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Effect of Mixed plantation on growth performance and above ground biomass of *Eucalyptus globulus* in highland area of central Ethiopia region

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Abstract

Monoculture plantations, particularly of Eucalyptus species, have faced criticism for their negative environmental impacts and limited contributions to biodiversity and local livelihoods. Mixed-species plantations are promoted as a more sustainable alternative, yet their adoption remains limited. This study evaluated the early-stage growth performance, yield, and aboveground biomass of ***E.globulus*** *in mixed plantations with four indigenous and exotic tree species—****H. abyssinica, P. falcatus, C. lusitanica****, and* ***J. procera****—in the highland area of Gummer district, central Ethiopia. A randomized complete block design with three replications was used, and data on height, diameter, survival, biomass, and carbon density were collected over four years. Results showed no significant negative effects of mixing on* ***E. globulus*** *growth, survival, or biomass accumulation compared to monoculture. Mixed stands, particularly those with* ***J. procera*** *and* ***C. lusitanica****, showed numerically higher growth rates and relative yields. Aboveground biomass and carbon density of* ***E. globulus*** *were comparable across treatments, while companion species contributed additional biomass, enhancing overall stand carbon stocks. The findings suggest that mixed-species plantations can serve as a viable alternative to monocultures without compromising the early productivity of* ***E. globulus****.*

Keywords: Biomass; Climate change; E.globulus; Growth performance; Mixed plantation;

1. Introduction

Monoculture plantations constitute the majority of the world's planted forests, with only a few tree genera, such as Eucalyptus, Pinus, and Tectona, being widely used [1], [2]. These plantations have been criticized for their negative impacts on local environments and ecosystem services [2], [3] and for failing to provide the variety of traditional forest goods that local people rely on, particularly concerning biodiversity conservation [4].
Research has demonstrated that mixed-species plantations can enhance stand-level productivity compared to monocultures. However, these comparative advantages have not translated into widespread commercial adoption, with mixed-species plantations accounting for less than 0.1% of industrial plantations globally [5]. Commercial and

experimental mixed plantations rarely provide data for financial analyses, and small landholders appear to be the primary innovators in establishing and demonstrating these systems [5]. Mixed-species plantations are often preferred for their potential to increase yield, provide better environmental protection, and support biodiversity conservation and restoration [6].

Among various monocultures, *Eucalyptus* plantations have faced the most criticism [7]. *Eucalyptus* species are known to suppress ground vegetation, resulting in reduced undergrowth and negatively impacting biodiversity conservation [8]. In contrast, mixed plantations offer greater diversity in both components and products. For example, Tyniel [9] recorded 39 woody plant species regenerating in a 20-year-old *E. camaldulensis* plantation in northeastern Zimbabwe. In the dry afro-montane areas of Ethiopia, Senbeta et al. [10] found 16, 13, and 17 woody species in 13-, 16-, and 22-year-old *E. globulus* plantations, respectively. Alem and Woldemariam [11]identified 46 woody species in a 31-year-old *E. grandis* plantation and 37 woody plants in a 27-year-old *E. camaldulensis* plantation in semi-arid areas of Ethiopia. However, these studies primarily focused on the growth and productivity of the plantation species themselves. Therefore, this research was designed to evaluate the effect of selected tree species on the early-stage growth of *E.globulus*. Despite a limited understanding of how to design, select species for, and manage mixed-species plantations, they are commonly promoted as environmentally preferable alternatives to monocultures [3], [5], [12]. This study aims to identify the most compatible tree species for mixed planting of E. globulus for productivity and aboveground biomass in the Gummer district.

2. Materials and Methods

2.1. Site Description

The study was conducted in the Gummer district, Gurage Zone, in the Central Ethiopia Region. According to the 2007 national census conducted by the Central Statistical Agency, the district had a total population of 80,178, of whom 37,495 were men and 42,683 were women; 2,923 individuals (3.65% of the population) lived in urban areas [13].

The major vegetation in the district includes exotic tree species such as *E.globulus, C. lusitanica, C. palmensis,* and *G. robusta,* as well as indigenous species like *J. procera, H. abyssinica, P. falcatus,* and *B. polystachya*. Based on personal observation, *E. globulus, J. procera, H. abyssinica,* and *C. lusitanica* are the dominant tree species. Farmers' preferred species include *E. globulus, G. robusta, C. palmensis*, *J. procera, H. abyssinica,* and *P. falcatus*, selected for their wood products and environmental services. Bamboo is the only notable non-timber forest product in the district (CEARI, Central Ethiopia Agricultural Research Institute Quick Survey, 2025). Like most farmers in Ethiopia, those in the Gummer district practice mixed crop-livestock farming. The major crops grown are barley, faba bean, wheat, potato and enset, and fruit tree like apple (*Molus domestica*) and Plum (*Prunus*
Salicina) being the top contributors to farmers' income. Sheep, cattle, and horses constitute the largest proportion of the livestock population.

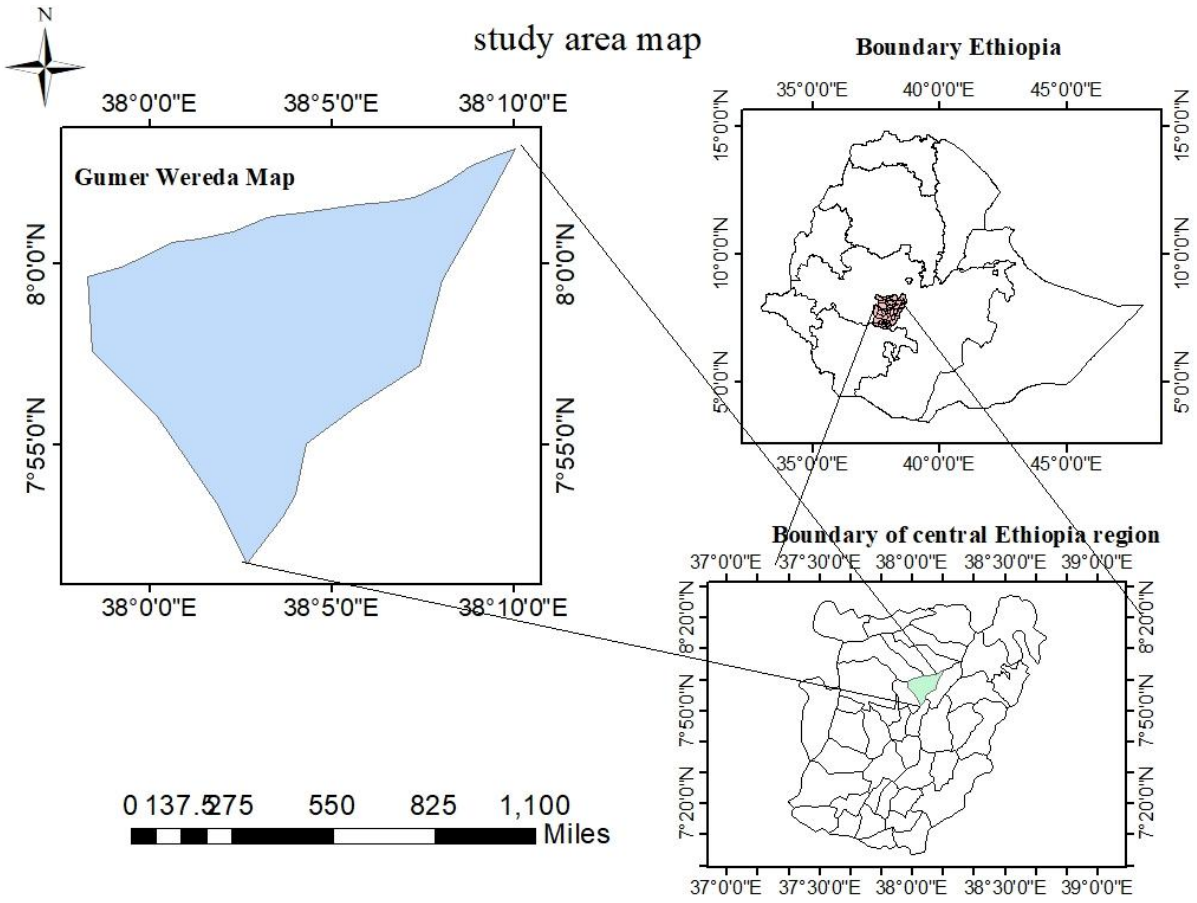


Figure 1 study area map

2.2. Experimental Design

2.2.1. Source of plant material

The seeds of Eucalyptus globulus, Hagenia abyssinica, Podocarpus falcatus, Juniperus procera, and *Cupressus lusitanica were obtained from* ***Ethiopia forest development department of Forest seed,*** government-recognized, quality seed supplier in Ethiopia (an organization responsible for seed quality control and development in Ethiopian forest development)***.*** *The supplier is the official government body responsible for seed quality control and forest development in Ethiopia. No wild collection coordinates apply as the material was commercially purchased.*

2.2.2. Design

Seedlings were raised at the nursery site of the Gummer District Agriculture Office. Field preparation began one month before planting, with planting holes dug to dimensions of 50 cm (depth) × 40 cm (width). Each plot measured 5 m × 5 m and consisted of six rows with six trees per row, totaling 36 seedlings per plot. Spacing between trees within and between rows was 1 m, while the distance between plots and

blocks was 4 m. In the mixed plantations, species were arranged in alternating rows, meaning each row of *E. globulus* was adjacent to a row of the companion species. The treatments were laid out in a Randomized Complete Block Design (RCBD) with three replications. Weeding and hoeing were uniformly applied to all plots twice a year during the first and second growing seasons. The five treatments used in the study were:

1. *E.globulus* monoculture
2. *E. globulus* + *H. abyssinica*
3. *E. globulus* + *P. falcatus*
4. *E. globulus* + *C. lusitanica*
5. *E. globulus* + *J. procera*



Figure 2: Field design of the experiment showing all treatments with three replications. Eg = *E. globulus* monoculture; Eg+Jp = *E. globulus* mixed with *J. procera*; Eg+H = *E. globulus* mixed with *H. abyssinica*; Eg+P = *E. globulus* mixed with *P. falcatus*; Eg+C = *E. globulus* mixed with *C. lusitanica*



Figure 3: Field status of *E. globulus* in a mixed plantation (left side) and a monoculture (right side)

2.3. Data Collection

Measurements were taken on six trees from two alternating interior rows within each plot. For most treatments, two rows of buffer trees separated measurement trees from trees in adjacent treatments. Early growth data, including height, DBH, and RCD, were recorded annually for four years. Survival counts were conducted during the second measurement season, 12 months after out-planting, and remained constant for trees assessed after this period. Height was measured using a ruler during the first two years and with an altimeter (e.g., Hypsometer) in years three and four. RCD and DBH were measured using calipers.

A destructive method was used to measure tree dimensions at different positions. Wood density was determined using the water displacement method with a graduated cylinder.

2.4. Data Analysis

Dendrometric measurements were recorded for all *E. globulus* trees in each plot. Basal area (BA, $m^2\ ha^{-1}$) and volume (Vt, $m^3\ ha^{-1}$) were calculated using standard inventory data. In the absence of local volume equations, total volume was calculated using a conventional volume equation [14]

$$RGR = \frac{\ln(V4) - ln\ (V1)}{(T4 - T1)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$ [15]

where ln is the natural logarithm, V_4 is the tree volume in year four, V_1 is the tree volume in year one, T_4 is year four, and T_1 is year one.

$$V = m(D^2/4)h.f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$ [14]

Where V is tree volume, DBH is diameter at breast height, h is tree height, and f is a form factor (0.42).

Basal area was calculated using the formula:

$$BA = \pi DBH^2/4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, BA is basal area and DBH is diameter at breast height.

Volume and basal area mean annual increments (MAI) were calculated as:

$$VMAI = \frac{volume\ of\ stand(m3/ha}{age\ of\ the\ stand} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$ [16]

$$BMAI = \frac{Basal\ area\ of\ stand(m3/ha}{age\ of\ the\ stand} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$[16]

Where VMAI is tree volume mean annual increment and BMAI is tree basal area mean annual increment.

Relative Yield

The relative height, DBH, basal area, and volume of *E. globulus* in mixed stands were calculated in comparison to pure stands.

$$RH = (H_{mix} - H_{mono})/H_{mono} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where, RH is relative height, H_{mono} is the height of *E. globulus* in monoculture, and H_{mix} is the height of *E. globulus* in a mixed plantation.

2.4.1. Aboveground Biomass

A total aboveground biomass and carbon stock of alive *E.globulus, P. falcatus, J. procera* tree were determined by nondestructive (indirect) method using species and site-specific allometric equations models. The carbon stock is directly estimated by multiplying the aboveground biomass by a carbon fraction of 0.47 (as a standard approximation), reflecting the proportion of dry biomass that is elemental carbon (IPCC, 2006 [17], [18]. For stand-level estimations, this process is repeated for all trees with in sample plots, with individual tree values summed and then scaled to a per hectare basis.

For *E.globulus:* $ln(Y) = -2.88 + 1.24ln(D) + 1.63ln(H) + 0.665ln(\rho) \dots\dots\dots\dots\dots\dots (7)$

Where, Y=above ground biomass of *E.globulus*, D= diameter breast height, *p*=wood density of *E. globulus* [19]

For *P. falcatus*

$ln(Total\ biomass) = ln(-0.125) + 1.785ln(DBH) \dots\dots\dots\dots\dots (8)$ [20]

For *J. procera*

$ln(Total\ biomass) = ln(-2.3072) + 2.321ln\ (DBH) \dots\dots\dots\dots (9)$ [20]

Where, DBH, diameter at breast height; ln, natural logarithm

$ACD = AGB \times 0.47 \dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$ [17], [18]

$BCD = ACD \times 0.24 \dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$ [17], [18]

Where, ACD is above ground carbon density and BCD is below ground carbon density.

R software was used for statistical analysis. A significance level of α = 0.05 was applied. Linear models (LM) and generalized linear models (GLM) were used to determine the

effects of year and treatment on the growth and yield of *E. globules*. The ggplot2 package was used for data visualization.

3. Results and Discussion

The results showed that the early-stage growth performance of *E. globules* was not significantly affected by mixing with different indigenous and exotic species. No significant differences were detected in height, root collar diameter, or branch number during the first two years.

3.1. Survival

The survival rate of *E. globulus* was generally high, exceeding 75% for most species across all experimental plots. The highest survival rate was recorded for *E. globulus* mixed with *J. procera* (96.27%), followed by *E. globulus* mixed with *C. lusitanica* (92.57%) and E. globulus mixed with P. falcatus (88.87%). Lower survival rates were observed in the pure plantation (85%) and n the mixture with *H. abyssinica* (75.9%)(fig.1). Several studies have found mixed-species plantations to be more productive than monocultures [21]. Debell et al. [22] similarly reported higher survival percentages for *Eucalyptus* in mixed stands compared to pure stands.

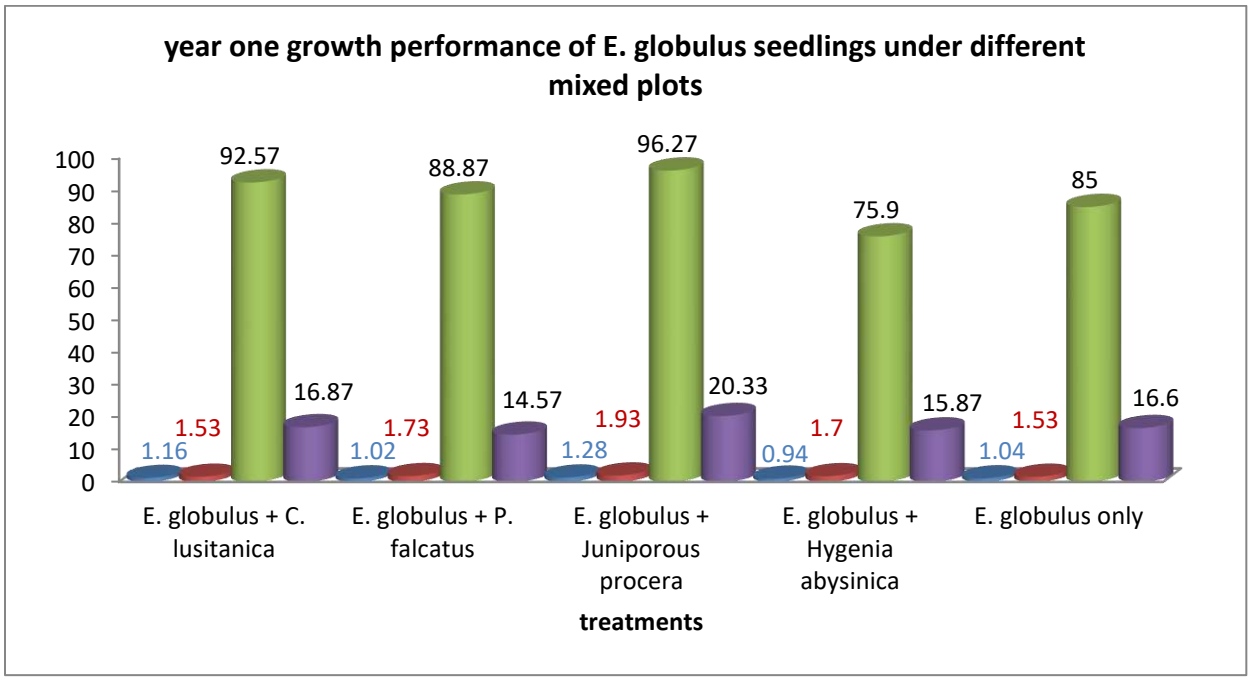


Figure 4 the growth performance of *E. globulus* tree seedling 12 months after planting (MAP)

3.2. Height

Over four years, the height of *E. globules* ranged from 0.94 m to 11.57 m. The greatest height (11.57 m) was achieved in plots where *E. globules* were mixed with *C. lusitanica*

at fourth year, while the lowest height (0.94m) was recorded in plots mixed with *H. abyssinica* in the first year. This may be because *H. abyssinica* exhibited more vigorous early growth than the other companion species, leading to greater competition for resources. Field observations also suggested that *E. globulus* height growth was better when mixed with slower-growing species like *J. procera* and *P. falcatus* (Table 1).

3.3. Diameter at Breast Height (DBH)

No significant differences between treatments were detected for DBH within a year. However, numerically, plots with *E. globulus* mixed *J. procera* had the highest DBH. The lack of significant differences in measured parameters (Table 1) during the early growth stage suggests that the companion trees did not yet exert a strong competitive effect on the fast-growing *E. globulus*. This finding aligns with a study on the Hamakua coast, where early height growth of Eucalyptus was very rapid (averaging nearly 4 m yr^{-1}) during the first four years, with no significant differences among treatments [23]. Parrotta et al. [24] also reported that competition from *E. robusta* did not significantly affect nitrogen fixation by *C. equisetifolia* during the early growth stage (6-24 months). This may be attributed to less intense competition in the field compared to pot studies. While *E. globules* likely competed for nitrogen, the net effect of competition for all resources may have been less than intraspecific competition among the companion species themselves [24]

3.4. Effect of Year on Growth and Yield of *E. globulus*

The height of *E. globules* was significantly affected by the interaction between year and planting mixture (Table 1). The mixture with *J. procera* consistently resulted in greater height over the three years. Overall, tree height was substantially greater in year three than in year one, demonstrating the species' fast growth rate. Monoculture *E. globules* exhibited a lower height growth rate compared to most mixed stands. This is consistent with research from Bangladesh, which showed that the initial growth performance of *A. auriculiformis* and *G. arborea* was better in combinations than in pure plantations [25]. In addition this study in line with the mean annual growth of *E. globulus* in fuelwood plantations varies between 10 and 30 m^3 ha^{-1} $year^{-1}$ in Ethiopian highlands.

Table 1Effect of year and planting system on the growth performance and yield of *E. globulus*

treatment Year	planting system	Height	DBH	Basal Area m2/ ha	Log Volume ton/ ha
year one	*E. globulus +C. lustanica*	1.15fg	1.55e	1.99f	2.59d
	E. globulus + P. falcatus	1.02g	1.71e	2.41f	2.76d
	E. globulus +J. procera	1.28efg	1.92e	3.11f	3.38d
	E. Globulus + H. abysinica	0.94g	1.68e	2.25f	2.04d
	E. globulus Mono	1.04g	1.55e	1.95f	1d
year two	*E. globulus +C. lustanica*	2.38de	3.23d	8.26ef	22.27d
	E. globulus + P. falcatus	2.45d	3.17d	7.98ef	20.74d
	E. globulus +J. procera	2.53d	3.16d	8.04ef	16.68d

	E. Globulus + H. abysinica	2.25def	2.94d	6.81f	14.02d
	E. globulus Mono	2.35de	3.01d	7.22f	13.34d
year three	*E. globulus +C. lustanica*	5.84c	5.06c	20.13d	131.9d
	E. globulus + P. falcatus	5.58c	5.22c	21.47d	125.25d
	E. globulus +J. procera	6.12c	5.34c	22.46d	109.84d
	E. Globulus + H. abysinica	5.52c	4.82c	18.37de	93.78d
	E. globulus Mono	5.65c	3.01c	19.83d	86.91d
year Four	*E. globulus +C. lustanica*	11.57a	9.89a	76.98a	100.17a
	E. globulus + P. falcatus	10.27b	8.97ab	64.48bc	704.45b
	E. globulus +J. procera	9.35b	8.88b	61.95c	457.31c
	E. Globulus + H. abysinica	9.53b	9.64ab	73ab	633.35b
	E. globulus Mono	9.23b	8.85b	62.05c	445.56c
	CV	14.67	11.75	26.73	49.95
	LSD	1.17	0.92	10.84	160.56

Values followed by the same letter within a column are not significantly different at $p<0.05$. E. g. = *E. globulus*

3.5. Relative Growth and Yield

The relative yield of *E. globulus* in mixed stands, compared to monoculture, was generally greater than or equal to one for most treatments by year four, indicating that mixing did not negatively impact yield and may have provided a relative advantage over time (Table 2). However, uncertainty about mixtures achieving consistently greater productivity than monocultures remains [26], [27]. As noted by Hossain et al. [28], many slow-growing, shade-demanding tropical trees are not synecologically suited to growing in open plantation environments, where they may suffer from weed competition.

Table 2:- The relative yields of *E. globulus* under mixed plantation compared to mono-crop system in height, DBH, basal-area and log-volume.

year	Planting system	Height	DBH	Basal Area	Log Volume
Yea one	*E. globulus +C. lustanica*	1.12ab	1.05	1.27	2.16ab
	E. globulus + P. falcatus	0.98ab	1.11	1.22	1.68ab
	E. globulus +J. procera	1.22ab	1.22	1.5	1.91ab
	E. Globulus + H. abysinica	0.94b	1.15	1.4	1.87ab
	E. globulus Mono	1ab	1	1	1b
year two	*E. globulus +C. lustanica*	1.01ab	1.08	1.16	1.71ab
	E. globulus + P. falcatus	1.05ab	1.05	1.12	1.58ab
	E. globulus +J. procera	1.08ab	1.05	1.09	1.2b
	E. Globulus + H. abysinica	1.17ab	0.99	0.99	1.14b
	E. globulus Mono	1ab	1	1	1b

year three	*E. globulus +C. lustanica*	1.03ab	1.02	1.05	1.57ab
	E. globulus + P. falcatus	0.98ab	1.05	1.11	1.47ab
	E. globulus +J. procera	1.08ab	1.07	1.14	1.27ab
	E. Globulus + H. abysinica	0.97ab	0.97	0.94	1.1b
	E. globulus Mono	1ab	1	1	1b
year Four	*E. globulus +C. lustanica*	1.26a	1.13	1.303	2.45a
	E. globulus + P. falcatus	1.13ab	1.04	1.13	1.85ab
	E. globulus +J. procera	1.01ab	1.01	1.04	1.07b
	E. Globulus + H. abysinica	1.03ab	1.09	1.22	1.52b
	E. globulus Mono	1ab	1	1	1b
	CV	16.72	15.3	32.14	49.95
	LSD	0.291	NS	NS	1.21

Values followed by the same letter within a column are not significantly different at p<0.05. NS = Not Significant.

This study aligns with findings from northern Germany, which reported that mixed-species tree stands achieved higher relative volume yields compared to pure stands [29]. Furthermore, in the mixed plantation, both *C. lusitanica* and *E. camaldulensis* exhibited significantly greater diameter at breast height (DBH) growth than in pure plantations (p = 0.0001 and p = 0.0076, respectively). This trend is consistent with another study [30], which also found a significant difference in DBH growth for *C. lusitanica* between mixed and pure stands (p = 0.001).

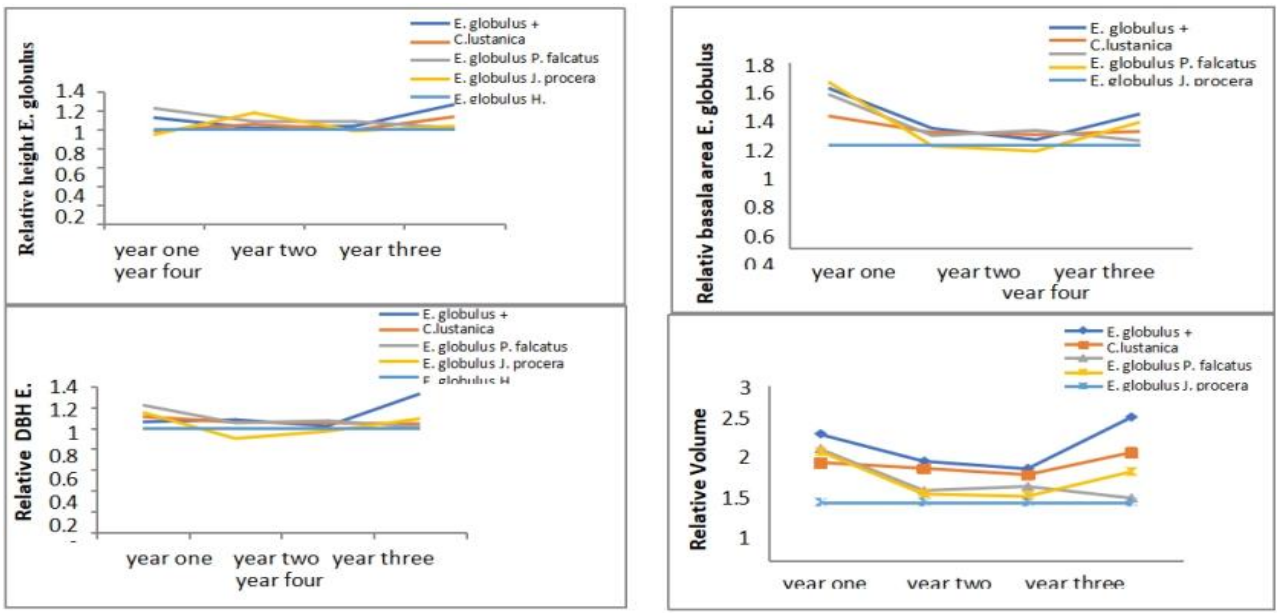


Figure 5:- Trends in relative yield increment of *E. globulus* in mixed plantations compared to monoculture over four years

3.6. Growth Rate of Height, DBH, and Volume

The highest mean height growth rate between year one and year three was observed for *E. globulus* mixed with *J. procera* (242.4%), while the lowest was in the mixture with *H. abyssinica* (229.1%) (Figure 6). For DBH, the highest mean growth rate was recorded in the mixture with *C. lusitanica* (175.83%), and the lowest was with *J. procera* (170.83%) (Figure 7). Stratified mixtures can enhance individual-tree growth rates and stem quality for species in the upper canopy while minimizing the proportion of taller species [31], [32]. A study in Hawaii similarly found that *Eucalyptus* diameters in stands with 50% Albizia were significantly larger than those in pure stands, with even larger diameters in stands with 66% Albizia [22]

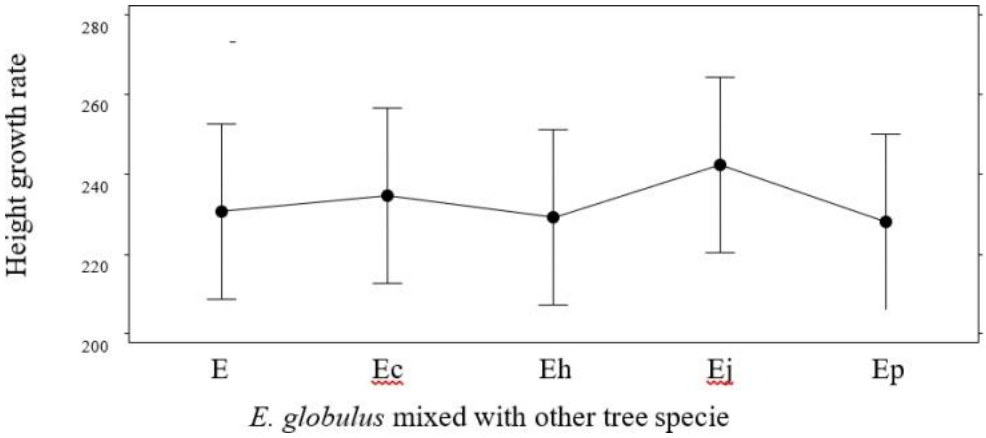


Figure 6 Means and 95% confidence intervals for height growth rate of *E. globulus* in different planting mixtures during early growth

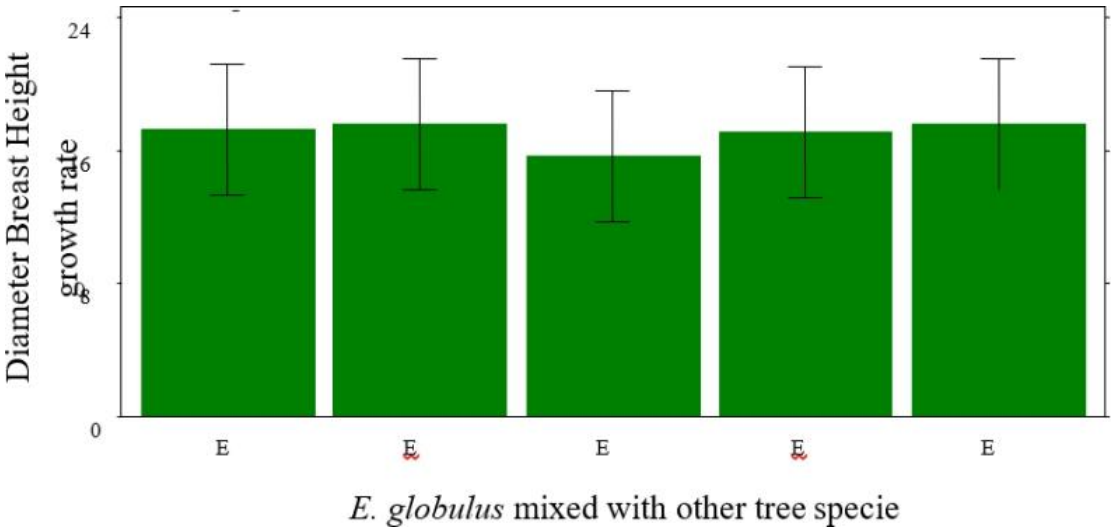


Figure 7 Means and 95% confidence intervals for root collar diameter growth rate of *E. globulus* in different planting mixtures during early growth. The treatment are read from left to right in order of (E = *E. globulus* only; Ec = with *C. lusitanica*; Eh = with H. *abyssinica*; Ej = with *J. procera*; Ep = with *P. falcatus)*

3.7. Mean Annual Volume Increament (MAVI)

The mean annual volume increment of *E. globulus* showed an increasing trend in mixed plantations compared to monocultures (Figure 8). While not always statistically significant, this trend suggests potential long-term benefits of mixing. This finding is supported by Pretzsch et al. [29], who reported higher relative volumes in mixed stands of oak and beech in Germany, and Alem et al. [30], who found significantly higher DBH growth for *C. lusitanica* and *E. camaldulensis* in mixed plantations compared to pure stands. On the other hand the study found no statistically significant difference in standing volume or mean annual increment between zero, first, second, and third coppice levels of *E.globulus* in North Shewa, Ethiopia. However, farmers reported that the first coppice produces higher yields, and second and third coppice levels resulted in more shoots per stump, leading to excessive stem density that may compromise wood quality[33].

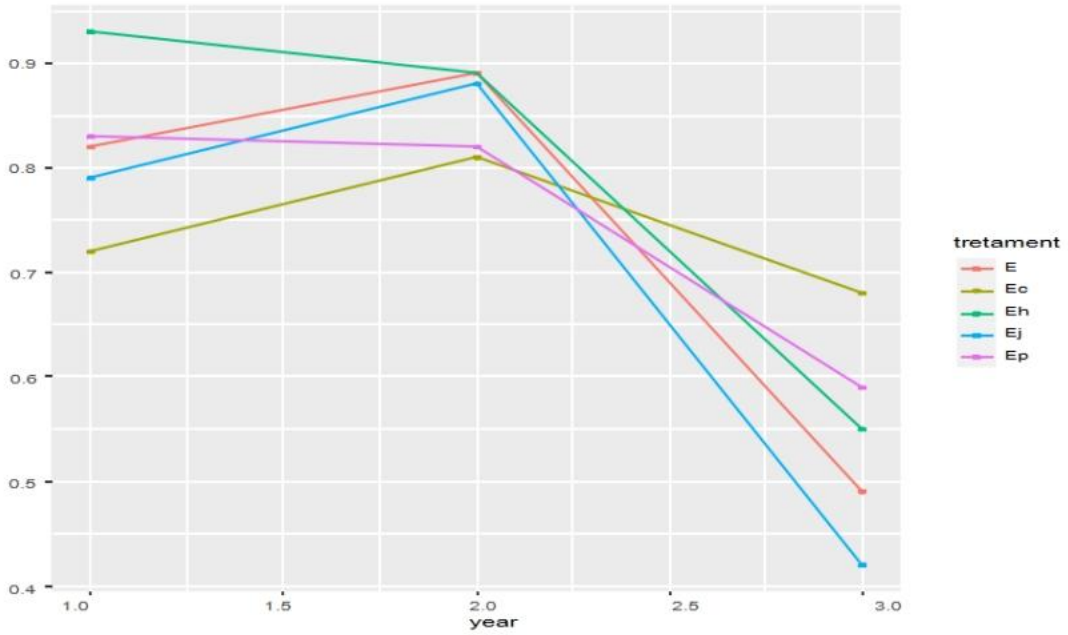


Figure 8 Trend of the mean annual volume increment rate of *E. globulus* over four years in different planting mixtures. (E = pure; Ec = with *C. lusitanica*; Eh = with *H. abyssinica*; Ej = with *J. procera*; Ep = with *P. falcatus*)

3.8. Aboveground biomass and Carbon Density in the stand

3.8.1. E.globulus

Aboveground biomass, aboveground carbon density, and belowground carbon density were analyzed for each tree species. The results showed no significant difference between *E. globulus* in monoculture and in mixed stands, indicating that mixed planting did not affect the aboveground biomass of *E. globulus* (Table 3). However, each mixed-species plot had the advantage of combining the aboveground biomass of both species. At four years, total biomass across mixed plots ranged from 19.2 to 31.4 $t \cdot ha^{-1}$, with corresponding aboveground carbon densities ranging from 9.02 to 14.7 $t \cdot ha^{-1}$. These

findings are consistent with a study in North Ethiopia, where aboveground biomass of *E. globulus* under four different spacing regimes was less than 25 t·ha^{-1} and carbon density less than 10 t·ha^{-1} at year three [34]. Similarly, a study in North Shewa reported that aboveground biomass increased significantly with coppice shoot age, ranging from 11 t·ha^{-1} in one-year-old stands to 153 t·ha^{-1} in nine-year-old stands [35]. A significant difference in biomass was observed only between the mixture with *H. abyssinica* and that with *P. falcatus*. Overall, these results suggest that mixing *E. globulus* with the tested species did not negatively affect its biomass or carbon density, aligning with findings by [36], who reported that mixing hybrid poplar with white spruce enhanced poplar wood production and carbon sequestration compared to monocultures.

Table 3:- Effect of mixed planting on aboveground biomass and carbon density of E. globulus.

Treatment	Above ground biomass (ton)	Above ground carbon Density (ton)	Below ground carbon density (ton)
E. globulus +C. lustanica	28.3ab	13.3ab	3.19ab
E. globulus + P. falcatus	31.4a	14.76a	3.54a
E. globulus +J. procera	21.3 ab	10.03ab	2.41ab
E. Globulus + H. abysinica	19.2 b	9.02b	2.16b
E. globulus mono	29.3 ab	13.74ab	3.29ab
CV	21.99	22.01	22.04
LSD	10.3	4.87	1.17

Values followed by the same letter within a column are not significantly different at p<0.05.

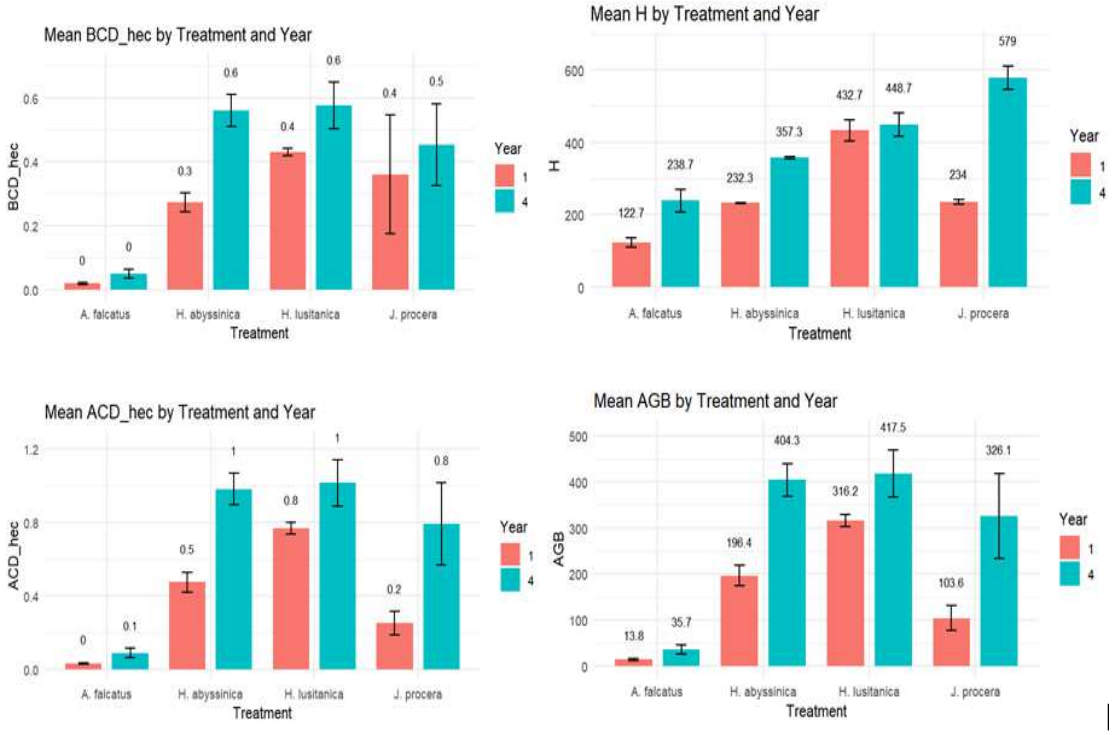


Figure 9 mean aboveground biomass and carbon density of *P. falcatus , H. abyssinica, C. lusitanica and J.procera* tree species in *E.globulus* mixed plantation

3.8.2. Companion Species

In this study, *J. procera*, *P. falcatus*, *H. abyssinica*, and *C. lusitanica* were evaluated as companion species in mixed-species plantations. Aboveground biomass for each species was estimated using species-specific allometric equations. As illustrated in Figure 9, no significant differences in aboveground biomass were observed among the species, except for *P. falcatus* (formerly *P. falcatus*), which had significantly lower biomass than the others. By the end of the four-year experiment, the remaining species attained substantially higher aboveground biomass, with values ranging from 35.7 to 417.5 t·ha^{-1}. These differences are likely attributable to variation in species growth rates, as *P. falcatus* and *H. abyssinica* reached heights of only 2.4 m and 4.5 m, respectively, at year four. These findings are consistent with previous studies reporting aboveground biomass values for *C. lusitanica* [37], *J. procera* and *P. falcatus* [20], and *H. abyssinica* [38].

4. Conclusions and Recommendations

This study demonstrates that mixing *E.globulus* with selected native and exotic tree species does not negatively affect its early growth, survival, or biomass accumulation. Instead, certain mixtures, particularly with *J. procera* and *C. lusitanica*, showed trends toward improved growth performance and higher relative yields. The inclusion of

companion species contributed additional aboveground biomass and carbon stocks, enhancing the overall productivity and ecological value of the stands. These findings support the potential of mixed-species plantations as a sustainable land-use option in the Ethiopian highlands.

It is recommended that future research extend monitoring beyond the early establishment phase to capture longer-term competitive and facilitative dynamics. Additionally, farmers and extension services should consider promoting species mixtures that balance productivity with ecological benefits, while further studies on species compatibility, economic viability, and management practices are encouraged to support wider adoption.

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Data availability: The datasets generated from the field experiment usingthe test tree species *(Eucalyptus globulus, Hagenia abyssinica, Podocarpus falcatus, Juniperus procera, and Cupressus lusitanica)* are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Competing interests: The authors declare no competing interests

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