Vol. 13(1): 102-119, January 2025

DOI: https://doi.org/10.23960/jsl.v13i1.1081

P-ISSN: 2339-0913
E-ISSN: 2549-5747

Jurnal Sylva Lestari

Journal homepage: https://sylvalestari.fp.unila.ac.id

Full Length Research Article

Enhancing Afforestation Success: Seedling Survival and Growth in Relation to Planting Pit Digging and Vegetation Control in Rashaya Al-Wadi, Lebanon

Mohammad Saleh[1], Safaa Baydoun[1], Wael Mostafa[2], Hisham Salman[2], Jamilah Borjac[1*]

[1] Beirut Arab University, Faculty of Science, Debbieh, Lebanon
[2] Association for Forests, Development and Conservation, Sagesse Street, Jdeidé, Lebanon
[*] Corresponding Author. E-mail address: j.borjac@bau.edu.lb

ARTICLE HISTORY:
Received: 15 September 2024
Peer review completed: 28 November 2024
Received in revised form: 14 December 2024
Accepted: 8 January 2025

KEYWORDS:
Afforestation success
Competitive vegetation
Environmental conservation
Pit-digging methods
Seedling survival

ABSTRACT

Afforestation is vital for environmental conservation but is hindered in arid and semi-arid regions by water scarcity and competitive vegetation. This study evaluates three pit-digging methods (traditional pits, hoedad, and auger tools) and three vegetation control strategies (mulching, mowing, and herbicide) in Rashaya al-Wadi, Lebanon. Six tree species (*Quercus calliprinos*, *Quercus infectoria*, *Pistacia palaestina*, *Pinus pinea*, *Pinus halepensis*, and *Cedrus libani*) were assessed using a randomized complete block design with 12 treatment combinations replicated across four blocks. Seedlings were planted with uniform spacing, and vegetation controls were applied once at planting. Survival and growth, measured biannually over two years as height and root collar diameter (RCD), were analyzed using ANOVA. Survival was highest with mulch (51%), followed by herbicide (35%), and lowest with mowing (1.2%) and control (1.4%). Height growth ranged from 6.75–30.44 cm with mulch, 3.72–36.89 cm with herbicide, 1.92–5.25 cm with mowing, and 1.81–6.08 cm with control. RCD growth followed similar trends. Traditional pits achieved the highest survival, while the hoedad tool had the lowest. Findings demonstrate that mulching with traditional pits enhances afforestation success and offers a sustainable solution for semi-arid regions. Further research is needed to refine methods for diverse sites.

1. Introduction

Afforestation, the planting of trees in areas devoid of them for the past 50 years, and reforestation, the planting of trees in recently deforested areas (Psistaki et al. 2024), are key strategies in the management of Global warming (Haghverdi and Kooch 2020; Mulyana et al. 2024). Considering their role in carbon sequestration (Lefebvre et al. 2021; Mulyana et al. 2024; Triatmojo et al. 2024), enhancing biodiversity, provision of habitats (Pei et al. 2018), and soil conservation (Guo et al. 2021; Korkanç 2014), they form the basis of sustainable land management strategies aimed at mitigating climate-related challenges.

The limited supply of water challenges afforestation in semi-arid environments. The success of such projects begins with the survival of tree seedlings, which depends on selecting species suited to local conditions (Bhusal et al. 2021; Chen et al. 2019; Reisman-Berman et al. 2019) and the use of appropriate pit-digging methods and competitive vegetation controls. Digging methods influence initial seedling survival by affecting seedling roots and soil compaction (Pradiko et al. 2016). Competitive vegetation controls such as mowing, herbicide application, and mulching have varied effects on seedling establishment (Häggström et al. 2024). As an environmentally friendly approach, mulching suppresses competition and enhances soil moisture retention and nutrient availability (Mechergui et al. 2021).

In remote regions such as the Al-Yabseh site in Rashaya al-Wadi, Lebanon, the logistical and financial challenges of supplemental watering pose a significant barrier to successful afforestation, especially in rough mountainous terrains. This necessitates using drought-resistant seedlings capable of establishing and thriving without irrigation. By ensuring early survival, such seedlings reduce long-term project costs and improve forest resilience to climate variability (Bhusal et al. 2021). Furthermore, afforestation projects using mixed species and intra-specific diversity, rather than monocultures, can enhance biodiversity (Liu et al. 2018; Wu et al. 2021), increase resistance to diseases (Jactel et al. 2017), and provide a range of ecosystem services, including nitrogen fixation, carbon sequestration (Warner et al. 2023), various forest products and ecotourism opportunities (Felton et al. 2016; Huuskonen et al. 2021).

Successful afforestation and reforestation efforts rely heavily on effective vegetation control and optimal pit-digging methods to enhance tree seedling survival and growth. Methods such as mowing, herbicide application, and mulching vary in effectiveness. While straightforward, mowing has limited impact on belowground competition (Borowski et al. 2024) and often necessitates the use of herbicides, which, though effective at promoting tree growth, raise concerns about environmental persistence, phytotoxicity, and the emergence of resistant weed populations (Bamal et al. 2024; Ghersa et al. 2020). Mulching offers a more sustainable approach by improving microclimatic conditions, soil moisture retention, and improving soil structure and increasing nutrient availability, thereby enhancing seedling survival and growth (Mechergui et al. 2021). Moreover, pit-digging methods, including traditional pits, mechanical augers, and hoedads, influence seedling survival and soil conditions. Studying the impacts of these methods is crucial for achieving long-term afforestation success.

While previous studies have explored various aspects of afforestation, few have examined the combined effects of vegetation control methods and pit-digging techniques on seedling survival under natural, water-limited conditions in semi-arid environments. This research addresses this gap by evaluating three vegetation control methods (cardboard sheet mulching, herbicide application, and mowing) and three pit-digging techniques (traditional pits, mechanical augers, and hoedads) in establishing six tree species: *Quercus calliprinos* Webb, *Quercus infectoria* G. Olivier, *Pistacia palaestina* Boiss., *Pinus pinea* L., *Pinus halepensis* Mill., and *Cedrus libani* A. Rich. These species were selected for their ecological importance, adaptability to semi-arid conditions, and relevance to Lebanon's natural forests.

A key aspect of this study is its focus on seedling adaptability under natural conditions without supplemental watering. Demonstrating the feasibility of afforestation without irrigation provides a model for reducing costs and improving the sustainability of afforestation initiatives. The findings aim to contribute to developing effective strategies for afforestation and reforestation in Lebanon and similar regions facing water scarcity.

The subsequent sections of this paper will present a comparative analysis of the survival and growth of the selected species under different vegetation control and planting methods, addressing key challenges of afforestation in semi-arid regions.

2. Materials and Methods

2.1. Study Site

The research site (**Fig. 1**) is situated in the town of Rashaya al-Wadi, located at the southern periphery of the Beqaa Valley on the western slopes of Mount Hermon in Lebanon. It was chosen for its semi-arid climate, representative of similar regions, rocky soil, cultural significance, and the need to restore its natural ecosystems. The elevation above sea level is 1.264 m, as measured using Google Earth Pro version 7.3.6.9796 (64-bit), at coordinates 33° 28' 47.99" N, 35° 52' 48.81" E. Rashaya experiences an average annual rainfall of 273.3 mm, and an annual snowfall of 145.9 mm, while temperatures vary from 0°C to 29°C (Weather Spark 2024). The site is characterized by rocky soil.

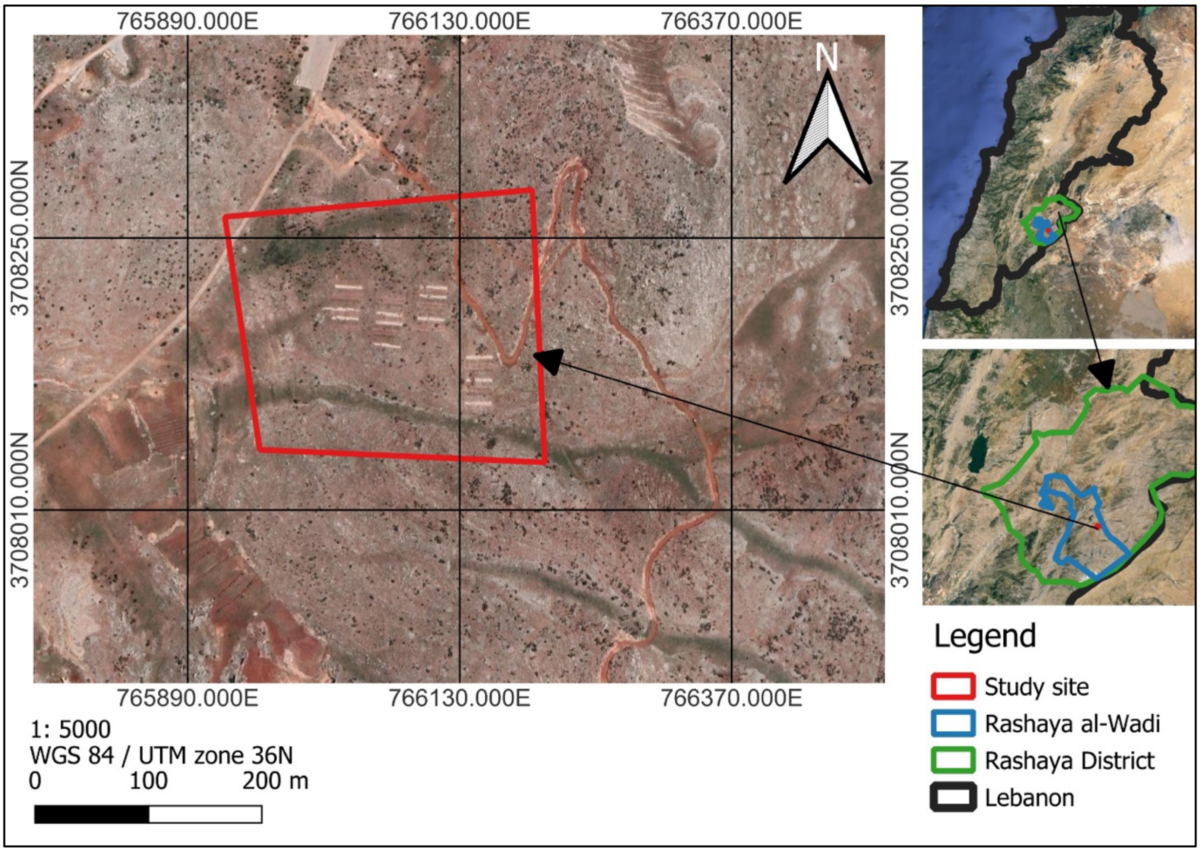


Fig. 1. Satellite image of the study site, Al-Yabseh, Rashaya al-Wadi.

2.2. Experimental design

To assess the effectiveness of various treatments on afforestation success, a randomized complete block design (RCBD) with four blocks was implemented (**Fig. 2** and **Table 1**). RCBD was chosen to minimize the effects of environmental variability across the study site. Seedlings of three broadleaf species (*Quercus calliprinos*, *Quercus infectoria*, and *Pistacia palaestina*) and three conifer species (*Pinus pinea*, *Pinus halepensis*, and *Cedrus libani*) were planted in a unified sequence. Each planting plot consisted of two rows: one for broadleaves and one for conifers, separated by one meter. This arrangement was chosen for its practicality during planting, ensuring consistent interspecific interactions across treatments and facilitating subsequent measurements. The same distance was maintained between adjacent seedlings. This arrangement, illustrated in

Fig. 2 and **Table 1**, was replicated eight times in each plot. Seedlings were positioned 1.5 meters from the plot edge.

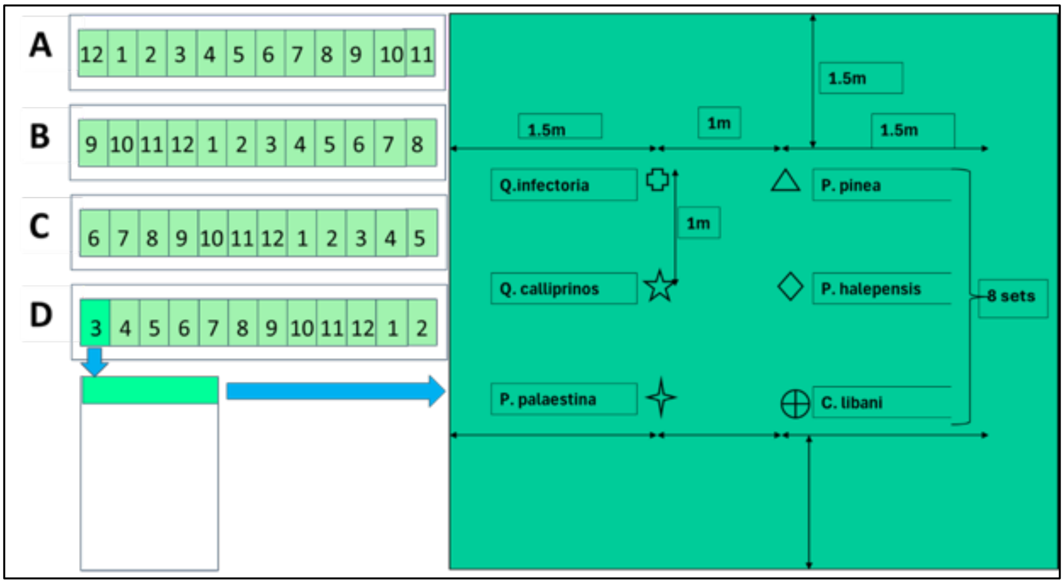


Fig. 2. Experimental design, 4 blocks each with 12 plots (different numbers represent different treatments).

Table 1. Combinations of digging methods and vegetation control approaches

Run	Combination
1	Hoedad tool + Mechanical mowing
2	Traditional digging pits 30 × 30 cm + Cardboard mulch
3	Hoedad tool + using Herbicides
4	Auger digging + control
5	Auger digging + using Herbicides
6	Hoedad tool + control
7	Traditional digging pits 30 × 30 cm + Mechanical mowing
8	Auger digging + Cardboard mulch,
9	Auger digging + Mechanical mowing
10	Traditional digging pits 30 × 30 cm + using Herbicides
11	Traditional digging pits 30 × 30 cm + control
12	Hoedad tool + Cardboard mulch

The experiment investigated the influence of two factors: pit digging method and vegetation control. Three pit digging methods (hoedad tool, traditional pits, and auger digging) and four vegetation controls (mulching, mechanical mowing, herbicide application (Glyphosate), and a control with no vegetation control) were selected for their practicality, cost-effectiveness in similar regions, resulting in twelve treatment combinations. Each block included all twelve combinations (**Table 1**), allowing for the evaluation of afforestation success in terms of seedling survival and growth under different planting and vegetation control conditions.

2.3. Planting and Treatment Methods

Mediterranean-native tree species were selected for this study based on their resilience to arid and semi-arid conditions and economic importance. Six species were chosen: *Q. calliprinos*, *Q. infectoria*, *P. palaestina*, *C. libani*, *P. pinea*, and *P. halepensis*. Seedlings aged one year were cultivated from seeds collected by the AFDC team from various locations across Lebanon and subsequently planted in a nursery. This approach aimed to maximize genetic diversity within the afforested area and enhance resilience to environmental variability.

Three vegetation control methods were implemented: mulching, mowing, and herbicide application. These techniques were applied only once when planting, regardless of vegetation regrowth, due to real-world limitations and the need to observe success under minimal management efforts. Mulching covered the plots with cardboard mats (1.2 m × 2 m) to prevent weed growth and conserve moisture. Mowing used a mower to cut down competing plants in the designated areas. For herbicide application, *Glyphosate herbicide* (Roundup USA) was applied at a rate of 300 ml per 1,000 m^2 to control vegetation growth.

Three planting approaches were employed. The traditional 30 × 30 pit method involved manually digging a pit 30 cm in diameter and depth to accommodate the seedling. The hoedad tool, equipped with a 38 cm long, 7.5 cm wide metal blade, was used. Finally, an earth auger was utilized to drill holes 20 cm in diameter and 30 cm deep. These methods were chosen to represent a set of labor-intensive and mechanized techniques, selected to test their applicability to semi-arid regions with rocky soil.

2.4. Survival and Growth Rates

Five measurement rounds were conducted between 3 April 2022 and 30 November 2023, on the specific dates of 3 April, 30 May, and 30 November 2022, and 30 May and 30 November 2023. The planting date, 3 April 2022, served as the baseline for subsequent measurements. The measurement dates were chosen to capture key growth stages: 30 May marks the onset of the dry season, while 30 November marks its end. Seedling survival was assessed by counting the surviving individuals of each species in every plot. Growth rates were determined by measuring height with a tape and root collar diameter (RCD) with a caliper. For each species and plot, the percentage of surviving seedlings was calculated. Growth parameters (height (H) and root collar diameter (RCD)) of three randomly selected seedlings were measured. If a seedling died, the last recorded H or RCD was used. The growth of height and RCD was calculated by subtracting the measurements recorded at the baseline or previous round from the current measurements. This analysis focused on data from November 2022 and 2023.

2.5. Statistical Analysis

Data analysis was conducted using one-way or two-way ANOVA with Type III sums of squares, which assess the significance of the different factors and their interactions while accounting for other factors. A significance level of $p<0.05$ was applied. Graphs were plotted as mean of the percentage survival (S) or height growth (ΔH) or RCD growth (ΔR) ± SEM (standard error of the mean).

3. Results and Discussion

3.1. Results

Fig. 3 and **Fig. 4** show the effects of vegetation controls and pit-digging methods on the survival rate, height growth, and root collar diameter (RCD) growth of the different species in 2022 and 2023.

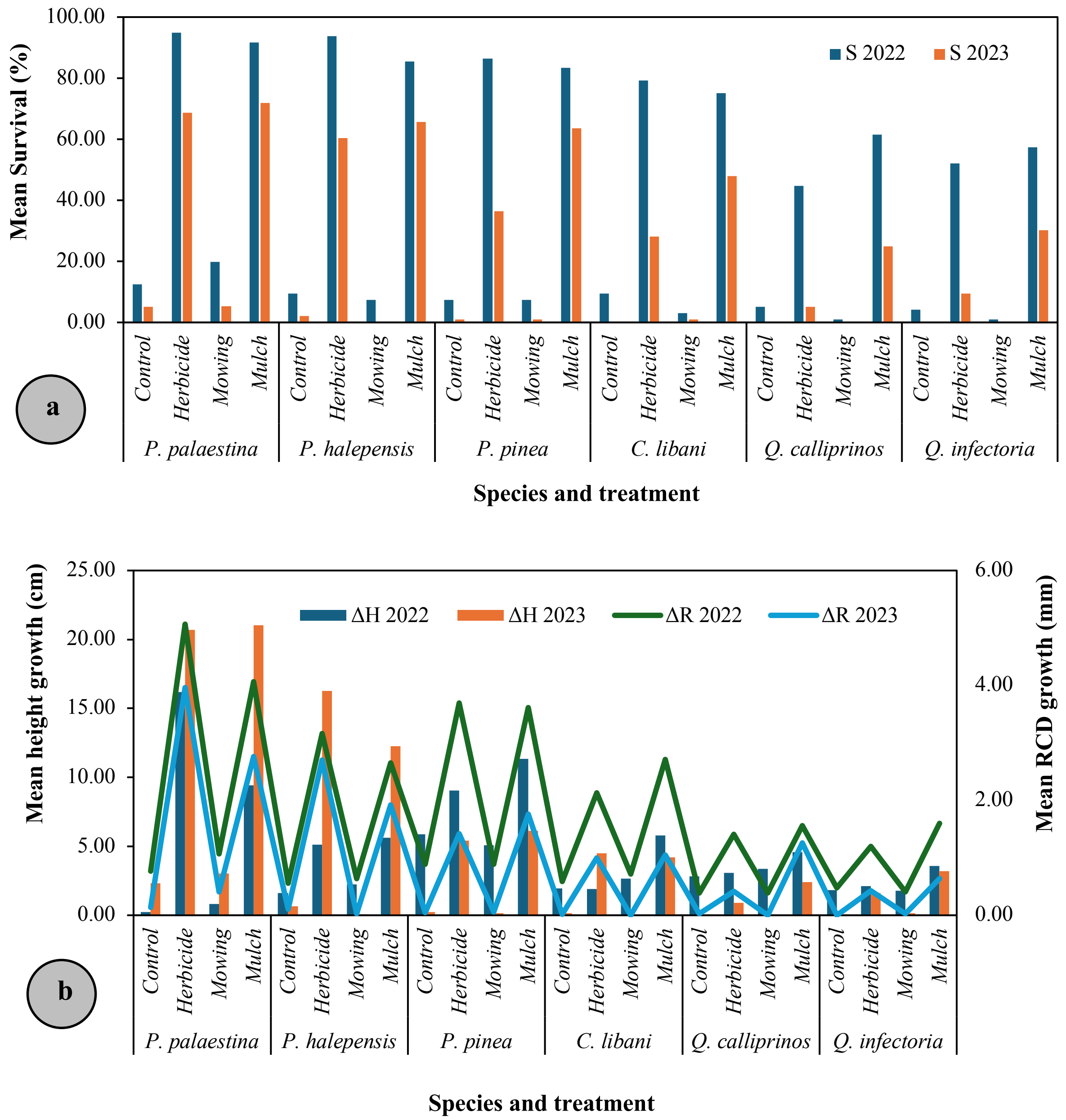
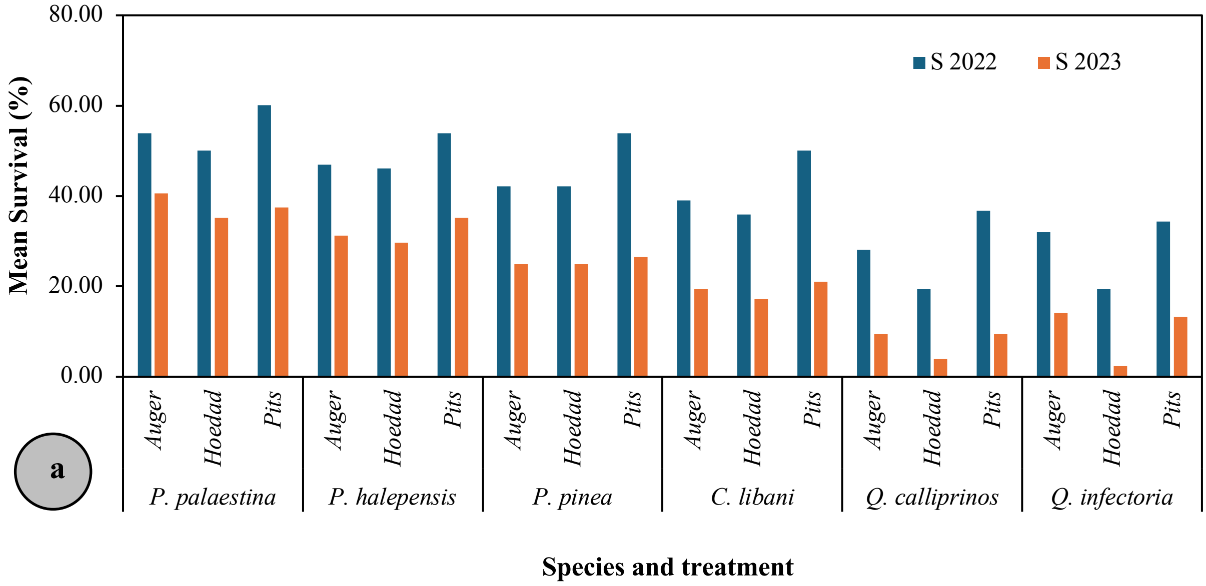


Fig. 3. Effect of vegetation controls on: (a) seedling survival, and (b) growth.

3.1.1. Survival rates

Across the two years, vegetation control methods had a stronger influence on survival rates than pit-digging methods. In 2022, *P. palaestina* exhibited the highest survival rates (55%), followed by *P. halepensis* (49%) and *P. pinea* (46%), while *Q. infectoria* and *Q. calliprinos* had notably lower rates (29% and 28%, respectively). Survival rates declined for all species in 2023, with the steepest reductions observed in *Q. calliprinos* (8%) and *Q. infectoria* (10%) (**Fig. 5**).

Treatments involving mulch and herbicide resulted in significantly higher survival rates than controls. In 2022, Pits × Herbicide, Auger × Mulch, and Pits × Mulch achieved survival rates above 75%, while controls were below 22%. In 2023, mulch treatments, particularly Pits × Mulch (55%) and Auger × Mulch (54%) maintained relatively higher survival rates despite overall declines. Control treatments consistently exhibited the lowest survival rates, with no seedlings surviving in certain configurations (**Fig. 6**).



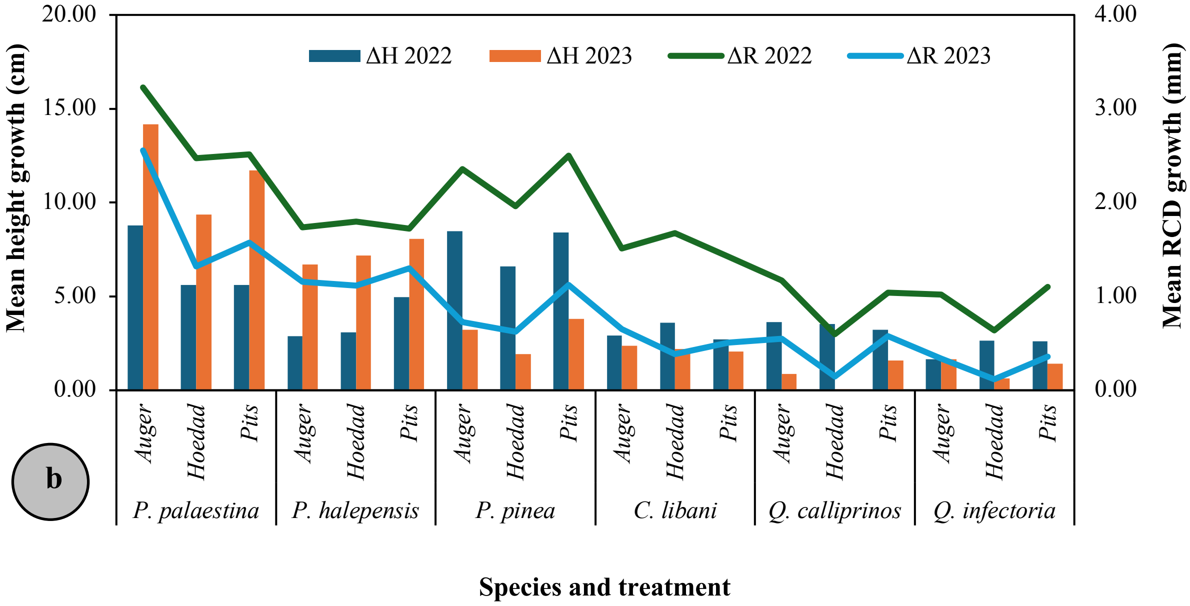


Fig. 4. Effect of pit digging methods on: (a) seedling survival, and (b) growth.

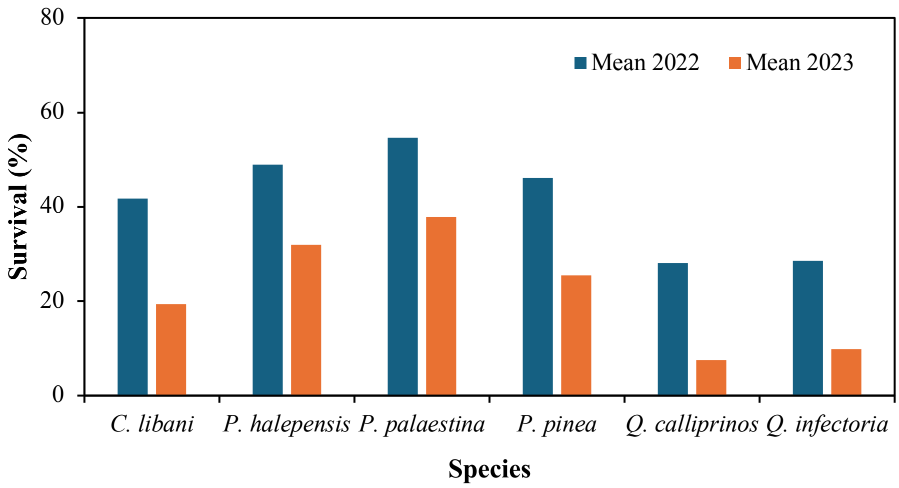


Fig. 5. Seedling survival rates of species in 2022 and 2023.

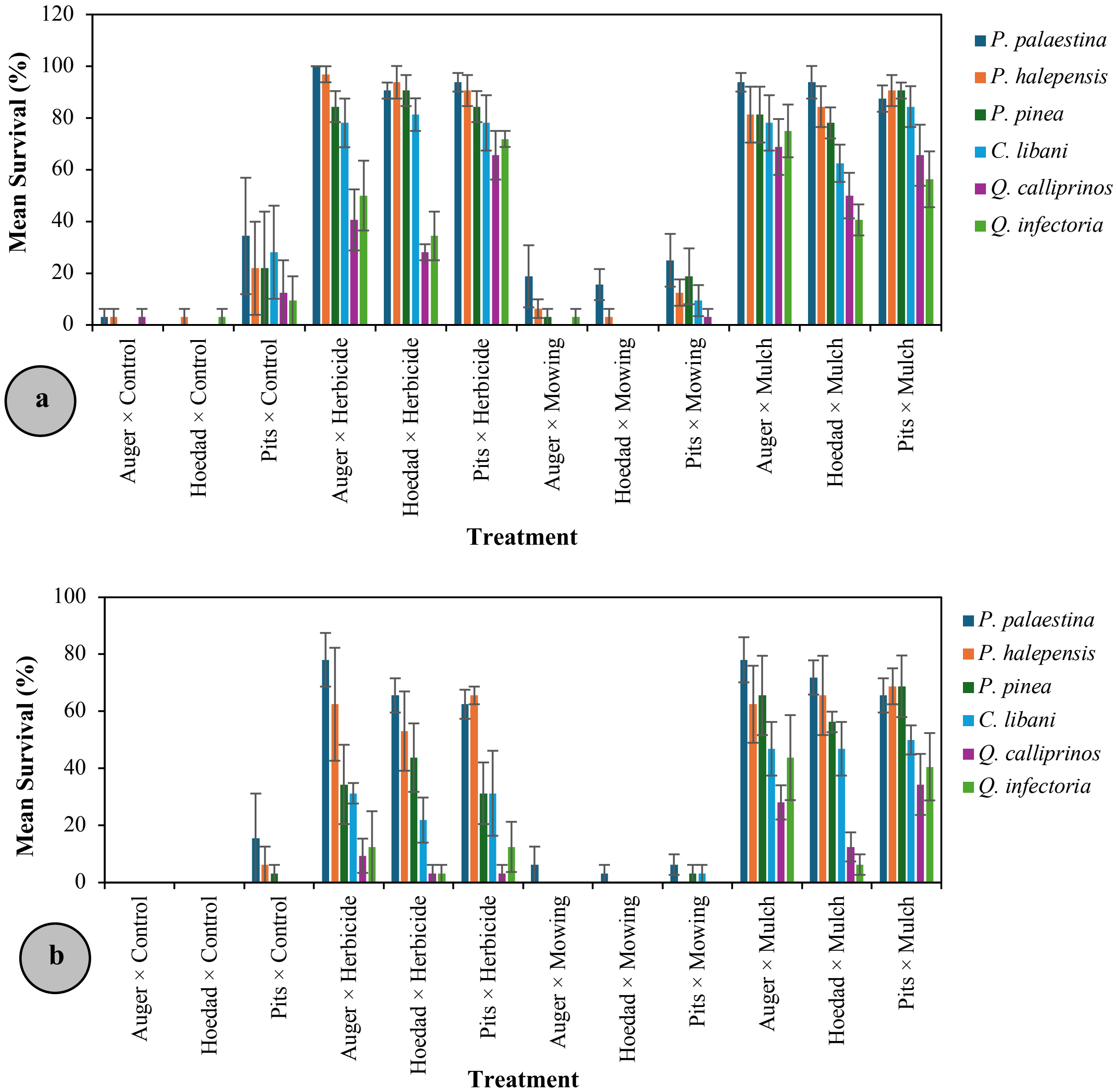


Fig. 6. Survival rates of different species versus planting approach: (a) year 2022, and (b) year 2023.

As shown in **Fig. 6**, species-specific responses revealed that *P. palaestina* showed the highest resilience, particularly under herbicide and mulch treatments, with survival rates exceeding 75% in 2022 and 78% in 2023. In contrast, *Q. infectoria* and *Q. calliprinos* displayed minimal survival, especially under control conditions. Survival varied significantly by vegetation control and species ($p < 0.001$), while pit-digging methods had a limited influence except for specific cases, such as *Q. calliprinos* in 2022 and *Q. infectoria* in both years. Possible reasons for the decline in survival rates observed in 2023 may include increased competition for resources following the degradation of vegetation controls, such as the loss of herbicide effectiveness or the breakdown of mulch, as well as heightened environmental stressors.

3.1.2. Height

Height growth mirrored survival results (**Fig. 7**). It was significantly influenced by vegetation control methods ($p < 0.001$). In 2022, herbicide treatments (e.g., Auger × Herbicide) resulted in the highest height increases across most species. *P. palaestina* had the greatest height growth under Auger × Herbicide (24.5 cm), while *Q. calliprinos* and *Q. infectoria* exhibited minimal increases under control treatments. In 2023, mulch treatments, particularly Pits × Mulch, supported notable growth for species like *P. halepensis* (18.5 cm) and *P. pinea* (7.4 cm).

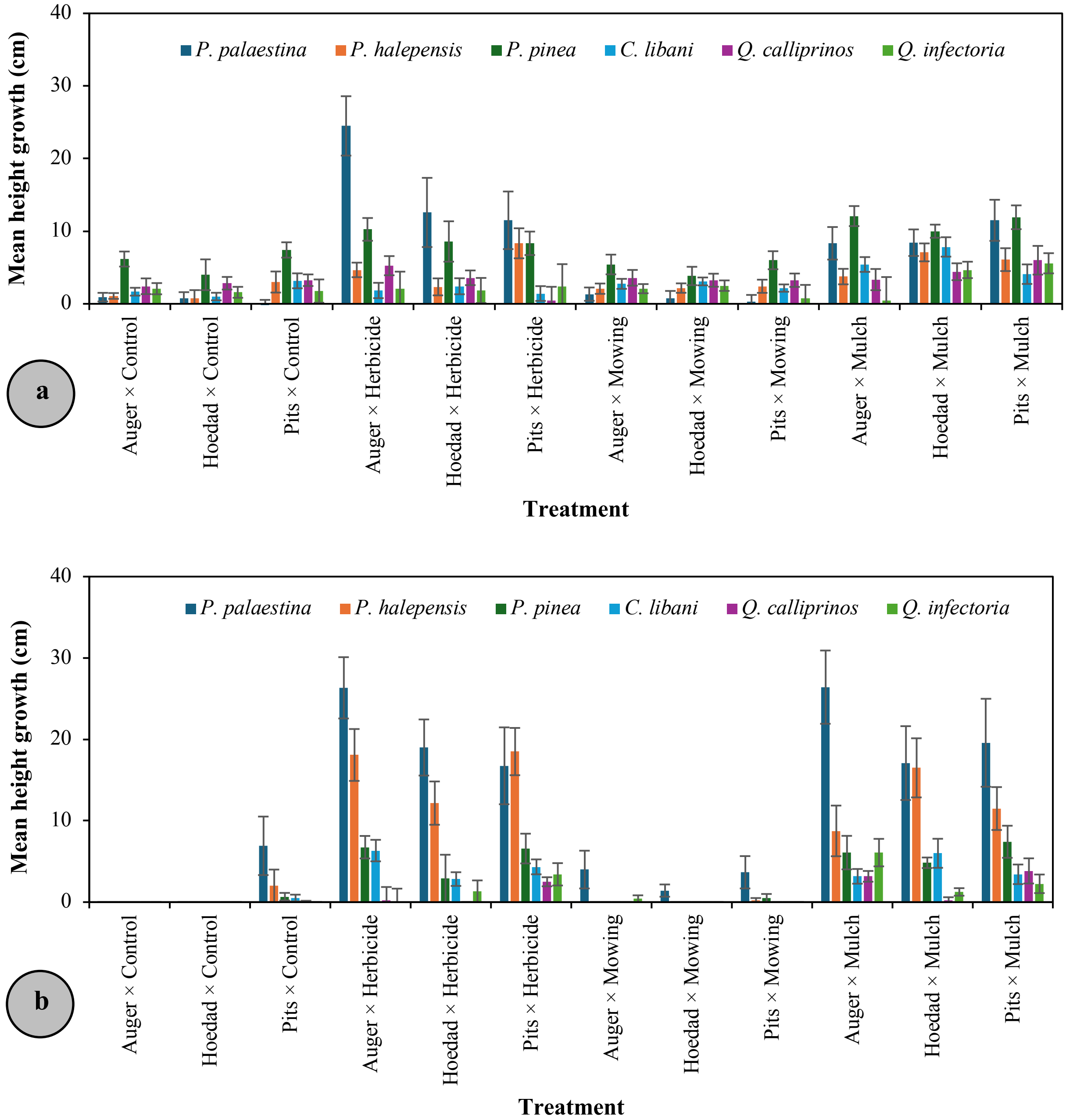


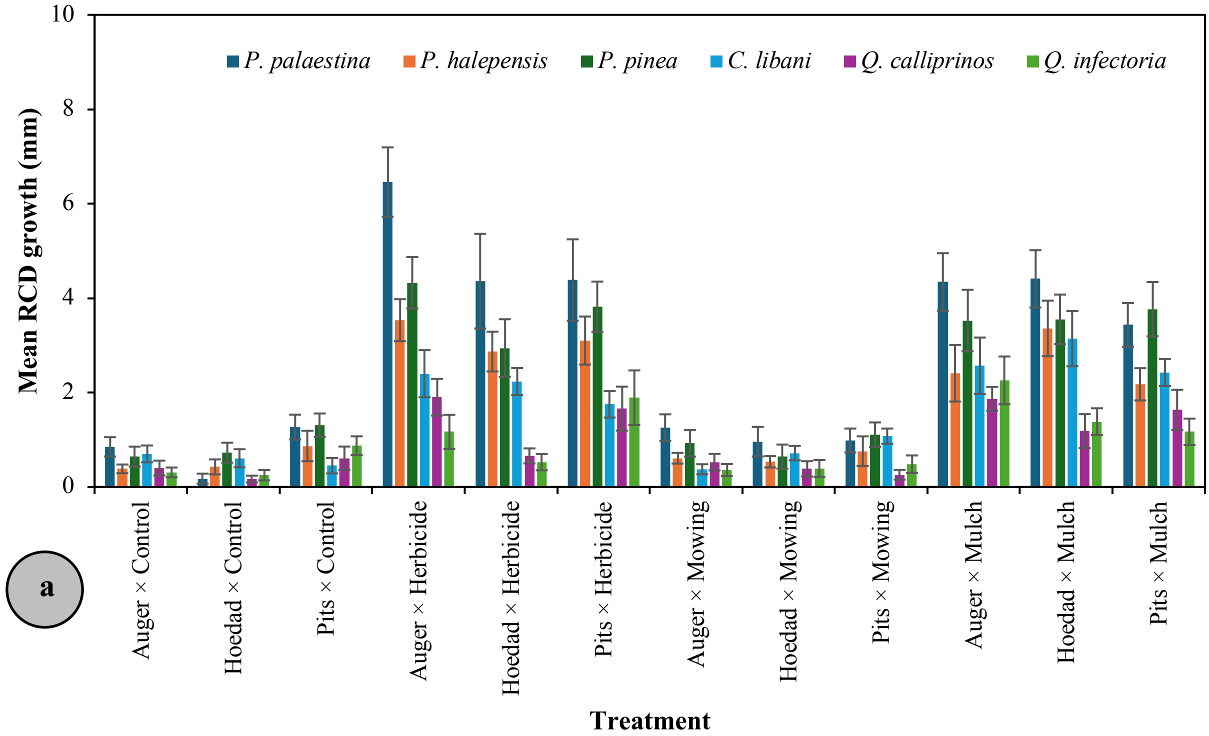
Fig. 7. Height increase versus species and planting approach: (a) year 2022, and (b) year 2023.

Species with higher resilience, such as *P. palaestina* and *P. halepensis*, consistently performed well under favorable treatments, while *Q. calliprinos* and *Q. infectoria* showed limited growth. Variations in height growth were not significantly influenced by pit-digging methods, except for specific combinations in *P. palaestina* (2022) and *Q. infectoria* (2023).

3.1.3. Root collar diameter (RCD)

As shown in **Fig. 8**, RCD growth followed similar trends to height growth and survival, with vegetation control methods significantly enhancing growth across species ($p < 0.001$). In 2022, *P.*

palaestina and *P. pinea* demonstrated the highest RCD growth under herbicide treatments (Auger × Herbicide and Pits × Herbicide), with values exceeding 4 mm. By 2023, mulch treatments, particularly Pits × Mulch, supported the highest RCD growth for most species, although overall growth rates were lower compared to 2022. Statistical significance in digging methods was limited, with notable exceptions such as *P. palaestina* (2023) and *Q. calliprinos* (2022 and 2023), where specific treatment combinations influenced growth.



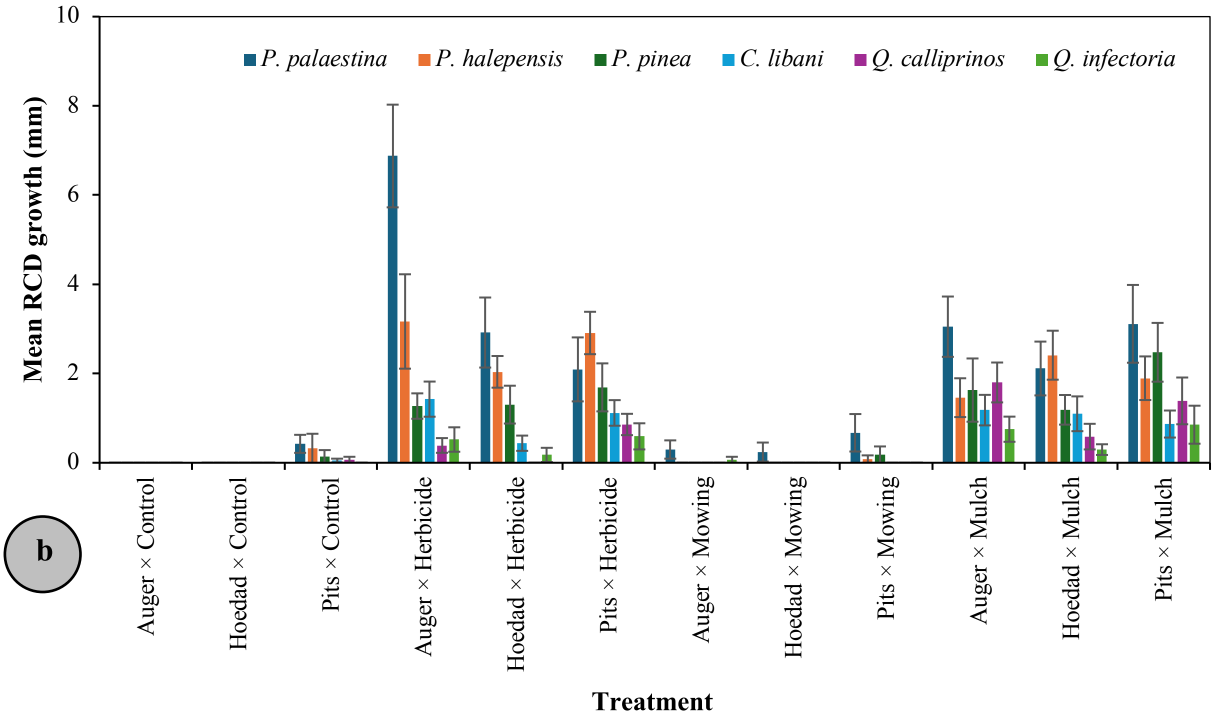


Fig. 8. RCD growth versus species and planting approach: (a) year 2022, and (b) year 2023.

3.2. Discussion

3.2.1. Summary of key findings

This study demonstrates that vegetation control methods significantly impact seedling survival and growth. Mulching was the most effective method, achieving the highest survival and growth rates, followed closely by herbicide application. However, herbicide effectiveness declined in the second year. Conversely, mowing and the absence of vegetation control resulted in the lowest survival and growth rates. Species selection also played a critical role, with *P. palaestina* exhibiting the highest survival, underscoring the importance of choosing species adapted to site conditions. Additionally, traditional pit-digging methods provided optimal conditions for survival compared to auger or hoedad tools.

3.2.2. Influence of vegetation control methods

The findings highlight mulching as a practical and effective vegetation control method for afforestation projects, particularly in semi-arid regions. Mulching enhances seedling establishment and growth by conserving soil moisture, regulating temperature, and suppressing competitive vegetation. Herbicide application, while initially effective, may not sustain its benefits over time, suggesting that single applications may be insufficient for prolonged success. In contrast, mowing's inefficiency indicates that it should not be prioritized, especially in resource-limited regions. These results provide actionable insights into selecting vegetation control methods that balance ecological benefits with practicality.

Regarding growth, using mulch or herbicide yielded the highest growth rates in both 2022 and 2023. Conversely, mowing and the absence of vegetation control resulted in the lowest growth rates. Although herbicide application did not produce the highest survival rates in 2023, its growth rates were comparable to mulching. These findings suggest that even when herbicides do not fully mitigate seedling mortality, they can still enhance growth, which has practical implications for afforestation strategies to establish healthy and robust tree populations.

As demonstrated in this study, the benefits of mulching are consistent with Silva et al. (2022), who reported that mulch increased growth and survival, and Magaju et al. (2020), who found that mulching increased survival. (Frezghi et al. 2021) further support our findings by demonstrating that mulching enhances growth and survival, even without watering, underscoring its utility in semi-arid environments. However, (Rahmani et al. 2021) found contrasting results, indicating that mulching enhanced root growth but not aerial growth, a discrepancy that may be attributed to site-specific conditions, species selection, or the duration of study monitoring. These contrasting outcomes emphasize the need for localized trials to optimize vegetation control strategies for specific ecological conditions.

Herbicidal application of Glyphosate has shown increased growth and survival, similar to the findings of McCaskill et al. (2019). Their study found that Imazapyr increased survival following a single treatment, while annual applications of Imazapyr and Hexazinone enhanced growth rates. However, applying Sulfometuron-methyl decreased survival rates (McCaskill et al. 2019). Differences between these findings and ours might stem from variations in herbicide type, application frequency, or site conditions. For instance, the single herbicide application in our trial may have limited its long-term effectiveness, underscoring the need to balance environmental impact with operational goals.

In this study, vegetation control treatments were applied only once at the start of the trial, reducing herbicide usage and minimizing environmental impact. This approach is particularly relevant for afforestation efforts in resource-limited areas where sustainability is important. However, this rendered the mowing treatment ineffective because other studies use mowing repeatedly to account for vegetation regrowth. Mowing removes only the aboveground parts of vegetation, while the roots remain undisturbed and continue to compete for moisture and nutrients.

Mulching's superior performance stems from its ability to conserve moisture by reducing evaporation and evapotranspiration, maintaining optimal soil temperature, and suppressing vegetation growth, thereby minimizing competition for resources with the newly planted seedlings (Shah et al. 2022). These multifaceted benefits make mulching an ideal choice for semi-arid regions where water conservation is crucial. Herbicide application also improved survival and growth by reducing competition, though its environmental implications warrant careful consideration. In contrast, the limited efficacy of mowing in this study suggests that it may not be a viable standalone vegetation control method under similar ecological conditions, particularly where repeated treatments are impractical.

3.2.3. Species-specific responses to treatments

Survival rates varied significantly among tree species, with *P. palaestina* demonstrating the highest survival, followed by *P. halipensis*, *P. pinea*, *C. libani*, *Q. caliprinos*, and *Q. infectoria* (**Fig. 5**). These variations reflect the differing adaptability of each species to the study site conditions, emphasizing the critical importance of selecting species well-suited to local environmental factors for successful afforestation initiatives.

The superior performance of *P. palaestina* may be attributed to its ecological resilience and inherent adaptability to semi-arid conditions, including its ability to tolerate drought and compete effectively for limited soil resources. Similarly, the relatively high survival of *P. halepensis* could be linked to its known adaptability to a wide range of environmental conditions, including arid and rocky soils, which resemble those at the study site. These characteristics suggest that both species could be priority candidates for afforestation projects in similar semi-arid regions.

This aligns with findings from several studies (Maringer et al. 2021) where different species exhibited varying survival rates. However, direct comparison of species combination responses across studies is challenging due to using other species combinations. Expanding knowledge of species-specific traits and their interactions with site conditions will be instrumental in refining species selection strategies for future afforestation efforts.

3.2.4. Influence of pit-digging methods on survival

Our study also found that pit-digging methods influenced seedling survival (**Fig. 4**), though to a lesser degree than vegetation controls. Traditional pits yielded the highest survival rates, followed by the soil auger, while the hoedad tool resulted in the lowest. These findings suggest that different digging methods create varying soil conditions, which impact root growth and subsequent survival, similar to the findings of Vadivel et al. (2024), where different digging methods had different effects on root growth.

Traditional pits likely provide optimal conditions for root development, followed by those dug with a soil auger. At the same time, the hoedad tool's poorer performance might be attributed to root damage caused by rocky soil conditions or the smaller pit size. These results underscore the importance of selecting appropriate planting methods based on soil characteristics to enhance seedling survival during afforestation.

Directly comparing these findings with previous studies is challenging because using three distinct pit-digging methods in this study results in varying pit shapes and sizes, influencing survival and growth. While Boja et al. found that larger auger-dug pits (200 mm) improved survival compared to smaller ones (150 mm) (Boja et al. 2018), the pits were dug using the same tool at the same depth, and the only difference was the diameter which makes comparison easy. The pits created by the hoedad tool were likely smaller than auger or traditional pits, potentially contributing to lower survival rates. However, there might be other reasons, such as uneven soil compaction. To date, no studies have specifically examined the impact of hoedad digging on tree seedling survival, limiting direct comparison with existing research. Future studies should account for these potential confounding factors to understand better how different pit-digging methods influence seedling survival under varying environmental conditions.

3.2.5. Combined effects of vegetation control and digging methods

When evaluating the combined impacts of vegetation controls and planting methods on survival, notable differences emerged (**Fig. 6**). Herbicide application combined with traditional pits proved most effective in November 2022, while mulch application in conjunction with conventional pits demonstrated superior performance by November 30, 2023. These findings emphasize the importance of tailoring planting techniques and vegetation control measures to specific environmental conditions to optimize seedling survival and overall afforestation success.

Treatment combinations influenced growth differently than survival (**Fig. 7** and **Fig. 8**). While consistent growth patterns were not evident across all species, each species exhibited distinct growth rates under different treatments. Interestingly, treatments maximizing root collar diameter growth did not always correlate with those promoting the highest height growth. These discrepancies might be attributed to stochastic factors, differential seedling responses to treatment-induced stresses, or genetic variation within the seed population. These findings emphasize the complexity of predicting growth in afforestation projects, highlighting the need for a comprehensive understanding and tailored management approaches to optimize growth and establishment.

3.2.6. Decline in survival over time

Survival rates declined from April 2022 to November 2022 and continued to decrease by November 2023, highlighting the impact of environmental stresses. This decline could be attributed to factors such as prolonged drought conditions, increased resource competition from surrounding vegetation, or the inability of some species to adapt to the prevailing semi-arid conditions. Monitoring seedling survival over extended periods is crucial for developing effective and sustainable practices. This long-term approach is essential for identifying these challenges, refining and developing afforestation strategies, enhancing resilience against environmental challenges like climate change and resource scarcity, and fostering the successful establishment of tree species in diverse ecological conditions.

3.2.7. Limitations of traditional growth metrics

Traditional growth metrics such as height or root collar diameter (RCD) increments are commonly used to assess growth but may not fully capture overall biomass accumulation. These metrics, while useful, often fail to reflect the complex growth dynamics of trees accurately. Biomass estimation through allometric equations offers a more comprehensive assessment of growth. For example, in a scenario where two seedlings are planted, one dies while the other doubles in height and RCD. Traditional growth metrics would assign zero growth to the dead seedling and calculate growth only for the surviving one, potentially overlooking biomass loss. Even using the last recorded living height or RCD for the dead seedling yields positive growth values for survivors but does not account for biomass loss.

In contrast, biomass estimation can accurately represent the increase in biomass of surviving seedlings while accounting for the loss. Since Biomass is not directly proportional to height or RCD, as demonstrated by varying allometric equations, traditional metrics are limited in capturing the full extent of growth and ecosystem productivity. Incorporating biomass estimation provides a more holistic understanding of growth and should be considered in future studies.

3.2.8. Recommendations

These findings suggest several recommendations to enhance afforestation success while addressing sustainability and resource management challenges. Mulching should be prioritized for its superior ability to conserve soil moisture and reduce resource competition, while reliance on single-use mowing should be avoided due to its limited effectiveness. Herbicide application should be optimized by balancing frequency with environmental impact, especially in semi-arid regions. Selecting resilient species like *P. palaestina* can maximize survival and growth rates under local environmental conditions. Traditional pits or soil augers are recommended for planting in rocky soils as they create favorable rooting conditions. Long-term seedling survival and growth monitoring are essential to refine strategies and address drought stress and resource competition challenges. Additionally, biomass estimation using allometric equations should be incorporated to provide a more comprehensive understanding of growth and ecosystem productivity, surpassing the limitations of traditional growth metrics.

4. Conclusions

This study investigated the effects of vegetation control methods and pit-digging approaches on the survival and growth of six tree species in the Beqaa region, Lebanon. Results indicate significant variations in survival among species, with *P. palaestina* demonstrating the highest rates. Combining mulching with traditional pit digging yielded optimal survival and growth due to the benefits of moisture conservation, reduced competition for resources, and enhanced root stability. In contrast, the hoedad method proved the least effective, likely due to smaller pit sizes and potential root damage. Herbicide application, while initially comparable to mulching, declined in efficacy over time, raising concerns about its environmental impact, including risks to soil health and water quality. These findings strongly support mulching as a sustainable and effective vegetation control method. The implications of this study extend beyond Lebanon, offering valuable guidance for afforestation strategies in semi-arid regions where resource constraints and water conservation are critical. By prioritizing methods that improve soil conditions and reduce reliance on chemical controls, afforestation efforts can achieve greater long-term success while minimizing environmental risks. Future research should investigate additional planting techniques and vegetation control combinations under diverse environmental conditions to identify the most effective strategies across varying sites. Long-term monitoring is essential to evaluate survival and growth trends, providing insights into species resilience and ecosystem sustainability. Species selection should be based on site-specific factors, including local soil characteristics, climate conditions, and the ecological adaptability of tree species. In conclusion, we recommend the following for afforestation practitioners: prioritize mulching and traditional pit-digging methods for improved survival and growth, particularly for species like *P. palaestina* in semi-arid regions; minimize herbicide use due to its environmental risks; and design afforestation plans tailored to local conditions to ensure sustainable outcomes. These approaches will contribute to successful afforestation projects and the restoration of degraded ecosystems.

Acknowledgments

The authors acknowledge Mr. Ali Ramadan and Mr. Hachem Saab for their significant contributions in planting seedlings, implementing vegetation controls, and providing valuable assistance with field measurements.

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