

Research Article

Effects of Silvicultural Treatments on Early Growth Performance of Artificial and Natural Regenerated *Cupressus lusitanica* (Mill.) Species at Yeraba Forest, Northern Ethiopia

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Cupressus lusitanica is widely cultivated in Ethiopia; however, its productivity is often constrained by inadequate silvicultural management, resulting in extended rotation periods. This study aimed to evaluate the effects of different silvicultural treatments on the early growth performance of *C. lusitanica* seedlings in the Yeraba State Forest. A randomized complete block design (RCBD) was implemented with four treatments. Three years after clear-cutting on a mature 25-year-old stand, seedling height, root collar diameter (RCD), and diameter at breast height (DBH) were measured. Data were analyzed using analysis of variance (ANOVA) in SPSS (Version 27), and results were summarized in tables and graphs. The results revealed significant differences among treatments at $p < 0.05$. Natural regeneration with strong thinning (NRST) produced the highest mean growth, with seedlings attaining a height of 3.81 m, a DBH of 3.21 cm, and an RCD of 4.45 cm. These values exceeded those of artificial regeneration (AR) (height 3.50 m, DBH 3.03 cm, RCD 4.09 cm) and NRMT (height 3.16 m, DBH 2.50 cm, RCD 3.37 cm). In contrast, NRWOI exhibited the lowest mean growth (height 1.81 m, DBH 1.67 cm, RCD 2.25 cm), likely due to intense intraspecific competition. The superior performance of NRST suggests that silvicultural interventions should prioritize density regulation to optimize resource availability and growth. Integrating NRST into plantation management plans could lower establishment costs compared with AR while maintaining high productivity. Future research should examine the long-term effects of thinning intensity on different adaptive and sustainable management of *C. lusitanica* in Ethiopia.

Keywords: *Cupressus lusitanica*; growth performance; regeneration; silvicultural treatment; thinning

1. Introduction

The demand for forest products continues to rise [1] as logging reduces the availability of alternative wood sources. Consequently, implementing optimal silvicultural practices is essential for sustainable forest management and shorter

wood production rotations. In the 21st century, silvicultural application is used more than conventional wood management [2]. According to Curtis [3], managed plantation forests offer an alternative to natural forests for short-rotation timber production. This cycle represents a sustainable forest management system. Therefore, more diverse

options are needed to ensure sustainable forest production while balancing wood demand and supply. Silvicultural treatments, from both natural and artificial regeneration (AR) of plantations after harvesting, are necessary to restore the ecosystem [4]. Despite helping *Cupressus lusitanica*'s natural regeneration, spontaneously occurring seedlings in immature plantations often experience high seedling mortality due to limited attention of the seedling bank [5]. Thus, applying optimal silvicultural treatments to *C. lusitanica* plantations significantly enhances the growth of their natural regeneration [6]. Site conditions and different silvicultural management practices impact the growth performance of both planted and naturally regenerated seedlings [7]. Repeated experiments show that *C. lusitanica* exhibits rapid early growth, with height increases of up to 1–2 m per year during the initial years [8]. According to Million [9], silvicultural treatment can improve the growth performance of AR. Similarly, Madhu et al. [10] found that silvicultural treatments of *C. lusitanica* plantations are also effective for natural regeneration. Ceccon [11] states that the main factors influencing early growth performance are natural and human-made factors that have a significant impact on *C. lusitanica*. Additionally, poor soil conditions, unclear planting goals, inadequate planning and planting methods, open grazing, and nursery care all contribute to superior growth performance. First, planting distance and techniques influence growth outcomes [12]. Other factors affecting growth performance include species-specific management, overall forest management practices, and breeding methods [13, 14]. Delayed weed control and insufficient care can also notably hinder growth [9]. As a result, planting forest tree species in degraded areas leads to significant variations in early growth performance [15].

Silvicultural practices, including thinning and pruning, are used for natural and AR of *C. lusitanica* species. One of the silvicultural choices during vegetation establishment is stand density, which is determined by the spacing between trees [16]. At least once a year during the first 2 years after establishment, thinning and weeding are performed [9]. It is recommended to maintain a weed-free zone of 1 m in diameter around each tree from planting until canopy closure; the exact size may vary depending on location and climatic conditions. Similarly, pruning side branches can greatly increase the amount of clear wood produced, as it creates a knot-free clear stem or bole. In a 25–30-year rotation, pruning for accessible *C. lusitanica* species begins 3 years after planting to produce high-quality, knot-free wood and achieve better growth performance [9, 17]. Natural regeneration requires more thinning than planting. This approach helps reduce the regeneration period while producing relatively larger trunk sizes per hectare [18]. The decline of *C. lusitanica* forests is primarily attributed to two factors: the establishment of extensive plantations and the prolonged time required to reach the final harvest [16]. Therefore, the production time can be reduced by using suitable silvicultural treatment methods. The most important and widely used silvicultural treatment methods are tree thinning and pruning, which improve tree growth [19]. Similarly, tree mulching reduces the risk of disease, insect

infestation, and damage by abiotic agents. Therefore, after 3–4 years of planting, the first planting should be thinned and pruned because delaying tree pruning can result in natural death and growth retardation [20]. Thinning is applied to offer healthy, adequate space for remaining trees to grow more. According to Piotto et al. [21], in planted forests, particularly those with *C. lusitanica*, the stand density decreases as tree diameter increases. Trees with the smallest diameters are typically removed early, allowing the remaining trees to grow to their maximum potential diameter [20]. According to Eshetu [22], plantation forests are primarily used for timber, poles, industrial raw materials, and construction wood.

C. lusitanica is widely planted in Ethiopia, covering approximately 76,050 ha of industrial forest [23]. However, due to inadequate silvicultural management, most commercially cultivated *C. lusitanica* plantations exhibit low productivity, poor quality, and require a long time to reach final yield [9]. According to Pukkala and Pohjonen [24] and Mamo and Habte [25], the cultivation of *C. lusitanica* in Ethiopia began in the 1950s. However, it is widely planted and distributed due to its rapid growth, high-quality wood, and adaptability to different conditions [17]. Today, this species serves as a primary source of timber for the forest enterprise and plays a key role in promoting afforestation programs in Ethiopia [26]. Knowledge about the silvicultural practices and planting of *C. lusitanica* in Ethiopia remains limited, despite the economic and environmental importance of afforestation. Natural regeneration can reduce establishment and maintenance costs, but the Ethiopian Forest Enterprise still struggles to implement effective silvicultural treatments for the species [26]. As a result, the majority of commercial *C. lusitanica* plantation products in the study area are of low quality and yield, primarily due to inadequate silvicultural management [9].

The Amhara Forest Enterprise has implemented silvicultural treatments in permanent experimental plots to enhance the growth of *C. lusitanica*. However, the effects of these treatments on early growth in the Yeraba forest have not been scientifically documented. This study aimed to assess the impact of silvicultural interventions on the early growth of both artificially planted and naturally regenerated *C. lusitanica* seedlings. Although *C. lusitanica* is an important industrial species, suitable silvicultural management practices for seedling growth have not been established. By identifying effective treatments, this study provides practical guidance for smallholder farmers, forestry organizations, field technicians, and forest enterprises to improve plantation management and support sustainable forest development.

2. Research Methodology

2.1. Description of Study Area. Yeraba State Forest is located in the East Gojam Zone of the Amhara National Regional State. It is 5 km southeast of Debre Markos city and 295 km north of Addis Ababa along the road to Bahir Dar (10°18'35"N, 37°45'29"E) (Figure 1). The state forest covers approximately 315 ha of forest land. The study focused on *C. lusitanica* plantations, though the surrounding landscape

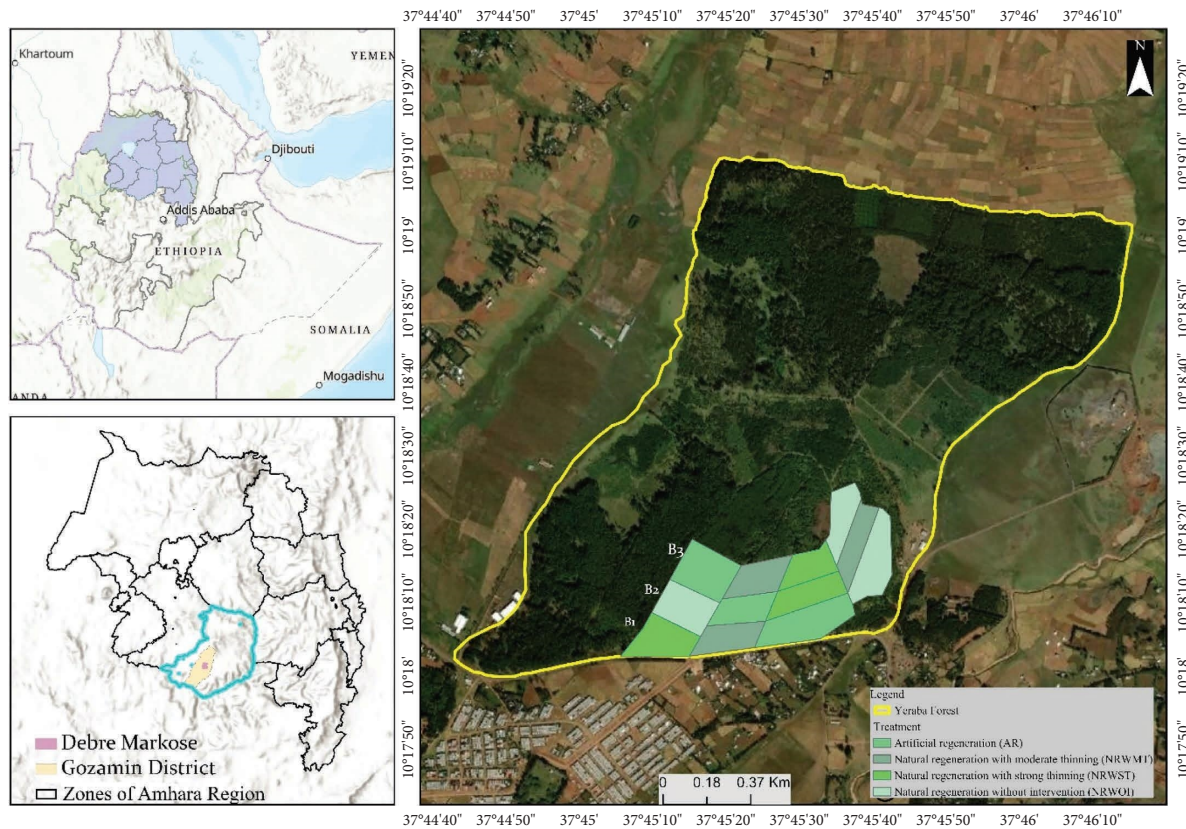


FIGURE 1: Map of the study area and experimental design.

includes mixed plantations of *Eucalyptus* spp., scattered smallholder woodlots, and remnant natural highland forests dominated by *Juniperus procera*, *Hagenia abyssinica*, *Erica* spp., and *Olea* spp. The area is a mosaic of land uses, including pasturelands (Angereb and Abedege), farmland (Engecha), and settlements (Chemoga), with gentle to moderate slopes of 2%–15% [27, 28]. Local livelihoods are primarily based on smallholder farming, livestock grazing, forest product collection, and supplementary activities, including beekeeping and medicinal plant harvesting. The forest lies within the broader Choke Mountains and Gish-Abbay watershed, providing scenic, ecological, and tourism value. Wildlife in remnant patches includes various small and medium-sized mammals and Afro-montane bird species, reflecting the ecological importance of integrating plantation and natural forest management [29, 30].

Land use has a long history of severe erosion damage. The surrounding grassland is very open-grazed. A few forests remain, and due to the scarcity of fuelwood in many areas, people have turned to using dung as an alternative energy. Medium-sized native trees form a dominant forest, but fragmented forest stands are also found. This forest is home to distinctive species, including *Eucalyptus globulus*, *C. lusitanica*, *Acacia melanoxylon*, and *Acacia decurrens*.

2.1.1. Climate. The forest's yearly average temperature was 16°C at an elevation of 2401–2551 m above sea level, where the woodland area exists. The main rainy season (*Meher*)

extends from May to October, while a shorter rainy season (*Belig*) occurs from January to April. Annual rainfall ranges from 1,200 to 1,380 mm, with an average of about 1,290 mm per year. The climate of the forest Midlands is 18.5°C, with temperatures ranging from 15°C to 22°C [30].

2.2. Forestry Practices and Coverage in the Study Area.

The number of trees planted in the research area has increased over the past few years. In 07 kebele, only 506 ha of land were covered by forest. Forest cover is distributed as follows: 63.24% government-owned, 21.74% private, 9.09% community-managed, and 5.93% church-owned. Those factors encouraged rural Kebele residents to plant tree seedlings annually, with a focus on *Eucalyptus* species and, occasionally, on *A. decurrens* and *C. lusitanica*. Yeraba State Forest has an area of 315 ha. Dejazmach Tshaye Enkuslase management units and their families use the forest as a recreational area. The forest area was only 5 ha when it was established, but it grew to 315 ha under the Derg regime [29]. Currently, the forest area covers 315 ha of land.

2.3. Experimental Design and Treatments. The field experiment was conducted in 2014 in *C. lusitanica* plantations of the Amhara Forest Enterprise, Yeraba Priority State Forest, following a randomized complete block design (RCBD) with three replications. The experiment applied four silvicultural treatments (Figure 1) to standardize plantation conditions following the clear-cutting of mature stands. Each

experimental plot measured 10 m × 10 m, and plots were separated by 5 m, while blocks were separated by 10 m to reduce edge effects and minimize interference between treatments.

The four silvicultural treatments included AR, which involved planting nursery-grown seedlings at a spacing of 2 m × 2 m immediately after clear-cutting; assisted natural regeneration with strong thinning (NRST), where natural regeneration of seedlings was supported through intensive thinning to reduce competition, applied at 2 m × 2 m spacing; assisted natural regeneration with moderate thinning (NRMT), which involved moderate thinning to reduce overcrowding, at spacing 2 m × 1 m; and natural regeneration without intervention (NRWOI), where natural regeneration was allowed to establish without any thinning or planting, serving as the control treatment.

Clarification of terminology: AR refers exclusively to planted seedlings, whereas NRST, NRMT, and NRWOI refer to naturally regenerated seedlings, which were either managed (thinning) or unmanaged/control.

Layout considerations: The arrangement of blocks followed a randomized layout, taking into account both site heterogeneity and minor altitudinal differences (2%–15%

slopes) across the study area to minimize bias. Randomization ensured that each treatment appeared once in each block, minimizing systematic variation due to site factors.

Timing of regeneration: AR seedlings were planted immediately after the clear-cut operation, while natural regeneration seedlings began to emerge within the first rainy season following clear-cutting. Assisted thinning treatments (NRST and NRMT) were applied after initial natural regeneration had been established sufficiently to allow the selective removal of competing individuals.

Age of plantation at clear-cutting: The *C. lusitanica* stand was approximately 25 years old at the time of harvesting, considered mature for the region's management standards (Figure 2).

The effect of the treatments on early growth performance was assessed 3 years after the silvicultural intervention. The silvicultural treatments assessed were natural regeneration density in the research area, regenerated seedlings, assisted NRST, and assisted NRMT. The classification of thinning intensity into "strong" (NRST) and "moderate" (NRMT) treatments was determined based on the corresponding residual rates of 21.6% and 43.1%, respectively, as calculated using (1).

$$\text{Residual rate (\%)} = \frac{\text{Existing seedlings}}{\text{Total seedling}} * 100 \dots\dots\dots (1)$$

The residual rate represents the proportion of seedlings that remain following thinning relative to the prethinning seedling population. A lower residual rate indicates a higher removal intensity and thus a stronger thinning treatment, whereas a higher residual rate reflects a lower removal intensity, corresponding to a moderate thinning treatment. Consequently, the designations "strong" and "moderate" are quantitatively defined according to the degree of natural regeneration retained after thinning, ensuring consistency and comparability among treatments.

3. Data Collection and Analysis

After 3 years of intervention with silvicultural treatments, quantitative data were collected on early growth performance using primary data sources in the field (seedling height, diameter at breast height [DBH], and root collar diameter [RCD]). The experimental treatments were assigned using a random sampling method. Accordingly, seedling height (m) was measured using a meter-marked wooden stick, DBH (cm) was measured with a tree caliper, RCD (cm) was measured using a digital caliper, and distances and plot dimensions were determined with a measuring tape. According to Senbeta and Teketay [31], height measurements are categorized into three groups: seedlings (height < 1 m), saplings (height 1–3 m), and trees (height > 3 m). Finally, ANOVA tables, graphs, and percentages were used to display the results of the descriptive statistical analysis using the SPSS Version 27 software program of

C. lusitanica's early growth performance, which was conducted using both artificial and natural regeneration of the gathered data.

4. Result

4.1. Survival Rate of Artificial and Natural Regeneration of *C. lusitanica* Seedlings. There were notable variations in seedling stocking density between treatments ($p < 0.05$). With a 93% survival rate, AR produced 2355 stems ha⁻¹, the lowest stocking density of treatments. With 100% survival, 2466 stems ha⁻¹ were produced by NRST, which did not statistically significantly differ from AR. The second-highest density, 4789 stems ha⁻¹, was achieved via NRMT. While 11,600 stems ha⁻¹, natural regeneration without intervention had the highest density (Table 1).

Figure 3 summarizes the impact of silvicultural treatments on stocking density. Treatments sharing the same letter are not significantly different, while those differences show significant differences. AR and NRST had similar and the lowest stocking levels, NRMT had significantly higher stocking, and NRWOI recorded the highest density.

4.2. Stem Form. Stem form assessment at 3 years of age indicated that 98% of the trees were straight, with an average of two stems per hectare exhibiting forked or twisted. No statistically significant differences were observed among the four treatments for either stem number or forking (Table 2). Similarly, logistic regression analysis showed no significant



FIGURE 2: Naturally regenerated seedlings at years one and three after a clear-cut of a 25-year-old *C. lusitanica* plantation.

TABLE 1: Survival rate of artificial and natural regeneration of *Cupressus lusitanica*

Survival rate	Year 1	Year 2	Year 3
Artificial regeneration	98%	97%	93%
Natural regeneration	100	100	98

TABLE 2: ANOVA of stem form variation under different silvicultural treatments.

Stem form	Source of variation				
	Sum of squares	df	Mean square	F	Sig.
Between groups	0.003	3	0.001	0.057	0.982
Within groups	32.427	1905	0.017		
Total	32.430	1908			

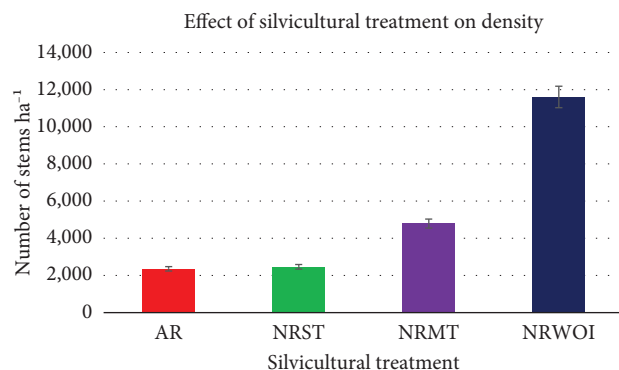


FIGURE 3: Effect of silvicultural treatment on the density of *C. lusitanica* after clear-cut.

treatment effects on the probability of forking (forked vs. unforked trees).

4.3. Effects of Silvicultural Treatments on Early Growth Performance in Yeraba Forest. Descriptive statistics for RCD, DBH, and height under different treatments were presented in Table 3. Among the treatments, NRST exhibited the highest mean values for all growth parameters (RCD = 4.33 cm (about 1.7 in), DBH = 3.21 cm (about 1.26 in), height = 3.81 m), followed closely by AR (4.09 cm (about 1.61 in), 3.03 cm (about 1.19 in), and 3.50 m, respectively). The NRMT treatment showed intermediate mean values (3.37 cm [about 1.33 in], 2.50 cm [about 0.98 in], and 3.16 m). In comparison, the natural regeneration without intervention (NRNI) treatment recorded the lowest averages (2.25 cm [about 0.89 in], 1.67 cm [about 0.66 in], and 1.81 m).

TABLE 3: Descriptive statistics of seedling growth parameters (mean $\pm$ standard error) under different silvicultural treatments.

Treatment	RCD (cm)	DBH (cm)	Height (m)
AR	4.09 $\pm$ 0.06	3.03 $\pm$ 0.04	3.50 $\pm$ 0.03
NRST	4.33 $\pm$ 0.05	3.21 $\pm$ 0.03	3.81 $\pm$ 0.03
NRMT	3.37 $\pm$ 0.04	2.50 $\pm$ 0.03	3.16 $\pm$ 0.02
NRWOI	2.25 $\pm$ 0.02	1.67 $\pm$ 0.01	1.81 $\pm$ 0.01

The pattern in Table 3 indicates that thinning intensity had a positive effect on seedling growth, particularly under strong thinning conditions. This enhancement is likely attributed to reduced intraspecific competition and improved availability of light, moisture, and nutrients for residual seedlings. Conversely, the no-intervention stands showed significantly lower growth performance, suggesting that high stand density suppressed seedling development.

4.3.1. Root Collar Diameter. The ANOVA Table 4 reveals that the treatment groups have a statistically significant effect on RCD ($p < 0.001$). R^2 value of approximately 0.63 indicates that the treatment explains a substantial proportion of the variance in the outcome variable. We perform post hoc pairwise comparisons using Tukey's test to determine which specific groups differ significantly from one another. According to Figure 4, the thickest RCD was recorded in assisted NRST, followed by AR. Assisted NRMT had the second-lowest RCD thickness, and the smallest mean DBH was recorded in the NRWOI.

TABLE 4: ANOVA of RCD variation under different silvicultural treatments.

Source variation	Sum of squares	df	Mean square	F	Sig.
Corrected model	1283.254 ^a	3	427.751	1075.603	0.000
Intercept	15755.782	1	15755.782	39618.747	0.000
Treatment	1283.254	3	427.751	1075.603	0.000
Error	757.590	1905	0.398		
Total	18632.509	1909			
Corrected total	2040.844	1908			

^aR-squared = 0.629 (adjusted R-squared = 0.628).

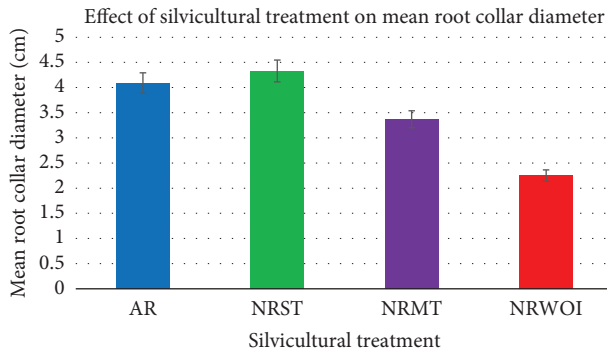


FIGURE 4: Effect of silvicultural treatments on mean RCD after 3 years.

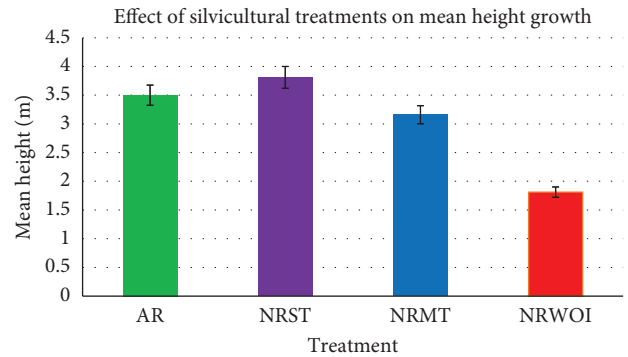


FIGURE 5: Effect of silvicultural treatments on mean height growth performance after 3 years.

TABLE 5: ANOVA table on the effects of silvicultural treatments on height variation at Year 3.

Source of variation	Sum of squares	df	Mean square	F	Sig.
Corrected model	1303.921 ^a	5	260.784	1397.535	0.000***
Intercept	11993.572	1	11993.572	64273.184	0.000***
Treatment	1300.232	3	433.411	2322.634	0.000***
Replication	18.871	2	9.435	50.564	0.000***
Error	355.106	1903	0.187		
Total	13914.758	1909			
Corrected total	1659.027	1908			

^aR-squared = 0.786 and adjusted R-squared = 0.785.

***Highly significant.

4.3.2. Height. As shown in Table 5, the ANOVA results indicate a highly significant difference ($p < 0.01$) in height after 3 years of silvicultural treatment. The highest mean height of the applied silvicultural treatment was found in NRST, followed by AR. In contrast, the lowest height was recorded in the control treatment (NRWOI).

Effect of Silvicultural Treatment on Early Height Growth Response in Yeraba State Forest. Statistically analyzed results of seedling and tree height (Figure 5) show that in natural regeneration, the highest growth response height was observed in NRST, followed by AR and NRMT. By contrast, the control treatment (NRWOI) showed the lowest growth performance in height.

4.3.3. Diameter at Breast Height. As shown in Table 6, the ANOVA results indicate the thickest significant difference

($p < 0.001$) in DBH after 3 years of silvicultural treatment. The mean thickness diameter of the applied silvicultural treatment was found in NRST, followed by AR. In contrast, the lowest thickness was recorded in the control treatment (NRWOI).

According to (Figure 6), the thickest DBH was recorded in NRST, followed by AR. NRMT had the second-lowest DBH thickness, and the smallest mean DBH was recorded in the NRWOI (control treatment).

4.4. Establishment Cost of Artificial and Natural Plantation Forest. According to Figure 7, natural regeneration without thinning exhibited the lowest establishment and tending costs, approaching zero. NRMT incurred intermediate costs of approximately 8000 ETB. In comparison, natural regeneration with strong thinning was slightly less costly, at around 7000 ETB, yet still considerably more economical than AR. AR demonstrated the highest costs, averaging approximately 14,000 ETB, nearly twice that of moderate thinning.

5. Discussion

The applied silvicultural treatments created an inverse relationship between stand density and growth performance, significantly influencing early growth and individual tree regeneration in the planted forest. Those differences might be related to the higher stand density and more competition for available water, nutrients, and light. In the control treatment (NRWOI), there were more than 11,000 seedlings per hectare in the study area. While our findings indicate this trend, Piotto et al. [21] and Mamo and Habbie [25] reported

TABLE 6: ANOVA for DBH variation under different silvicultural treatments.

Source of variation	Sum of squares	df	Mean square	F	Sig.
Corrected model	717.731 ^a	5	143.546	679.38	0.000**
Intercept	8589.987	1	8589.987	40654.91	0.000**
Treatment	714.154	3	238.051	1126.656	0.000**
Replication	13.603	2	6.801	32.19	0.000**
Error	402.085	1903	0.211		
Total	10223.563	1909			
Corrected total	1119.817	1908			

^aR-squared = 0.641 and adjusted R-squared = 0.640.

**Highly significant.

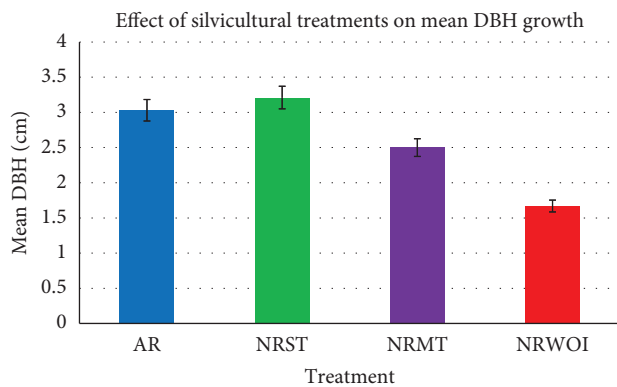


FIGURE 6: Effect of silvicultural treatments on mean DBH growth response after 3 years.

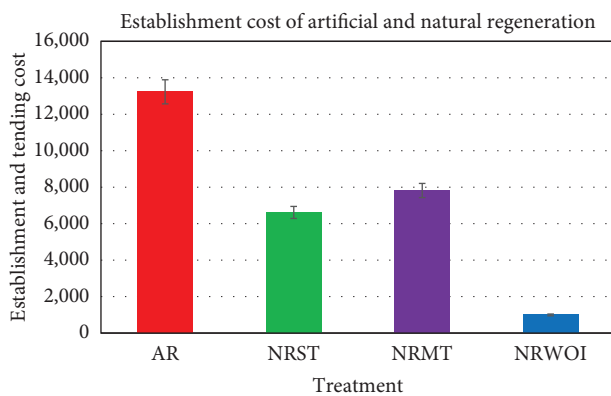


FIGURE 7: Establishment cost of artificial and natural plantation forests.

that unthinned *C. lusitanica* stands exhibit high basal area but low individual growth, likely due to differences in experimental site conditions, plantation age, and silvicultural practices. Silvicultural interventions, as noted by Piotto et al. [21, 32] and Mamo and Habtie [24], enhance DBH and height during early growth stages.

When comparing natural regeneration with artificially planted seedlings, natural regeneration consistently showed superior height and DBH growth [10]. The observed discrepancies among studies can be attributed to variations in environmental conditions and silvicultural practices [33, 34]. These results suggest that early growth performance of *C. lusitanica*,

whether naturally or artificially regenerated, is influenced by site heterogeneity, management practices, and early tending activities such as microenvironmental modification, mechanical site preparation, and release treatments [35, 36].

Our results further demonstrate that thinning, particularly strong thinning, significantly improves early growth in naturally regenerated stands. In contrast, control plots with over 11,000 seedlings per hectare exhibited the poorest performance, likely due to excessive competition. This supports the established principle that reducing stand density enhances resource allocation to remaining individuals. While thinning increases individual tree growth, unthinned stands may retain higher basal area but show lower growth per tree [21].

Interestingly, natural regeneration subjected to intensive thinning outperformed artificial planting in both height and DBH, corroborating El Zein et al. [10]. This superior performance is likely due to better root system development, minimal transplant shock, and local adaptation. These findings highlight the importance of promoting and systematically managing natural regeneration, particularly in resource-constrained environments.

In light of these considerations, natural regeneration with minimal to moderate thinning is often the most cost-effective option [37, 38]. However, regeneration methods should not be chosen on cost alone; managers must balance financial feasibility with objectives such as timber quality, ecological outcomes, species diversity, and resilience to disturbance [39, 40]. Ultimately, the regeneration strategy represents a trade-off between short-term savings and long-term stand performance.

From a cost-efficiency standpoint, natural regeneration without thinning represents the most economical approach to stand establishment, as it depends on existing seed sources or seed banks and requires minimal site preparation or maintenance. However, the absence of silvicultural intervention often leads to overly dense, uneven stands with reduced diameter growth, lower timber quality, and greater vulnerability to pests and diseases. The introduction of thinning operations effectively mitigates these issues by regulating stand density and enhancing the growth of selected stems. While thinning increases operational costs, it yields long-term benefits in terms of stand structure, stability, and timber value.

Among thinning intensities, moderate thinning generally offers an optimal balance between cost and biological

benefit, whereas strong thinning requires slightly higher expenditures but provides greater improvements in growth performance and stand quality. In contrast, AR, though effective in achieving desired stand composition, spacing, and genetic quality, remains the most capital-intensive method due to high labor, seedling, and maintenance costs.

Overall, these findings underscore the importance of optimizing thinning intensity within naturally regenerated stands to achieve a sustainable balance between economic efficiency and ecological performance. Strong thinning appears particularly advantageous for promoting early stand development and ensuring long-term productivity, while moderate thinning offers a practical compromise for resource-limited management scenarios.

6. Conclusion and Recommendation

This study demonstrates that silvicultural interventions, particularly thinning, have a pronounced influence on the early growth performance of *C. lusitanica* seedlings. Among the treatments tested, NRST produced the greatest improvements in height and diameter growth, significantly outperforming both moderate thinning and AR. In contrast, NRWOI resulted in poor growth due to excessive competition among seedlings. These results highlight the importance of regulating stand density during the early postharvest years to promote vigorous seedling development and efficient resource utilization.

Encouraging natural regeneration through intensive thinning provides a cost-effective and ecologically sustainable approach to *C. lusitanica* management in Ethiopia. This method not only enhances seedling growth and shortens rotation periods but also reduces plantation establishment costs and improves timber quality. By minimizing disturbance to naturally regenerated seedlings and maintaining appropriate spacing, forest managers can promote robust stand development and ensure long-term productivity.

Based on these findings, it is recommended that strong thinning be adopted in naturally regenerated *C. lusitanica* stands to accelerate growth and reduce rotation age. AR should be restricted to areas where natural regeneration is insufficient or absent. During the first year of establishment, seedlings should be protected from unnecessary disturbance to prevent exposure to excessive sunlight and moisture loss. Maintaining selectively open spaces within stands can further reduce competition and enhance resource availability. NRST should therefore be integrated into forest management plans as a sustainable, low-cost strategy for plantation establishment and forest restoration. Finally, long-term (> 10 years) monitoring and research should be conducted to assess the effects of thinning intensity on stand structure, biomass, wood quality, carbon sequestration potential, and economic viability, thereby strengthening the scientific basis for sustainable management of *C. lusitanica* in Ethiopia.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

Ethics Statement

No human or animal tissues were used in this study. Procedurally, the similarity index was measured using an authentic score before journal selection. Then, the plagiarism result was evaluated and confirmed before submission to the International Journal of Forestry Research.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

The authors were involved in all aspects of the study, including proposal preparation, data collection, and acquisition of secondary data under limited internet access, not funding, data analysis, and manuscript writing. They also reviewed, edited, and commented on the final manuscript.

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