.83^{a}	32.61^{ab}	52.08^{a}	71.79^{ab}	7.18^{bcd}	24.25^{a}	36.23^{ab}	57.86^{a}	79.75^{ab}
261	5.38^{d}	9.9^{de}	13.52^{ef}	17.03^{ef}	26.92^{gh}	5.98^{d}	11de	15.02^{ef}	18.92^{ef}	29.91^{gh}
262	4.9^{d}	7.00^{e}	14.32^{ef}	29.23^{bcde}	31.59^{efgh}	5.45^{d}	7.77^{e}	15.91^{ef}	32.47^{bcde}	35.1^{efgh}
64	4.93^{d}	9.79^{de}	14.69^{ef}	28.50^{bcde}	42.07^{cdefg}	5.48^{d}	10.87^{de}	16.32^{ef}	31.66^{bcde}	46.74^{cdefg}
270	4.92^{d}	6.63^{e}	8.87^{f}	12.32^{f}	16.63^{h}	5.46^{d}	7.37^{e}	9.85^{f}	13.68^{f}	18.47^{h}
GJ 09	6.36^{bcd}	20.93^{ab}	32.67^{ab}	53.85^{a}	86.06^{a}	7.06^{bcd}	23.25^{ab}	36.30^{ab}	59.83^{a}	95.61^{a}
SE(m)±	0.46	1.50	2.68	4.56	6.31	0.51	1.67	2.97	5.06	7.01

Means with different superscript letter in the same column indicate significant difference ($p<0.05$) according to Duncan's Multiple Range Test

Table 2. Variation in carbon stocks of *M. dubia* progenies in South Gujarat

Progeny	Carbon stocks (kg/tree)					Carbon stocks (t/ha)				
	Age (years)									
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
24	3.54^{bc}	8.74^{b}	12.99^{bcd}	15.50^{bcde}	20.93^{cdefg}	3.93^{bc}	9.71^{b}	14.43^{bcd}	17.22^{bcde}	23.26^{cdefg}
28	2.87^{cd}	5.83^{de}	9.12^{def}	12.84^{def}	17.26^{efgh}	3.19^{cd}	6.48^{de}	10.14^{def}	14.27^{def}	19.18^{efgh}
32	2.61^{d}	5.19^{de}	8.01^{ef}	10.18^{ef}	15.08^{fgh}	2.90^{d}	5.77^{de}	8.90^{ef}	11.31^{ef}	16.75^{fgh}
69	2.84^{cd}	4.55^{de}	9.60^{de}	13.59^{cdef}	16.55^{efgh}	3.16^{cd}	5.06^{de}	10.66^{de}	15.10^{cdef}	18.38^{efgh}
75	3.80^{b}	8.38^{bc}	14.52^{bc}	19.08^{bcd}	31.22^{bc}	4.22^{b}	9.31^{bc}	16.13^{bc}	21.20^{bcd}	34.68^{bc}
114	2.56^{d}	4.36^{de}	12.67^{bcd}	21.56^{ab}	26.50^{cde}	2.84^{d}	4.84^{de}	14.08^{bcd}	23.95^{ab}	29.44^{cde}
159	2.89^{cd}	4.76_{de}	9.47^{de}	11.67^{def}	22.33^{cdefg}	3.21^{cd}	5.28^{de}	10.52^{de}	12.97^{def}	24.81^{cdefg}
195	3.72^{b}	10.55^{ab}	14.49^{bc}	20.77^{abc}	25.81^{cdef}	4.13^{b}	11.72^{ab}	16.10^{bc}	23.08^{abc}	28.67^{cdef}
233	2.50^{d}	3.99^{de}	5.82^{ef}	11.46^{def}	20.33^{defg}	2.78^{d}	4.43^{de}	6.47^{ef}	12.73^{def}	22.59^{defg}
263	3.06^{bcd}	6.19^{cd}	10.35^{cde}	14.37^{bcde}	18.04^{defgh}	3.40^{bcd}	6.88^{cd}	11.5^{cde}	15.97^{bcde}	20.04^{defgh}
259	4.61^{a}	12.39^{a}	18.87^{a}	21.25^{abc}	28.24^{bcd}	5.13^{a}	13.77^{a}	20.96^{a}	23.61^{abc}	31.37^{bcd}
260	3.30^{bcd}	11.13^{a}	16.63^{ab}	26.56^{a}	36.61^{ab}	3.66_{bcd}	12.37^{a}	18.48^{ab}	29.51^{a}	40.67^{ab}
261	2.74^{d}	5.05^{de}	6.9^{ef}	8.69^{ef}	13.73^{gh}	3.05^{d}	5.61^{de}	7.66^{ef}	9.65^{ef}	15.26^{gh}
262	2.50^{d}	3.57^{e}	7.30^{ef}	14.91^{bcde}	16.11^{efgh}	2.78^{d}	3.96^{e}	8.11^{ef}	16.56^{bcde}	17.9^{efgh}
64	2.52^{d}	4.99^{de}	7.49^{ef}	14.53^{bcde}	21.46^{cdefg}	2.79^{d}	5.55^{de}	8.32^{ef}	16.15^{bcde}	23.84^{cdefg}
270	2.51^{d}	3.38^{e}	4.52^{f}	6.28^{f}	8.48^{h}	2.79^{d}	3.76^{e}	5.02^{f}	6.98^{f}	9.42^{h}
GJ 09	3.24^{bcd}	10.67^{ab}	16.66^{ab}	27.47^{a}	43.89^{a}	3.60^{bcd}	11.86^{ab}	18.51^{ab}	30.51^{a}	48.76^{a}
SE(m)±	0.23	0.77	1.37	2.32	3.22	0.26	0.85	1.52	2.58	3.58

Means with different superscript letter in the same column indicate significant difference ($p<0.05$) according to Duncan's Multiple Range Test

Table 3. Variation in carbon sequestration of *M. dubia* progenies in South Gujarat

Progeny	Carbon sequestration (kg/tree)					Carbon sequestration (t/ha)				
	Age (years)									
	1	2	3	4	5	1	2	3	4	5
24	12.98^{bc}	32.08^{b}	47.67^{bcd}	56.89^{bcde}	76.82^{cdefg}	14.42^{bc}	35.64^{b}	52.96^{bcd}	63.21^{bcde}	85.35^{cdefg}
28	10.55^{cd}	21.39^{de}	33.49^{def}	47.13^{def}	63.35^{efgh}	11.72^{cd}	23.77^{de}	37.21^{def}	52.37^{def}	70.38^{efgh}
32	9.58^{d}	19.04^{de}	29.40^{ef}	37.37^{ef}	55.33^{fgh}	10.64^{d}	21.16^{de}	32.66^{ef}	41.52^{ef}	61.47^{fgh}
69	10.43^{cd}	16.7^{de}	35.23^{de}	49.87^{cdef}	60.72^{efgh}	11.59^{cd}	18.55^{de}	39.14^{de}	55.40^{cdef}	67.46^{efgh}
75	13.93^{b}	30.77^{bc}	53.28^{bc}	70.02^{bcd}	114.57^{bc}	15.48^{b}	34.19^{bc}	59.20^{bc}	77.79^{bcd}	127.29^{bc}
114	9.40^{d}	16.00^{de}	46.5^{bcd}	79.11^{ab}	97.25^{cde}	10.44^{d}	17.78^{de}	51.66^{bcd}	87.89^{ab}	108.05^{cde}
159	10.61^{cd}	17.45^{de}	34.76^{de}	42.84^{def}	81.96^{cdefg}	11.78^{cd}	19.39^{de}	38.62^{de}	47.6^{def}	91.06^{cdefg}
195	13.65^{b}	38.7^{ab}	53.17^{bc}	76.24^{abc}	94.72^{cdef}	15.16^{b}	43.00^{ab}	59.07^{bc}	84.70^{abc}	105.23^{cdef}
233	9.19^{d}	14.64^{de}	21.37^{ef}	42.06^{def}	74.62^{defg}	10.21^{d}	16.27^{de}	23.75^{ef}	46.73^{def}	82.91^{defg}
263	11.22^{bcd}	22.72^{cd}	38.00^{cde}	52.75^{bcde}	66.19^{defgh}	12.46^{bcd}	25.24^{cd}	42.21^{cde}	58.61^{bcde}	73.54^{defgh}
259	16.94^{a}	45.49^{a}	69.25^{a}	77.99^{abc}	103.64^{bcd}	18.82^{a}	50.53^{a}	76.94^{a}	86.65^{abc}	115.14^{bcd}
260	12.10^{bcd}	40.86^{a}	61.03^{ab}	97.48^{a}	134.36^{ab}	13.44^{bcd}	45.39^{a}	67.81^{ab}	108.30^{a}	149.27^{ab}
261	10.07^{d}	18.53^{de}	25.31^{ef}	31.88^{ef}	50.39^{gh}	11.19^{d}	20.59^{de}	28.12^{ef}	35.42^{ef}	55.99^{gh}
262	9.18^{d}	13.10^{e}	26.8^{ef}	54.71^{bcde}	59.12^{efgh}	10.20^{d}	14.55e	29.77^{ef}	60.78^{bcde}	65.69^{efgh}
64	9.23^{d}	18.32^{de}	27.49^{ef}	53.34^{bcde}	78.75^{cdefg}	10.26^{d}	20.35^{de}	30.54^{ef}	59.26^{bcde}	87.49^{cdefg}
270	9.20^{d}	12.41^{e}	16.60^{f}	23.05^{f}	31.12^{h}	10.22^{d}	13.79^{e}	18.44^{f}	25.61^{f}	34.57^{h}
GJ 09	11.90^{bcd}	39.17^{ab}	61.15^{ab}	100.80^{a}	161.07^{a}	13.22^{bcd}	43.52^{ab}	67.94^{ab}	111.99^{a}	178.95^{a}
SE(m)±	0.85	2.81	5.01	8.53	11.81	0.95	3.12	5.57	9.48	13.13

Means with different superscript letter in the same column indicate significant difference ($p<0.05$) according to Duncan's Multiple Range Test

kg/tree/year and 35.79 t/ha/year) potential was of progeny Gj09.

Progeny 260 showed statistically at par carbon stock (7.32 kg/tree/year and 8.13 t/ha/year) and carbon sequestration potential (26.87 kg/tree/year and 29.85 t/ha/year) to progeny Gj09. Minimum carbon stock and carbon sequestration rate was of progeny 270 (Fig. 2 and 3).

Carbon sequestration potential of *M. dubia* under spatial geometries

The results expressed that biomass production and productivity of *M. dubia* differed significantly (p<0.05) under different spatial configurations (Table 4). At 1-year of age, maximum individual tree biomass (7.39 kg/tree), carbon stock (7.77 kg/tree) and carbon sequestration (13.84 kg/tree) was maximum in 3x2 m spaced plantations. In 2nd, 3rd and 4th years of age maximum per tree biomass (15.90, 26.10 and 37.24 kg), carbon stock (8.11, 13.31 and 18.99 kg) and carbon sequestration (29.76, 48.85 and 69.70 kg) was recorded under 3x3 m planting geometry (Table 4). At 5 years' age of trees in 4x4 m spatial geometry provided highest biomass, carbon stock and carbon sequestration to the tune of 53.30, 27.18 and 99.77 kg/tree, respectively.

Owing to maximum number of trees under 2x2 m spaced plantations (table 4), from 1st till 5th year of age, provided significantly highest biomass (18.07, 25.42, 41.23, 69.09 and 101.46 t/ha), carbon stocks (9.21, 12.97, 21.03, 35.24 and 51.75 t/ha) and carbon sequestration (33.82, 47.59, 77.16, 29.31 and 189.91 t/ha). The data in figure 4a and 5a pinned out that the individual tree biomass productivity, carbon stock and carbon sequestration potential amounting to 10.66, 5.44 and 9.95 kg/tree was under 4x2 m spatial configuration. However, as a results of maximum tree stocking per hectare, 2x2 m spaced plantations provided highest biomass productivity (20.29 t/ha/year), carbon stocks (10.35 t/ha/year) and carbon sequestration potential to the tune of 24.94 t/ha/year (Fig. 4b and 5b).

The variation in growth and productivity of tree species varies from location to location due to edapho-climatic attributes and genetic worth of material (Lodhiyal *et al.,* 2002; Luna *et al.* 2009; Luna *et al.* 2011, Thakur *et al.* 2023). The productivity of *M. dubia* in the present study is comparable with that reported in some of the released varieties of *M. composita* (Kumar *et al.,* 2017).

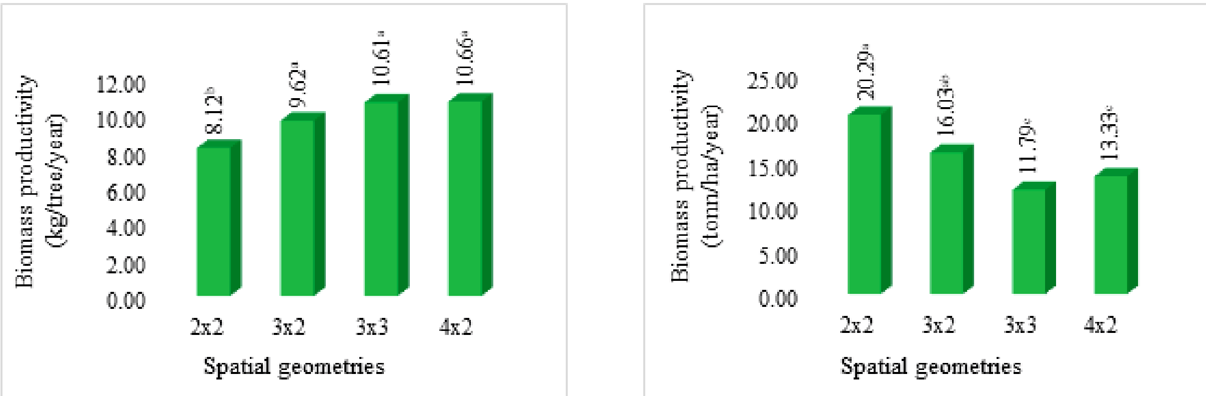

Figure 4. Variation in per tree [SE(m)± 0.45] and per hectare biomass [SE(m)± 0.76] productivity of *M. dubia* at the age 5 years under different spatial geometries in South Gujarat, means with different superscript letter in each bar indicate significant difference (p<0.05) according to Duncan's Multiple Range Test

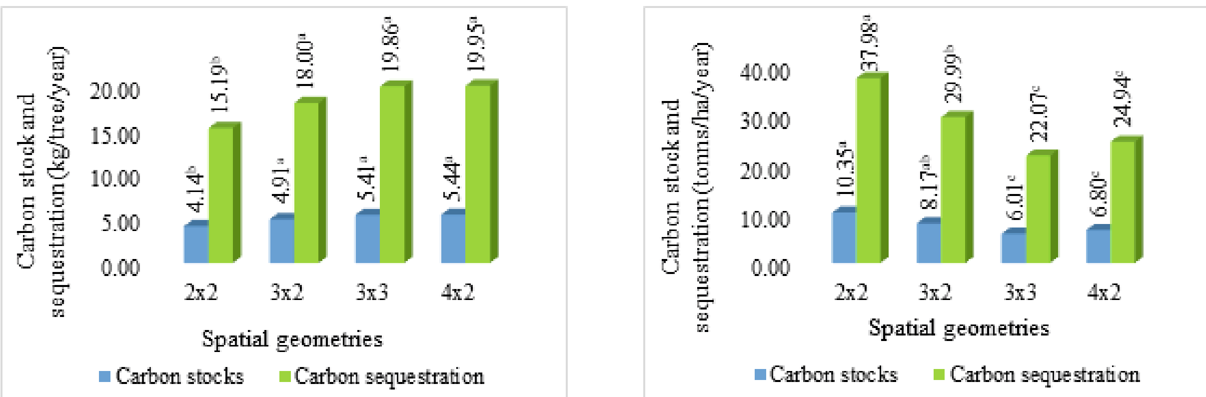

Figure 5. Variation in a) per tree carbon stock [SE(m)± 0.39] and carbon sequestration [SE(m)± 1.42] potential (kg/tree/year) and b) per hectare carbon stock [SE(m)±0.31] and carbon sequestration [SE(m)±1.12] potential of *M. dubia* at the age 5 years under different spatial geometries in South Gujarat, means with different superscript letter in each bar indicate significant difference (p<0.05) according to Duncan's Multiple Range Test

Table 4. Variation in biomass production, carbon stock and carbon sequestration of *M. dubia* under different spatial geometries in South Gujarat

Spatial geometry (m)	Age (years)									
	1	2	3	4	5	1	2	3	4	5
	Biomass (kg/tree)					Biomass (t/ha)				
2x2	7.23^{a}	10.17^{c}	16.49^{c}	27.64^{c}	40.58^{b}	18.07^{a}	25.42^{a}	41.23^{a}	69.09^{a}	101.46^{a}
3x2	7.39^{a}	11.95^{bc}	18.64^{bc}	34.04^{ab}	48.10^{a}	12.31^{b}	19.92^{b}	31.06^{b}	56.72^{b}	80.13^{b}
3x3	6.39^{b}	15.90^{a}	26.10^{a}	37.24^{a}	53.06^{a}	7.10^{d}	17.67^{bc}	28.99^{b}	41.37^{c}	58.95^{c}
4x2	7.21^{a}	12.54^{b}	21.97^{b}	32.76^{b}	53.30^{a}	9.01^{c}	15.68^{c}	27.47^{b}	40.96^{c}	66.63^{c}
SE(m)±	0.17	0.59	1.14	1.22	2.25	0.29	1.00	1.83	1.85	3.78
	Carbon stocks (kg/tree)					Carbon stocks (t/ha)				
2x2	3.69^{a}	5.19^{c}	8.41^{c}	14.09^{c}	20.70^{b}	9.21^{a}	12.97^{a}	21.03^{a}	35.24^{a}	51.75^{a}
3x2	3.77^{a}	6.1^{bc}	9.51^{bc}	17.36^{ab}	24.53^{a}	6.28^{b}	10.16^{b}	15.84^{b}	28.93^{b}	40.86^{b}
3x3	3.26^{b}	8.11^{a}	13.31^{a}	18.99^{a}	27.06^{a}	3.62^{d}	9.01^{bc}	14.79^{b}	21.10^{c}	30.06^{c}
4x2	3.68^{a}	6.40^{b}	11.21^{b}	16.71^{b}	27.18^{a}	4.60^{c}	8.00^{c}	14.01^{b}	20.89^{c}	33.98^{c}
SE(m) ±	0.09	0.30	0.58	0.62	1.15	0.15	0.51	0.93	0.94	1.93
	Carbon sequestration (kg/tree)					Carbon sequestration (t/ha)				
2x2	13.53^{a}	19.03^{c}	30.87^{c}	51.73^{c}	75.96^{b}	33.82^{a}	47.59^{a}	77.16^{a}	129.31^{a}	189.91^{a}
3x2	13.84^{a}	22.38^{bc}	34.90^{bc}	63.72^{ab}	90.02^{a}	23.05^{b}	37.28^{b}	58.14^{b}	106.16^{b}	149.97^{b}
3x3	11.96^{b}	29.76^{a}	48.85^{a}	69.70^{a}	99.31^{a}	13.28^{d}	33.07^{bc}	54.27^{b}	77.44^{c}	110.34^{c}
4x2	13.49^{a}	23.48^{b}	41.13^{b}	61.33^{b}	99.77^{a}	16.87^{c}	29.35^{c}	51.41^{b}	76.66^{c}	124.71^{c}
SE(m) ±	0.32	1.11	2.13	2.29	4.22	0.55	1.87	3.42	3.46	7.08

Means with different superscript letter in the same column indicate significant difference ($p<0.05$) according to Duncan's Multiple Range Test

Jinger *et al.* (2025) have reported carbon stocks of 16.39 t/ha to 58.30 t/ha, and carbon sequestration to the tune of 60.20 t/ha and 214.20 t/ha in sole *M. dubia* plantation and under agroforestry (*M. dubia*+Lemon grass) systems in central Gujarat India at the age of 5 years spaced at 3 × 3 m. These findings are in congruity with our range carbon sequestration at same spacing and age in *M. dubia* germplasm and spatial geometry study plantations. Kumar *et al.* (2024), in dry zone of Karnataka, India, reported the carbon stocks of 40.10 to 118.80 t/ha and biomass CO_2 147.10 375.90 t/ha to of different *M. dubia* progenies at the age of 6 to 7-year-old plantations spaced at 5 × 5 m. The carbon stock and carbon sequestration of some progenies at the age of 5 years in the present study fall within the range reported by these workers. Singh *et al.* (2022) have also reported carbon stock of 10.96 t/ha and Carbon dioxide sequestration amounting to 40.17 t/ha from 2-year-old *M. dubia* which are in accordance with that provide by some progenies and spatial geometry evaluations in our study. Similar individual tree range of carbon sequestration from *M. dubia* (at 5 × 4 m spacing) at different age gradation (1 to 3 years) have been reported by Choudhury *et al.* (2025).

The plantation spacing is known to influence growth and morphology of individual trees as well as quantity and quality of wood produced. Narrower spacing decrease individual growth and increase tree mortality through excessive intraspecific competition (Akers *et al.,* 2013; Thakur *et* *al.,* 2024). Conversely though wider planting spacing favor diameter/girth growth, enhances stem taper substantially. Higher stem taper values tend to reduce merchantable volume of individual trees at a particular diameter at breast height. It has been reported that at stand level, volume increases with narrower planting plans to a reasonable levels (Cardoso *et al.,* 2013) and hence the biomass. The biomass production and productivity in present study has been recorded to be higher in narrower spacing/highest tree density which is in agreement with these findings.

The analysis of teak spacing studies revealed negative coordination for planting spacing, volume production, basal area and other wood characters which increase with increased plantation spacing (Perez-Cordero and Kanninen, 2003). Similarly, teak height and DBH (diameter at breast height) at age of 14 years was significantly lower in spacing of 2x2 m compared spacing regimes of 3x3 m and 4x4 m (Eliakimu *et al.,* 2015). Similar growth behavior was exhibited by *M. dubia* for present study, which might have contributed by microsite differences for height, as it is sensitive to differences in site quality. Reduced competition in wider planting spacing results in attaining higher DBH/GBH, which may be attributed to effective use of more growing space for crown and root development (Eliakimu *et al.*, 2015). The higher individual stem biomass has been reported with widest plantation spacing, which is in line with results of several other studies (Zhang *et al.,* 2013; Eliakimu *et al.,* 2015) and hence the carbon stocks and carbon sequestration was higher.

4. CONCLUSION

The results indicated that among 17 progenies, GJ09 produced maximum biomass and average maximum productivity, carbon stocks and carbon sequestration at the age of 5 years. Progeny GJ09 had carbon stock and carbon sequestration rate. This progeny can be further taken up for plantation programmes for higher sequestration rate. Further, there was significant variation in biomass productivity, carbon stock and carbon sequestration among individuals under different spatial geometries. At the age of 5-years, the individual tree biomass, carbon stock and carbon sequestration was maximum under 4×2 m spacing, nonetheless, owing to the maximum tree per hectare, 2×2 m spatial configuration yielded maximum biomass, carbon stocks and carbon sequestration potential. Hence, *M. dubia* has great potential for carbon sequestration.

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