



Full Length Research Article

Optimizing Afforestation Techniques for *Cedrus* and *Pinus* in Semi-Arid Mediterranean Lebanon: Insights from Chmistar Field Trials

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ABSTRACT

Afforestation in semi-arid Mediterranean environments is frequently constrained by water scarcity, shallow rocky soils, and strong competition from herbaceous vegetation, resulting in low seedling establishment and growth. This research evaluated the effects of three planting methods (traditional pits, hoedad, and auger) and four vegetation control treatments (mulching, mowing, herbicide application, and no vegetation control) on the early establishment of three native Mediterranean conifer species (*Cedrus libani*, *Pinus halepensis*, and *Pinus pinea*) at Chmistar, eastern Lebanon, from 2022 to 2024. The experiment used a randomized complete block design (RCBD) with four blocks and 48 plots, with 24 seedlings per plot. Seedling survival, height growth, and root collar diameter (RCD) growth were assessed annually. Data were analyzed using analysis of variance (ANOVA) at a significance level of ≤ 0.05 . Vegetation control had a significantly greater influence on seedling performance than planting technique. Across all species, the hoedad $\times$ mulch treatment produced the highest survival rates, reaching 97.9% in 2022 and maintaining 70.8% in 2024. *P. halepensis* showed the highest survival under this treatment, reaching 87.5% in 2022 and 2023 and remaining at 75.0% in 2024. In contrast, *P. pinea* and *C. libani* reached a maximum survival rate of 68.8% in 2024. Height growth was also enhanced by effective vegetation control, with maximum annual increments reaching 41.7 cm for *P. halepensis*, 20.8 cm for *P. pinea*, and 20.8 cm for *C. libani*. Similarly, maximum RCD increments reached 1.50 cm, 1.08 cm, and 1.24 cm for *P. halepensis*, *P. pinea*, and *C. libani*, respectively. Overall, mulching consistently improved seedling survival and growth across species and years, demonstrating that vegetation control is a more important determinant of early conifer establishment than planting technique under semi-arid Mediterranean conditions. These findings highlight the importance of combining effective vegetation management with site-adapted species selection to enhance afforestation success in water-limited environments.

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1. Introduction

Coniferous forests constitute a major ecological component of Mediterranean mountainous and semi-arid landscapes, providing essential ecosystem services such as soil stabilization, water

regulation, carbon sequestration, and biodiversity conservation (Escudero et al. 2026; Nocentini et al. 2022). In the eastern Mediterranean, native conifer species such as *Cedrus libani*, *Pinus pinea*, and *Pinus halepensis* are key structural components of forest ecosystems. However, Mediterranean drylands are characterized by irregular rainfall patterns and prolonged summer droughts, creating harsh conditions that limit tree establishment and growth (González-Zamora et al. 2023; Maestre et al. 2016). In Lebanon and across the eastern Mediterranean region, coniferous forests have experienced substantial declines due to land-use change, overgrazing, recurrent wildfires, and increasing climatic stress (Ermitão et al. 2024; Peñuelas et al. 2017). Consequently, afforestation and ecological restoration programs increasingly rely on native conifer species to rehabilitate degraded landscapes and restore ecosystem functioning (Buthelezi et al. 2025).

Despite these efforts, afforestation success remains highly variable in semi-arid environments. The establishment phase is often the most critical stage because seedlings must survive under conditions of limited water availability, shallow rocky soils, and strong competition from herbaceous vegetation (Grossnickle and MacDonald 2018; Maestre et al. 2016). Competition for soil moisture is particularly important during the first years after planting, when root systems are still poorly developed and seedlings are highly vulnerable to drought stress. Therefore, management practices that reduce competition and improve soil water availability are expected to play a central role in determining afforestation success.

Vegetation control has been widely recognized as an effective means of improving seedling establishment in water-limited environments. Among the available approaches, mulching can reduce soil evaporation, moderate soil temperature fluctuations, and suppress competing vegetation, thereby improving soil moisture availability for transplanted seedlings (Coello et al. 2018; Hueso-González et al. 2017; Oliet et al. 2023). Other vegetation control methods, such as mowing and herbicide application, can reduce competition but may not improve soil microclimatic conditions to the same extent (Araújo et al. 2025). Consequently, differences among vegetation control strategies may have important implications for seedling survival and growth under semi-arid conditions.

Species-specific ecological traits may further influence responses to environmental stress and management practices. *P. halepensis* and *P. pinea* are generally characterized by relatively rapid early growth and greater resilience, although their performance remains strongly influenced by site conditions and management interventions (Alsanousi et al. 2025; Carneros et al. 2009). In contrast, *C. libani* exhibits slower juvenile development and a more conservative growth strategy, which may increase its sensitivity to drought and competition during the establishment phase (Zsolnay et al. 2023). These differences suggest that the effectiveness of vegetation control practices may vary among species according to their ecological characteristics.

Planting methods may also contribute to seedling establishment by influencing root penetration, soil disturbance, and access to water. Traditional planting pits, hoedad planting, and mechanized auger drilling differ in their suitability depending on soil depth, compaction, and stone content (Chen et al. 2024; Wang et al. 2024). However, the effectiveness of planting methods may depend on their interaction with vegetation control practices and species-specific responses.

Although numerous studies have investigated vegetation control or planting methods separately, empirical evidence evaluating their combined effects on native Mediterranean conifer species remains limited, particularly under the semi-arid conditions of Lebanon. In addition, the relative importance of vegetation control, planting technique, and species-specific traits during early seedling establishment remains unclear. This knowledge gap limits the development of

evidence-based recommendations for afforestation and restoration programs in the eastern Mediterranean region.

Therefore, this study aimed to assess the effects of planting methods and vegetation control strategies on the survival and early growth of *C. libani*, *P. pinea*, and *P. halepensis* at a semi-arid site in eastern Lebanon. The research sought to identify site-adapted management practices that can enhance the success of conifer afforestation in semi-arid Mediterranean environments. We hypothesized that: (1) mulching would increase seedling survival and growth more than mowing, herbicide application, or no vegetation control due to its ability to conserve soil moisture and reduce competition; (2) *P. halepensis* would exhibit greater survival and growth than *P. pinea* and *C. libani* because of its higher tolerance to semi-arid conditions; and (3) vegetation control would exert a stronger influence on seedling establishment than planting technique.

2. Materials and Methods

2.1. Study Area

The experiment was conducted at the Chmistar afforestation site in eastern Lebanon (**Fig. 1**), which is representative of semi-arid Mediterranean conditions. The site is characterized by low and irregular annual rainfall, prolonged summer drought, and marked interannual climatic variability. Soils are generally shallow, stony, and calcareous, with limited water-holding capacity, creating challenging conditions for seedling establishment. These environmental constraints make the site suitable for evaluating the effectiveness of planting methods and vegetation control strategies under realistic restoration conditions.

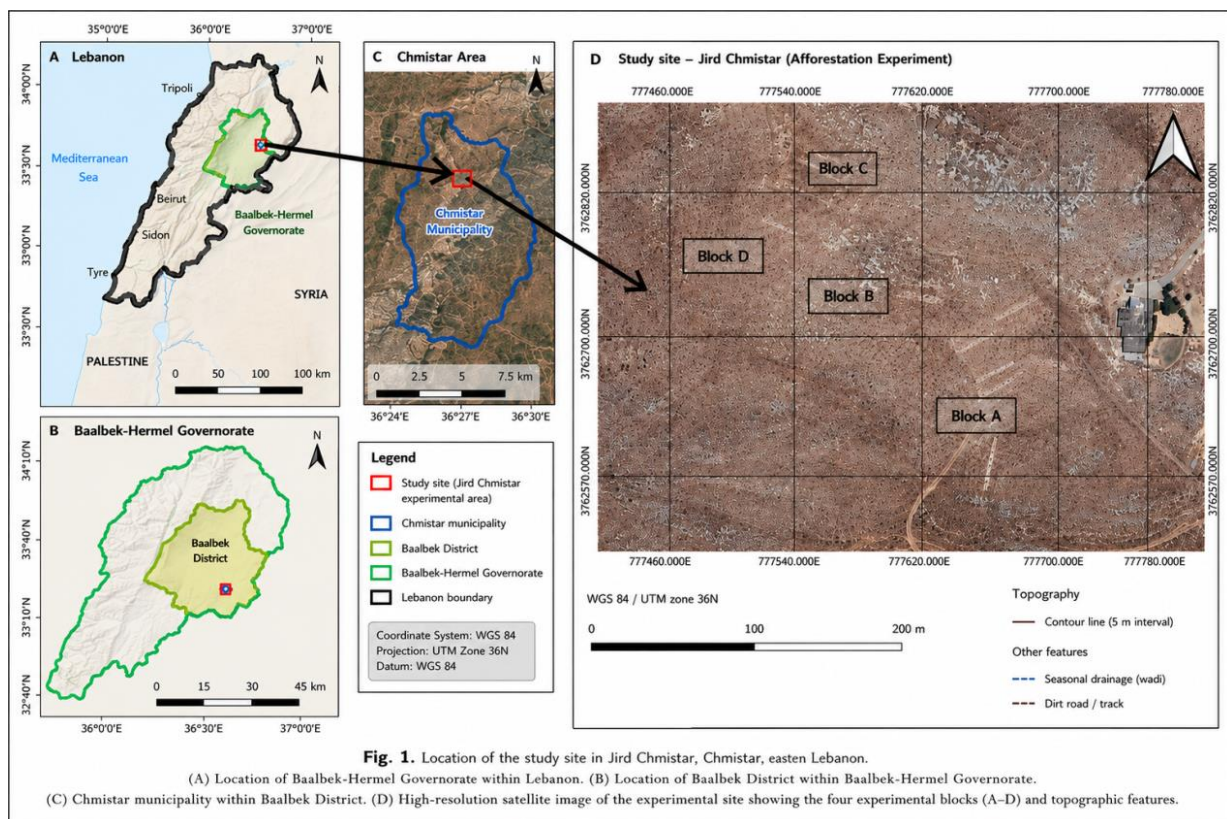


Fig. 1. Satellite image of the study site, Jird Chmistar, Chmistar.

2.2. Plant Material

Seedlings of three native Mediterranean conifers (*Cedrus libani*, *Pinus pinea*, and *Pinus halepensis*) were selected for this research. This study assesses conifer growth and survival. These species were selected and tested due to their ecological importance and widespread use in afforestation programs in Lebanon and the Eastern Mediterranean region. The seedlings were one-year-old at the time of planting and were produced in local nurseries in 0.5 L containers. No hardening or acclimatization procedure was applied to the seedlings prior to outplanting. **Table 1** shows the initial height and root collar diameter of the seedlings at the time of planting.

Table 1. Initial height and root collar diameter (RCD) of the three seedling species at the time of planting. Values are presented as mean $\pm$ SEM

Group	Species	Height (cm)		RCD (cm)	
		Mean	SEM	Mean	SEM
Conifers	<i>C. libani</i>	12.67	0.25	0.435	0.07
	<i>P. pinea</i>	11.46	0.26	0.494	0.06
	<i>P. halepensis</i>	31.07	0.69	0.453	0.07

2.3. Experimental design

The experiment was established on 20 March 2022 using a randomized complete block design (RCBD) with four blocks. Treatments consisted of three planting methods (traditional pits, hoedad planting, and auger planting) and four vegetation control strategies (mulching, mowing, herbicide application, and no vegetation control), resulting in twelve treatment combinations (**Table 2**). Each treatment combination was represented once per block and fully replicated across the four blocks to account for spatial heterogeneity within the site.

Table 2. Combinations of planting method and vegetation control treatment

Planting Method (P)	Vegetation Control (V)			
	V1 Mulching	V2 Mowing	V3 Herbicide Application	V4 No Vegetation (Control)
P1 Traditional Pits	P1V1	P1V2	P1V3	P1V4
P2 Hoedad Planting	P2V1	P2V2	P2V3	P2V4
P3 Auger Planting	P3V1	P3V2	P3V3	P3V4

Each experimental plot, measuring 4 meters in width and 26 meters in length, had a total area of 104 m² and contained 24 conifer seedlings. The three selected conifer species (**Fig. 2**) were planted using a consistent arrangement with a spacing of 1 m between seedlings, and this species arrangement was replicated eight times within each plot (8 sets $\times$ 3 species = 24 seedlings). The first and last seedlings were positioned 1.5 m from the plot boundaries to minimize edge effects. A total of 48 plots (12 treatment combinations $\times$ 4 blocks) were included in the experiment, resulting in a total sample size of 1,152 seedlings (**Table 3**). Each treatment combination was conducted to study the effects of planting method, vegetation control treatment, and their interactions on seedling survival and growth to be evaluated under comparable field conditions.

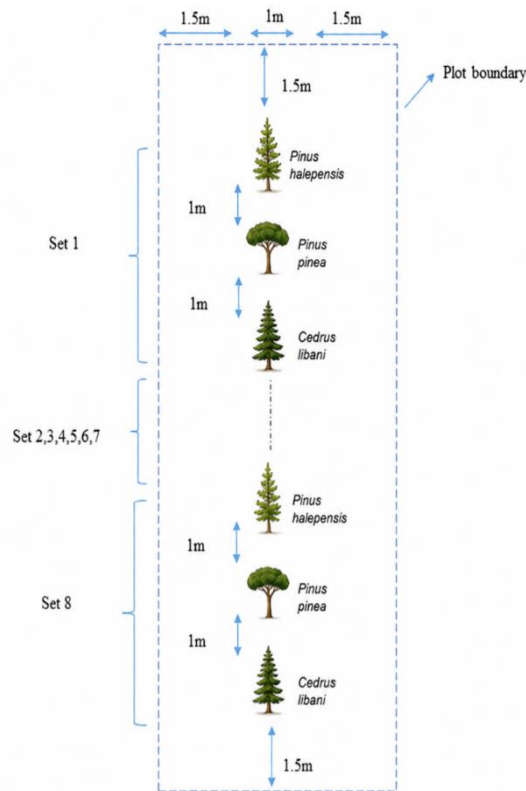


Fig. 2. Plot layout and species arrangement for the experimental design to evaluate seedling survival and growth.

Table 3. Layout of the randomized complete block design (RCBD) showing treatment assignment per block

BLOCK 1	BLOCK 2	BLOCK 3	BLOCK 4
12	9	6	3
1	10	7	4
2	11	8	5
3	12	9	6
4	1	10	7
5	2	11	8
6	3	12	9
7	4	1	10
8	5	2	11
9	6	3	12
10	7	4	1
11	8	5	2

2.4. Planting Methods

Three planting methods commonly used in afforestation projects were evaluated: traditional pit planting, hoedad planting, and auger planting. One-year-old seedlings grown from seeds collected by the AFDC team from different locations across Lebanon and raised in a nursery were planted in the field on 20 March 2022.

The traditional pit method consisted of manually excavating planting holes measuring 30 cm in diameter and 30 cm in depth. Hoedad planting was performed using a hoedad tool equipped

with a metal blade 38 cm long and 7.5 cm wide. The blade was inserted into the soil to create a planting slit, the seedling was positioned vertically with its root system fully extended, and the slit was then closed to ensure adequate root–soil contact. For auger planting, holes were drilled using a mechanical earth auger with a diameter of 20 cm and a depth of 30 cm.

All seedlings were planted at the root collar level to avoid excessive burial or root exposure. The excavated soil was returned to the planting hole and manually compacted around the root system to eliminate air pockets and promote good root–soil contact. No irrigation was applied after planting, allowing seedling establishment to depend entirely on natural precipitation. These planting methods were selected to represent both labor-intensive and mechanized approaches and to evaluate their suitability for afforestation under semi-arid conditions characterized by shallow and rocky soils.

2.5. Data collection

The field measurements were carried out in June 2022, June 2023, and June 2024. Seedling survival was assessed by counting all surviving seedlings of each species in each plot. Survival percentage was calculated using the following equation:

$$\text{Survival (\%)} = \left(\frac{\text{Number of surviving seedlings}}{\text{Number of initially planted seedlings}} \right) \times 100 \quad (1)$$

Height and root collar diameter of three randomly selected seedlings per plot were measured using a tape measure and calipers at the initial assessment. The selected seedlings were subsequently monitored throughout the study whenever they remained alive; no replacement seedlings were introduced following mortality. For each plot and each measurement round, the mean height and mean root collar diameter were calculated from the surviving originally selected seedlings. Thus, if one or two of the selected seedlings died, the measurements of the remaining one or two seedlings were used to calculate the plot-level mean for that round. These plot-level mean values were used to describe growth over time. Height growth and root collar diameter growth were calculated as the difference between the mean value at a given measurement round and the mean value at the previous round:

$$\text{Height growth (cm)} = \text{Mean height at current round} - \text{Mean height at previous round} \quad (2)$$

$$\text{RCD Growth (cm)} = \text{Mean RCD at current round} - \text{Mean RCD at previous round} \quad (3)$$

When no living seedlings remained in a plot, the previous plot-level mean was retained as an imputed value solely to calculate zero growth for the corresponding interval. This carried-forward value represents an imputed value and not an actual measurement after complete mortality.

2.6. Statistical analysis

The response variables analyzed in this study were seedling survival percentage, height growth, and root collar diameter growth. Analyses were conducted separately for each assessment period: from planting on 20 March 2022 to the first assessment in June 2022, from June 2022 to June 2023, and from June 2023 to June 2024. Analyses were performed independently for each species. Two-way analyses of variance (ANOVA) with Type III sums of squares were performed using JASP version 0.98, with planting method and vegetation control as fixed factors.

For each treatment combination, means and standard errors of the mean were calculated. Statistical significance was evaluated at $p \leq 0.05$. Tukey's honestly significant difference test was used for pairwise comparisons among treatment means for all treatments, regardless of ANOVA significance. Graphs were constructed using the mean values of seedling survival percentage, height growth, and root collar diameter growth, and are presented as mean $\pm$ standard error of the mean.

Because the same plots were measured repeatedly from 2022 to 2024, the repeated observations were not pooled across years into a single conventional analysis of variance. Instead, each assessment period was analyzed separately. This approach allowed treatment effects to be evaluated at discrete post-planting intervals and avoided treating repeated observations from the same plots across years as independent within a single model. Accordingly, time was not included as a repeated factor, and a repeated-measures or mixed-effects covariance structure was not fitted. The statistical inferences presented here therefore apply to each measurement period separately.

Tukey's HSD post hoc comparisons were performed within the same ANOVA model used for each response variable, species, and assessment period. Grouping letters are presented in the tables for descriptive completeness; however, they were interpreted only when the corresponding ANOVA effect was statistically significant. Where the ANOVA indicated a non-significant effect, the grouping letters were not considered evidence of statistically significant differences among treatments.

3. Results and Discussion

3.1. Results

3.1.1. Seedling Survival

Seedling survival varied markedly among vegetation-control treatments, species, and monitoring year. Across all conifer species, mulching consistently produced the highest survival rates throughout the monitoring period (2022–2024), whereas untreated control plots performed the poorest. Herbicide and mowing treatments resulted in intermediate survival rates, while *Pinus halepensis* generally showed the highest survival across treatments and years.

Lebanese cedar survival decreased, particularly in the first year after planting, while *Pinus pinea* showed an average survival rate. Vegetation management, rather than planting technique, strongly influenced overall survival patterns, and the effect of planting method on survival rate was relatively limited. Differences between traditional pits, hoedad, and auger planting were generally small and became apparent only when combined with specific vegetation control treatments, especially mulching.

Over years of observation and across all species (**Fig. 3**), the hoedad $\times$ mulch combination consistently achieved the highest survival rates, reaching 97.9% at the first assessment on 1 June 2022, conducted at the beginning of the dry season, and remaining at 70.8% by June 2024, after two dry seasons had passed. Because the first assessment was conducted at the beginning of the dry season, the 2022 values represent survival at the first assessment rather than survival after a complete dry season.

For *P. halepensis*, survival was highest under hoedad $\times$ mulch, reaching 87.5% in both 2022 and 2023 and declining to 75.0% in 2024 (**Fig. 3a**). Other treatments showed substantially lower survival, especially in non-mulched plots. *P. pinea* exhibited high early survival under hoedad $\times$

mulch and pits $\times$ mulch treatments. In 2024, survival reached 68.8% under both treatments, while survival in non-mulched treatments was markedly lower (**Fig. 3b**). Similarly, *Cedrus libani* showed the highest survival under hoedad $\times$ mulch and pits $\times$ mulch. By 2024, both treatments maintained survival rates of 68.8%, whereas survival under mowing, herbicide, and control treatments remained low (**Fig. 3c**). The ANOVA results for survival are presented in **Table 4**, and Tukey's HSD grouping letters are shown in **Table 5**.

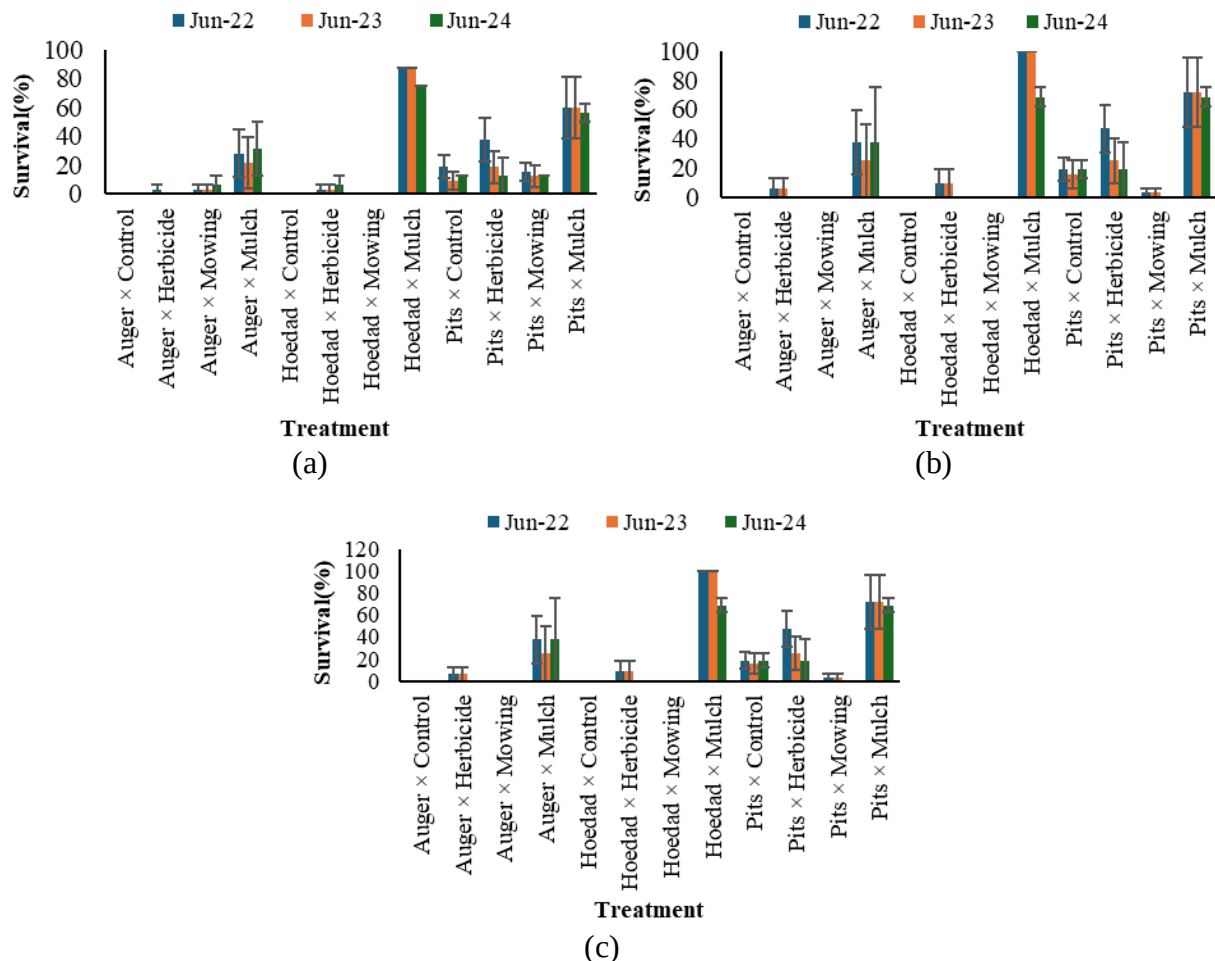


Fig. 3. Mean survival of (a) *P. halepensis*, (b) *P. pinea*, and (c) *C. libani* under different planting methods and vegetation control treatments.

Table 4. Summary of two-way ANOVA results (p -values) for the effects of planting method (PM), vegetation control (VC), and their interaction (PM $\times$ VC) on seedling survival of *C. libani*, *P. pinea*, and *P. halepensis* across 2022, 2023, and 2024. ANOVA was performed independently for each species. Significant effects are indicated at $p < 0.05$

Factor	<i>C. libani</i>			<i>P. pinea</i>			<i>P. halepensis</i>		
	2022	2023	2024	2022	2023	2024	2022	2023	2024
PM	0.014	0.027	0.193	0.004	0.012	0.042	0.095	0.248	0.05
VC	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
PM $\times$ VC	0.032	0.036	0.753	0.013	0.01	0.082	0.07	0.088	0.071

Table 5. Tukey's HSD grouping letters for mean survival percentage of *C. libani*, *P. pinea*, and *P. halepensis* under vegetation control (VC), planting method (PM), and their interaction (PM × VC) across 2022, 2023, and 2024. ANOVA was performed independently for each species. Within each factor and year, treatments sharing the same letter are not significantly different ($p > 0.05$)

Factor	Treatment	<i>C. libani</i>			<i>P. pinea</i>			<i>P. halepensis</i>		
		2022	2023	2024	2022	2023	2024	2022	2023	2024
VC	Control	a	a	a	a	a	a	a	a	a
	Herbicide	a	a	a	a	a	a	a	a	a
	Mowing	a	a	a	a	a	a	a	a	a
	Mulch	b	b	b	b	b	b	b	b	b
PM	Auger	a	a	a	a	a	a	a	a	ab
	Hoedad	ab	ab	a	ab	b	ab	a	a	a
	Pits	b	b	a	b	b	b	a	a	b
PM × VC	Auger × Control	a	a	a	a	a	a	a	a	a
	Hoedad × Control	a	a	a	a	a	a	a	a	a
	Pits × Control	ab	ab	a	ab	a	a	a	a	abc
	Auger × Herbicide	a	a	a	a	a	a	ab	ab	abc
	Hoedad × Herbicide	a	a	a	a	a	a	a	a	a
	Pits × Herbicide	abc	ab	a	ab	ab	a	ab	ab	abc
	Auger × Mowing	a	a	a	a	a	a	a	a	a
	Hoedad × Mowing	a	a	a	a	a	a	a	a	a
	Pits × Mowing	a	a	a	ab	a	a	a	a	ab
	Auger × Mulch	ab	ab	a	ab	ab	ab	ab	ab	bc
	Hoedad × Mulch	c	c	a	c	c	c	b	b	c
	Pits × Mulch	bc	bc	a	bc	bc	bc	ab	ab	c

3.1.2. Height Growth

Height growth varied among vegetation control treatments, species, years, and treatment combinations (**Fig. 4**). Seedlings growing under mulching showed the greatest height increments across species and years, whereas mowing and control treatments generally resulted in lower growth. Overall, *P. halepensis* exhibited the highest height increments among the three species. For *P. halepensis*, the greatest height increase was recorded under auger × herbicide in 2022 (41.7 cm), under auger × mulch in 2023 (9.8 cm), and under pits × mulch in 2024 (19.8 cm) (**Fig. 4a**). In *P. pinea*, height growth was highest under auger × mulch in 2022 (13.8 cm), while pits × mulch resulted in the greatest increases in both 2023 (12.1 cm) and 2024 (20.8 cm) (**Fig. 4b**). For *C. libani*, the largest height increments were observed under pits × herbicide and pits × mulch in 2022 (7.5 cm), under hoedad × mulch in 2023 (17.7 cm), and under pits × mulch in 2024 (20.8 cm) (**Fig. 4c**). The ANOVA results for height growth are presented in **Table 6**, and Tukey's HSD grouping letters are shown in **Table 7**.

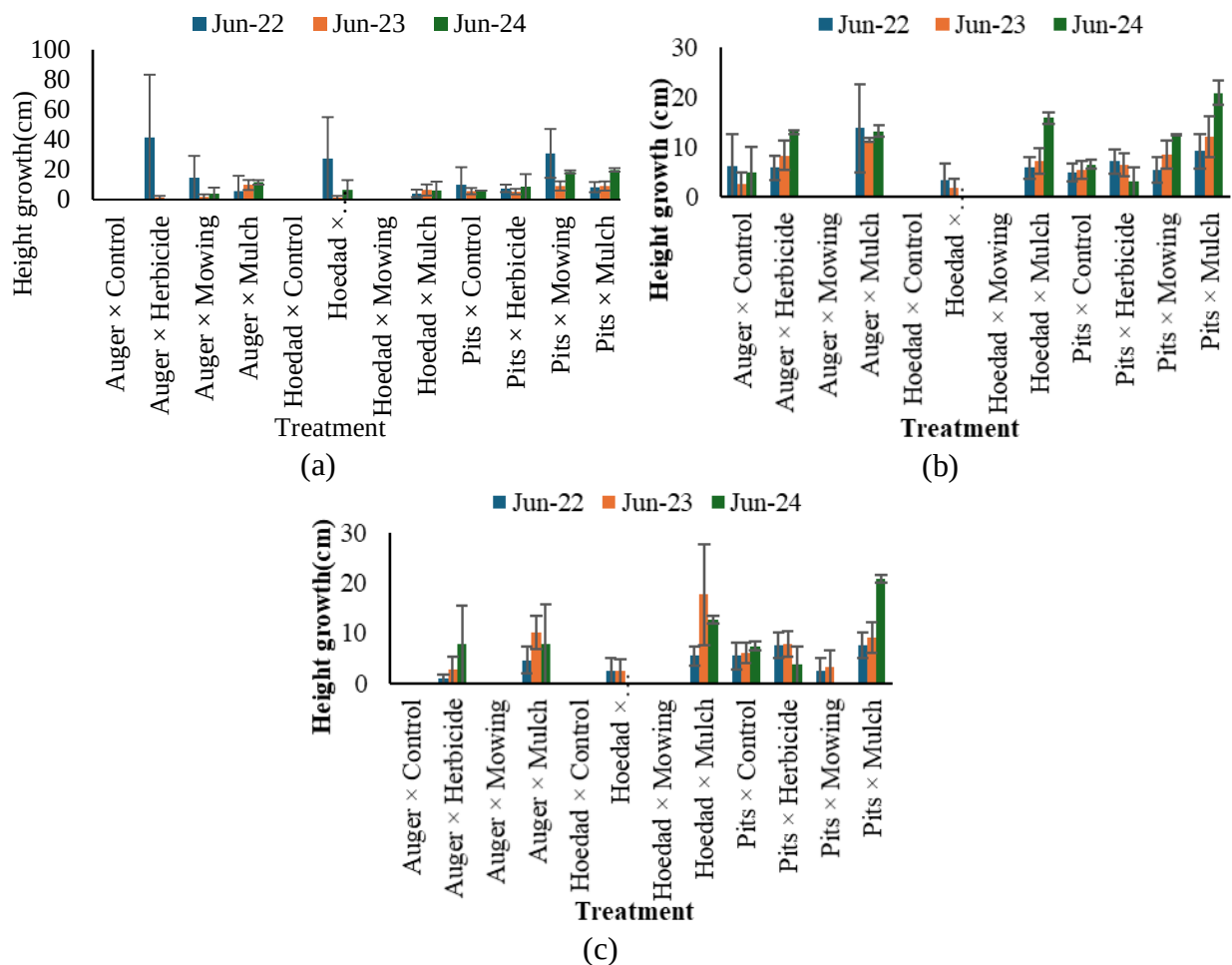


Fig. 4. Height growth of (a) *P. halepensis*, (b) *P. pinea*, and (c) *C. libani* under different planting methods and vegetation control treatments.

Table 6. Summary of two-way ANOVA results (p -values) for the effects of planting method (PM), vegetation control (VC), and their interaction (PM × VC) on height growth of *C. libani*, *P. pinea*, and *P. halepensis* across 2022, 2023, and 2024. ANOVA was performed independently for each species. Significant effects are indicated at $p < 0.05$

Factor	<i>C. libani</i>			<i>P. pinea</i>			<i>P. halepensis</i>		
	2022	2023	2024	2022	2023	2024	2022	2023	2024
PM	0.005	0.432	0.137	0.187	0.003	0.001	0.784	0.004	0.004
VC	0.014	0.002	0.002	0.086	< 0.001	< 0.001	0.353	0.004	0.032
PM × VC	0.907	0.504	0.274	0.887	0.432	0.002	0.709	0.598	0.397

3.1.3. Root Collar Diameter Growth

Although most planting method × vegetation control interactions for root collar diameter (RCD) growth were not statistically significant (**Table 8**), numerical differences were observed among treatments. Root collar diameter (RCD) growth varied among species, years, and treatment combinations (**Fig. 5**). Unlike seedling survival and height growth, no single vegetation control treatment consistently produced the highest RCD growth across all species and years. Treatment combinations showed considerable variation, suggesting that diameter growth responses varied with vegetation control, planting method, and species.

Table 7. Tukey's HSD grouping letters for mean height growth of *C. libani*, *P. pinea*, and *P. halepensis* under vegetation control (VC), planting method (PM), and their interaction (PM × VC) across 2022, 2023, and 2024. Different letters indicate significant differences at $p < 0.05$. ANOVA and post-hoc tests were performed independently for each species

Factor	Treatment	<i>C. libani</i>			<i>P. pinea</i>			<i>P. halepensis</i>		
		2022	2023	2024	2022	2023	2024	2022	2023	2024
VC	Control	ab	a	a	a	a	a	a	a	a
	Herbicide	ab	a	a	a	ab	a	a	a	ab
	Mowing	a	a	a	a	a	a	a	ab	ab
	Mulch	b	b	b	a	b	b	a	b	b
PM	Auger	a	a	a	a	ab	b	a	a	a
	Hoedad	a	a	a	a	a	a	a	a	a
	Pits	b	a	a	a	b	b	a	b	b
PM × VC	Auger × Control	a	a	a	a	ab	ab	—	a	a
	Hoedad × Control	a	a	a	a	a	a	a	a	a
	Pits × Control	a	a	a	a	ab	abc	a	a	a
	Auger × Herbicide	a	a	a	a	ab	bcd	a	a	a
	Hoedad × Herbicide	a	a	a	a	ab	a	a	a	a
	Pits × Herbicide	a	a	a	a	ab	ab	a	a	a
	Auger × Mowing	a	a	a	a	a	a	—	a	a
	Hoedad × Mowing	a	a	a	a	a	a	a	a	a
	Pits × Mowing	a	a	a	a	ab	bcd	—	a	a
	Auger × Mulch	a	a	a	—	b	bcd	a	a	a
	Hoedad × Mulch	a	a	a	a	ab	cd	a	a	a
	Pits × Mulch	a	a	a	a	b	d	a	a	a

For *P. halepensis*, the highest RCD increments were consistently observed under pits × control, reaching 0.101 cm in 2022, 0.059 cm in 2023, and 0.15 cm in 2024 (**Fig. 5a**). For *P. pinea*, the greatest RCD growth occurred under auger × mulch and pits × herbicide in 2022 (0.075 cm). However, in 2023 and 2024, pits × control produced the highest RCD increments, reaching 0.063 cm and 0.108 cm, respectively (**Fig. 5b**). Similarly, *C. libani* exhibited the highest RCD growth under the auger × mulch and pits × herbicide treatments in 2022 (0.104 cm). In contrast, the pits × control treatment resulted in the greatest RCD increments in subsequent years, reaching 0.053 cm in 2023 and 0.124 cm in 2024 (**Fig. 5c**). The ANOVA results for RCD growth are presented in **Table 8**, and Tukey's HSD grouping letters are shown in **Table 9**.

Overall, the results indicate that RCD growth responses were less consistent than those observed for survival and height growth. While mulch treatments promoted high RCD growth in some cases, control treatments also produced some of the highest diameter increments, particularly during the later years of monitoring.

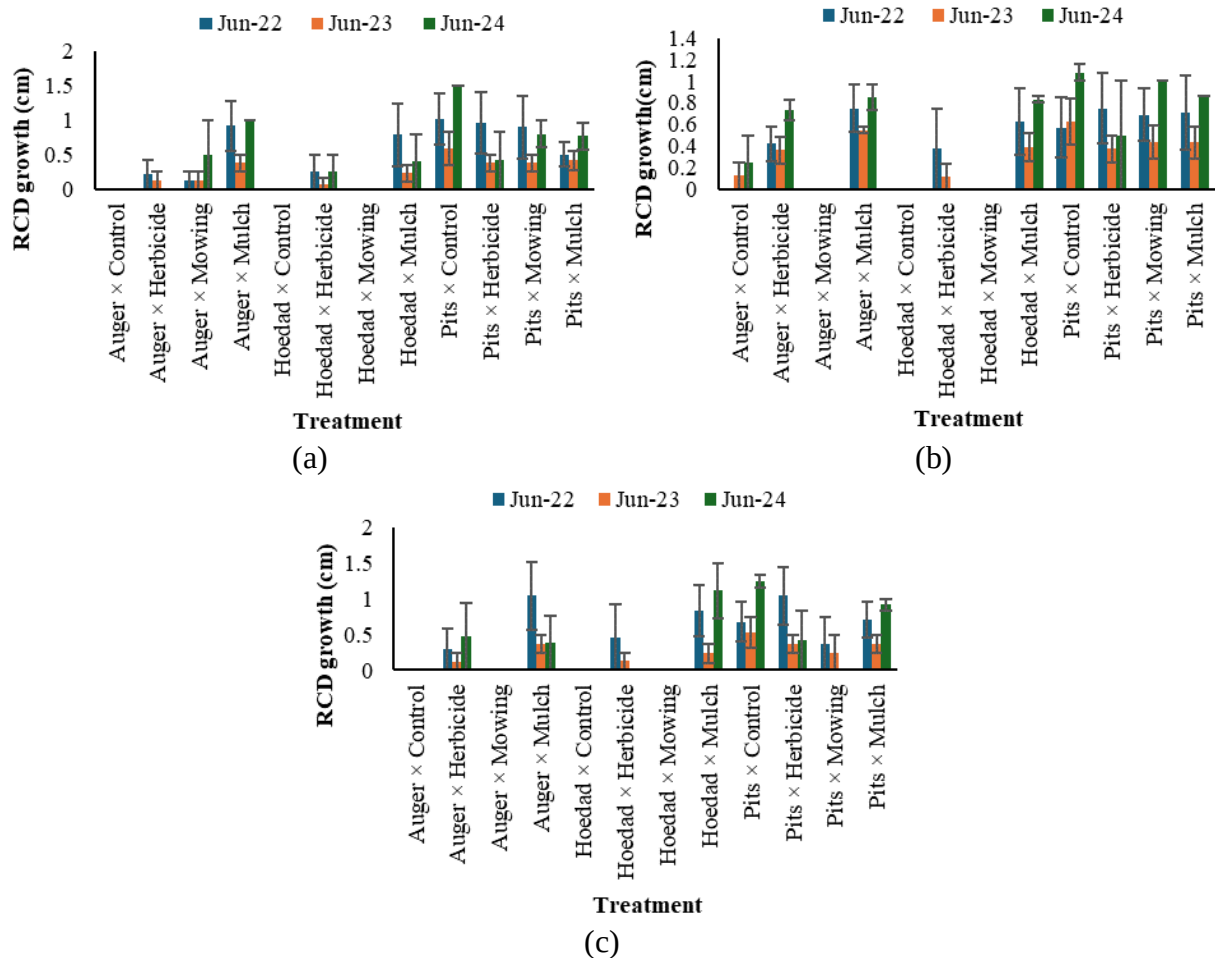


Fig. 5. Root collar diameter (RCD) growth of (a) *P. halepensis*, (b) *P. pinea*, and (c) *C. libani* under different planting methods and vegetation control treatments.

Table 8. Summary of two-way ANOVA results (p -values) for the effects of planting method (PM), vegetation control (VC), and their interaction (PM × VC) on root collar diameter (RCD) growth of *C. libani*, *P. pinea*, and *P. halepensis* across 2022, 2023, and 2024. ANOVA was performed independently for each species. Significant effects are indicated at $p < 0.05$

Factor	<i>C. libani</i>			<i>P. pinea</i>			<i>P. halepensis</i>		
	2022	2023	2024	2022	2023	2024	2022	2023	2024
PM	0.148	0.005	0.056	0.028	0.001	< 0.001	0.015	< 0.001	0.005
VC	0.019	0.174	0.011	0.04	0.027	0.012	0.32	0.321	0.153
PM × VC	0.636	0.578	0.055	0.79	0.109	0.017	0.212	0.492	0.057

Overall, the results demonstrate pronounced differences in early conifer establishment in response to vegetation control and species identity. However, the effects of the treatments on height and RCD growth were generally less pronounced than those observed for survival. As indicated by the ANOVA results (**Tables 4, 6, and 8**) and Tukey's HSD grouping letters (**Tables 5, 7, and 9**), vegetation control showed significant effects on growth in several species and assessment years, whereas planting method also affected growth in several cases. In contrast, significant planting method × vegetation control interactions were limited to specific species and assessment periods. These findings indicate that the effects of the experimental treatments on growth traits varied depending on species and assessment year.

Table 9. Tukey's HSD grouping letters for mean root collar diameter (RCD) growth of *C. libani*, *P. pinea*, and *P. halepensis* under vegetation control (VC), planting method (PM), and their interaction (PM × VC) across 2022, 2023, and 2024. Different letters indicate significant differences at $p < 0.05$. ANOVA and post-hoc tests were performed independently for each species

Factor	Treatment	<i>C. libani</i>			<i>P. pinea</i>			<i>P. halepensis</i>		
		2022	2023	2024	2022	2023	2024	2022	2023	2024
VC	Control	ab	a	ab	a	ab	ab	a	A	a
	Herbicide	ab	a	ab	a	ab	a	a	A	a
	Mowing	a	a	a	a	a	a	a	A	a
	Mulch	b	a	b	a	b	b	a	A	a
PM	Auger	a	a	a	ab	a	a	a	A	a
	Hoedad	a	a	a	a	a	a	a	a	a
	Pits	a	b	a	b	b	b	b	b	b
PM × VC	Auger × Control	a	a	a	a	ab	ab	a	a	a
	Hoedad × Control	a	a	a	a	a	a	a	a	a
	Pits × Control	a	a	a	a	b	b	a	a	b
	Auger × Herbicide	a	a	a	a	ab	ab	a	a	a
	Hoedad × Herbicide	a	a	a	a	ab	a	a	a	ab
	Pits × Herbicide	a	a	a	a	ab	ab	a	a	ab
	Auger × Mowing	a	a	a	a	a	a	a	a	ab
	Hoedad × Mowing	a	a	a	a	a	a	a	a	a
	Pits × Mowing	a	a	a	a	ab	b	a	a	ab
	Auger × Mulch	a	a	a	a	ab	ab	a	a	ab
	Hoedad × Mulch	a	a	a	a	ab	ab	a	a	ab
	Pits × Mulch	a	a	a	a	ab	ab	a	a	ab

3.2. Discussion

3.2.1. Survival Response to Vegetation Control

These findings, regardless of monitoring period or plant type, show that vegetation management is a crucial factor in the successful establishment of Mediterranean conifers in water-stressed environments. Our use of mulch significantly increased survival rates and enhanced early growth dynamics. This reflects the positive response of both subsurface and surface mulch in reducing water loss through evaporation, minimizing competition from vegetation cover, and alleviating water stress in plants.

These responses may be related to the potential effects of soil surface covering on soil moisture retention, soil temperature regulation, and microsite conditions during the establishment phase.

These findings are consistent with evidence from Mediterranean forest restoration and post-disturbance forest studies (Carra et al. 2022; El-Beltagi et al. 2022; Lucas-Borja et al. 2021; Ortega et al. 2023; Prats et al. 2016). Recent research consistently shows that soil surface treatments create more favorable microenvironmental conditions for early plant growth in semi-arid Mediterranean environments. Such treatments conserve water and significantly improve seedling establishment in drought-prone ecosystems by reducing soil evaporation, moderating soil temperature fluctuations, and enhancing moisture retention in topsoil layers (Carra et al. 2022; Lucas-Borja et al. 2021; Ortega et al. 2023).

The beneficial effects of mulching documented in this study are also consistent with recent findings reported for Mediterranean pine plantations (Carra et al. 2022; Lucas-Borja et al. 2021;

Navidi et al. 2023; Ortega et al. 2023). The higher survival and growth observed under mulching may be associated with reduced water loss and improved soil moisture conditions, as reported for similar environments. These effects may have contributed to the higher survival rates and growth observed in mulch-treated seedlings.

Conversely, the lower survival observed under mowing and untreated treatments may be related to greater competition from surrounding vegetation, particularly for water and nutrients. Similar competitive constraints have been reported in Mediterranean restoration studies, where ecosystems are increasingly exposed to severe climatic and seasonal aridity (Fernández-García et al. 2021; García de León et al. 2023; Herol et al. 2024). These findings further emphasize the importance of reducing competition during the critical early establishment phase.

The use of herbicides to control weeds showed only moderate effectiveness in improving early growing conditions. While chemical treatments effectively reduced the biomass of competing plants, mulching practices provided greater protection against the effects of local climate conditions than chemical treatments alone.

The absence of physical soil cover may result in greater soil evaporation and temperature fluctuations under semi-arid conditions, which could partly explain the lower performance observed in non-mulched treatments.

Recent research indicates that chemical methods often increase water loss through evaporation and alter soil water properties, while weed control practices in Mediterranean drylands can modify subsurface competition and soil moisture dynamics. Studies have shown that long-term herbicide use for vegetation control may reduce soil water content compared with untreated vegetation (Boutagayout et al. 2025). Alternative approaches, such as soil solarization, have emerged as environmentally compatible weed-control strategies that can modify local soil moisture and microclimatic conditions (Kanellou et al. 2023; Shinde et al. 2023). In addition, herbicide use combined with tillage and broader soil management practices may alter microbial activity and soil biogeochemical properties in semi-arid agricultural systems (Nthebere et al. 2025). Finally, recent reviews emphasize the importance of balancing biodiversity conservation with soil and water protection through agroecological weed management strategies in Mediterranean landscapes (Machado et al. 2024).

3.2.2. Height Growth Response

Height growth was strongly influenced by vegetation control treatments, with mulching generally promoting greater growth than mowing, herbicide application, or untreated controls. The positive response observed under mulching was consistent across monitoring years and species, indicating that vegetation management plays an important role not only in seedling survival but also in subsequent growth performance. Similar positive effects of mulch treatments on early seedling growth have been reported in Mediterranean restoration studies and pine plantations (Carra et al. 2022; Lucas-Borja et al. 2021; Navidi et al. 2023; Ortega et al. 2023).

The results obtained at Chmistar were also broadly consistent with those reported from the parallel experiment conducted at Rashaya al-Wadi (Saleh et al. 2025), where mulched plots similarly produced greater height increments than mowing, herbicide, and control treatments. Although the magnitude of growth differed between sites, reflecting differences in local environmental conditions, the general response pattern remained similar. This consistency across

two semi-arid Mediterranean sites strengthens the evidence that vegetation management is a major determinant of early conifer growth.

3.2.3. Root Collar Diameter (RCD) Response

Root collar diameter growth showed trends that were generally consistent with the overall establishment response. Treatments that promoted better survival and height growth frequently resulted in greater diameter increments, although the magnitude of RCD response varied among species and years. Compared with survival, RCD growth exhibited greater variability among treatment combinations, suggesting that diameter development may be influenced by multiple factors operating during the establishment phase.

The observed variability in RCD growth should also be interpreted together with survival data. Since growth measurements were calculated using surviving seedlings only, treatments with high mortality may have retained the most vigorous individuals, potentially contributing to higher average growth values among the remaining seedlings. Similar considerations have been reported in long-term afforestation studies where growth assessments are necessarily limited to surviving individuals.

Comparison with Rashaya al-Wadi showed a similar overall trend, with vegetation control exerting a stronger influence on diameter development than planting method. In both studies, treatments associated with improved establishment success generally produced better RCD performance, further supporting the importance of vegetation management during the early stages of afforestation (Saleh et al. 2025).

3.2.4. Species Differences

3.2.4.1. *Pinus halepensis*

Among the studied species, *P. halepensis* consistently exhibited the highest survival rates and the strongest growth performance across treatments and monitoring years. Its superior performance was particularly evident under mulching treatments, where survival remained relatively high throughout the study period. These results are consistent with the ecological characteristics of *P. halepensis*, which is widely recognized as one of the most drought-tolerant conifers in Mediterranean environments (Alsanousi et al. 2025; Carneros et al. 2009). The results obtained in Chmistar closely resemble those reported at Rashaya al-Wadi, where *P. halepensis* also demonstrated superior establishment success compared with the other conifer species (Saleh et al. 2025). The consistency of this response across different semi-arid sites highlights the suitability of *P. halepensis* for afforestation and restoration programs under challenging Mediterranean conditions.

3.2.4.2. *Pinus pinea*

P. pinea exhibited intermediate performance between *P. halepensis* and *C. libani*. Survival and growth responses improved substantially under mulch treatments, while mowing and untreated controls generally resulted in lower performance. Although *P. pinea* did not achieve the same level of establishment success as *P. halepensis*, it maintained acceptable survival and growth under favorable vegetation-management conditions.

A similar response was observed at Rashaya al-Wadi, where *P. pinea* benefited from vegetation control and particularly from mulching treatments (Saleh et al. 2025). These results suggest that successful establishment of *P. pinea* in semi-arid environments depends strongly on appropriate site management during the early years after planting.

3.2.4.3. *Cedrus libani*

C. libani generally exhibited lower survival and slower early growth than the pine species, particularly during the first years following planting. This response is consistent with previous studies describing the relatively conservative growth strategy of cedar seedlings and their greater sensitivity during the establishment phase (Zsolnay et al. 2023).

Despite its lower overall performance, *C. libani* responded positively to mulching, which consistently improved both survival and growth compared with mowing, herbicide, and control treatments. Similar trends were reported in the Rashaya al-Wadi experiment (Saleh et al. 2025), indicating that effective vegetation management can substantially improve cedar establishment even under semi-arid Mediterranean conditions.

3.2.5. *Planting-Method Effects and Interactions with Vegetation Control*

Unlike vegetation control treatments, which could be compared against untreated controls, pit planting methods lacked a true 'no-pit' reference because every seedling requires a planting hole-pit digging is an unavoidable component of establishment, not an optional treatment. Comparisons among pit designs thus reflected variations in pit size or configuration rather than the presence or absence of soil preparation itself. These differences in soil disturbance and pit configuration were not consistently associated with differences in seedling performance. The observed pattern may reflect the greater contribution of vegetation control to seedling establishment under the conditions of this study.

The three planting methods evaluated in this study differ in the degree of soil disturbance and planting-hole configuration: traditional pits provide a larger manually excavated hole, hoedad planting creates a narrow low-disturbance slit, and auger planting produces a uniform but smaller mechanized hole.

Despite these differences, planting method generally had a weaker effect on seedling performance than vegetation control, as shown by the ANOVA results, in which vegetation control was highly significant for survival across all species and years. In contrast, planting method and many planting-method interactions were significant only for certain species and measurement periods (Tables 4, 6, and 8). This pattern may be related to differences in soil and site conditions, although the specific mechanisms underlying the observed treatment responses were not directly evaluated in the present study. Significant planting method × vegetation control interactions occurred, for example, for the survival of *C. libani* and *P. pinea* during 2022–2023 and for the height and RCD growth of *P. pinea* in 2024, while most interactions for *P. halepensis* and for overall height and RCD growth were not statistically significant. Therefore, the higher numerical survival and growth observed under combinations such as hoedad × mulch and pits × mulch should be interpreted as evidence that effective vegetation control, particularly mulching, can enhance the performance of different planting methods, rather than as consistent proof of the superiority of one specific planting technique under these site conditions.

3.2.6. *Practical Implications for Afforestation*

Overall, these findings strengthen the growing body of evidence showing that mechanical or chemical vegetation control alone is frequently insufficient to overcome the pronounced hydrological constraints characteristic of semi-arid Mediterranean ecosystems. In such environments, and under ongoing climate change with increasing drought frequency and severity, soil water availability remains the principal determinant of early seedling survival and establishment (Acevedo et al. 2024; Blanco-Rodríguez et al. 2023; Fasakhodi et al. 2024; Puértolas et al. 2024; Zhao and Sun 2025). These results further highlight the importance of integrated management approaches that prioritize moisture conservation during the critical establishment phase.

The comparison with the Rashaya al-Wadi site provides additional evidence supporting the strong influence of vegetation control on early establishment success. At the same time, differences in overall performance between sites clearly reflect the regulatory role of local soil characteristics and climatic conditions in determining afforestation outcomes. In Rashaya, despite variations in soil depth and moisture availability, mulch-covered plots consistently exhibited higher survival rates and improved early growth of conifer seedlings compared with the current study site. The recurrence of this pattern across ecologically diverse semi-arid Mediterranean environments further underscores the effectiveness of mulching as a management intervention (Saleh et al. 2025).

3.2.7. *Study Limitations and Future Research*

Several limitations should be considered when interpreting the present findings. First, the experiment was conducted at a single semi-arid site and covered the first three years following planting (2022–2024). Therefore, the observed treatment responses may not be directly generalizable to sites with different climatic, soil, or vegetation conditions. In addition, longer-term monitoring is needed to determine whether the observed differences in seedling survival and growth persist as seedlings develop.

Second, we did not directly measure soil moisture, soil temperature, vegetation biomass, or competition intensity during the study period. Consequently, although previous studies provide plausible explanations for the positive response observed under mulching, the present experiment could not directly evaluate the mechanisms underlying differences in seedling survival and growth. The observed treatment responses should therefore be interpreted primarily in terms of seedling performance rather than as direct evidence of changes in soil moisture, temperature, or vegetation competition.

Third, initial seedling size differed among the three species at planting (**Table 1**), which may have contributed to differences in survival and growth among species. Although treatment effects were analyzed separately for each species, species-level comparisons should therefore be interpreted with this variation in initial seedling size in mind.

Finally, spatial variation in soil depth, rock content, and other microsite characteristics may have contributed to variability in seedling performance. The randomized complete block design was used to reduce the influence of spatial heterogeneity; however, some microsite variation is unavoidable in field-based afforestation experiments.

Future studies should extend monitoring across multiple sites and longer periods and incorporate direct measurements of soil moisture, soil temperature, vegetation biomass, and other

relevant environmental variables. Such measurements would help clarify the mechanisms underlying the treatment responses observed in this study and improve the development of site-adapted afforestation strategies for semi-arid Mediterranean environments.

4. Conclusions

This research demonstrated that vegetation control was the primary factor influencing the early establishment of Mediterranean conifer species under the semi-arid conditions of Chmistar, Lebanon. Among the evaluated treatments, mulching consistently improved seedling survival and growth, whereas planting methods alone generally exerted a limited influence unless combined with effective vegetation management. These findings highlight the importance of reducing competition during the critical post-planting period to improve afforestation success. Species responses differed according to their ecological characteristics and adaptation to drought-prone environments. *Pinus halepensis* exhibited the highest overall survival and growth performance across treatments, confirming its suitability for afforestation under harsh semi-arid conditions. In contrast, *Cedrus libani* showed greater sensitivity during the establishment phase, particularly under conditions of limited resource availability. Comparison with the parallel experiment conducted at Rashaya al-Wadi further confirmed the positive contribution of vegetation control to seedling establishment. However, differences in overall performance between sites indicate that local environmental factors, particularly soil depth, stoniness, and water availability, strongly influence treatment effectiveness and should be considered when planning restoration programs. The conclusions of this research primarily apply to the early establishment phase (2022–2024) under the environmental conditions of the Chmistar site. Therefore, long-term monitoring is required to determine whether the observed differences in survival and growth persist as plantations mature and to evaluate the long-term effectiveness of vegetation-control and planting-method treatments under semi-arid Mediterranean conditions.

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Author Contributions

D.E.B., J.B., S.B.: Conceptualization, Supervision, Formal Analysis, Writing – Review and Editing; A.H.S.: Investigation, Data Curation, Writing – Original Draft Preparation; M.A.S.: Formal Analysis, Investigation; W.M.: Conceptualization, Writing – Review and Editing.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this manuscript, the authors used OpenAI's GPT-5.3 (Generative Pre-trained Transformer model) to assist with language refinement and improve the clarity and structure of the text. After using this tool, the authors carefully reviewed, edited, and validated the content as needed and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

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