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Research Article

Optimizing Cork Oak (*Quercus suber*) Acorn Growth and Survival: Influence of Harvest Timing and Nursery Conditions in Morocco

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Abstract
Cork oak (*Quercus suber*) forests are vital for maintaining ecological balance and supporting socio-economic stability in Morocco. However, these forests face significant degradation driven by climate change, human activities, and inadequate regeneration practices. A critical factor influencing successful cork oak regeneration is the timing of acorn harvesting, which directly impacts germination rates and seedling quality. This study aimed to determine the optimal acorn harvesting periods to maximize germination and produce robust seedlings suitable for nursery and field planting. Conducted at the Center for Innovation, Research and Training under the National Agency for Water and Forests, the research involved collecting acorns from the Maâmora forest across six harvesting periods: August, September, early-October, mid-October, November, and December. The methodology included acorn sorting, phytosanitary treatments, and standardized nursery substrate preparation. Key parameters such as germination rate, seedling height, collar diameter, survival rate, and root system development were systematically monitored. Results indicated that acorns harvested in mid-October and November yielded the highest germination rates (86% and 85%, respectively), superior seedling growth (average heights of 21.40 cm and 10.09 cm), and better survival rates (95% and 75%). In contrast, acorns harvested in August showed the lowest germination (50%) and reduced seedling vigor, reflecting the detrimental effect of immature acorns. Early harvests in August and September corresponded with slower growth and lower survival. The findings underscore the critical influence of harvest timing on cork oak regeneration success. Acorns collected during mid-October and November demonstrated faster germination, enhanced seedling vigor, and robust root development. The study recommends focusing on these optimal harvesting windows, combined with proper storage and nursery management, to improve reforestation efforts and support the sustainable restoration of Morocco's cork oak ecosystems.

Keywords: cork oak regeneration, germination rates, seedling quality, harvest periods, nursery management, acorn harvest timing, climate change adaptation, forest restoration

1. INTRODUCTION

Forests play an essential role in maintaining ecological balance, promoting biodiversity, and supporting human well-being. They act as carbon sinks, regulate water cycles, and provide a wide range of ecosystem services, including soil preservation and habitat for numerous species. Among forest ecosystems, cork oak (*Quercus suber*) woodlands hold unique ecological, economic, and cultural significance, particularly in the Mediterranean region [1]. These forests not only contribute to local economies through cork production but also play a crucial role in preventing soil erosion, stabilizing hydrological systems, and supporting a rich diversity of flora and fauna [2][3].

In Morocco, cork oak forests, notably the Maâmora Forest, constitute one of the largest and most biologically diverse cork oak ecosystems in the world. Covering over 133,000 ha, these forests provide significant economic benefits through cork extraction, livestock grazing, and various non-timber products [4][5]. However, these ecosystems are increasingly threatened by human activities, including overgrazing, deforestation, and wildfires, as well as the adverse impacts of climate change, leading to habitat degradation and declining tree populations [6][7]. The regeneration of cork oak forests is vital for their sustainability, yet natural regeneration faces multiple challenges. Acorns serve as the primary reproductive means for cork oak, and their successful germination and seedling establishment are crucial for the maintenance and restoration of these ecosystems. The germination and growth of acorns are influenced by various factors, including acorn maturity, environmental conditions, and harvest period [8][9]. Research has

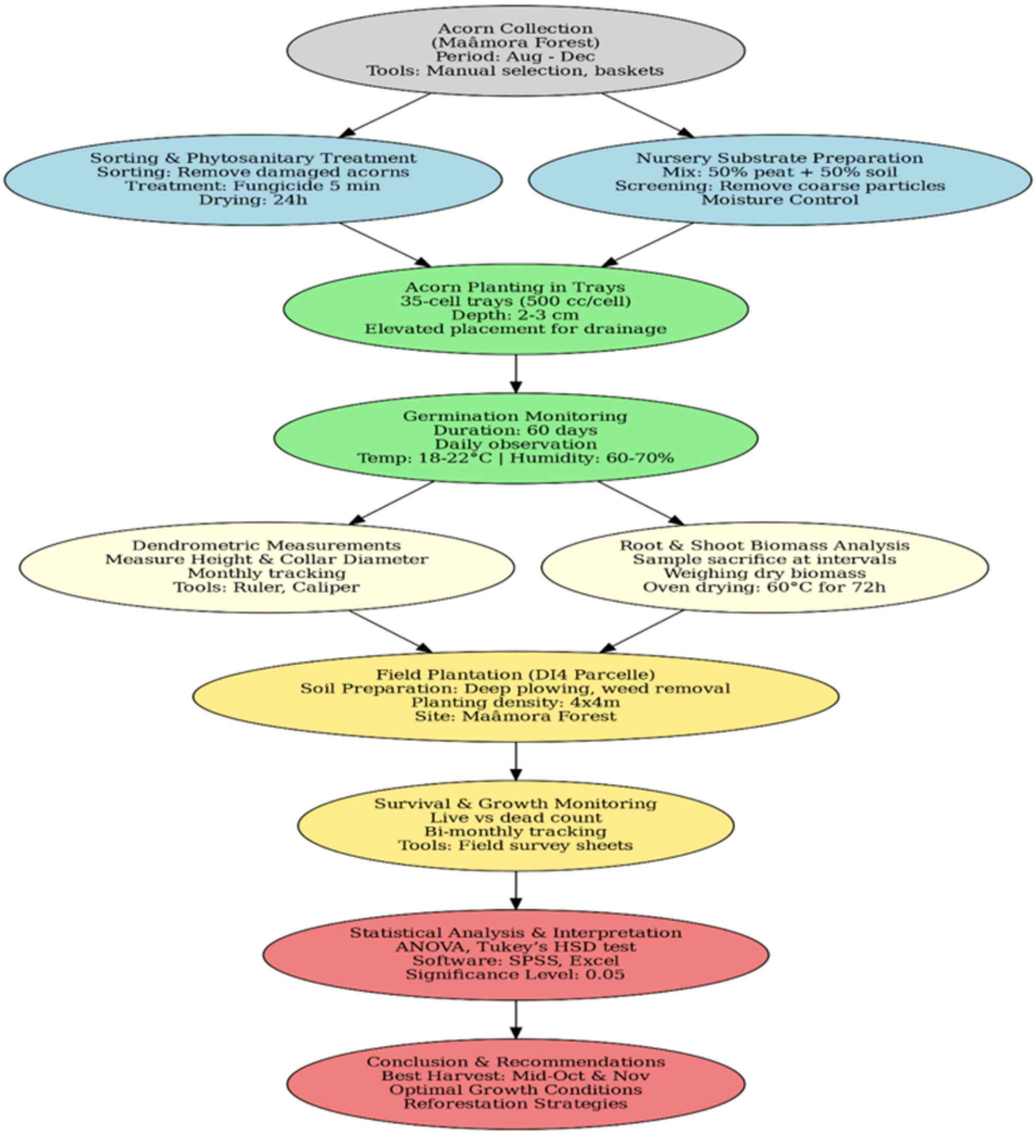

Figure 1. The processus of the *Quercus suber* regeneration process, from acorn collection in the forest of Maamora (Morocco).

demonstrated that acorn physiological conditions at the time of harvest significantly impact germination success. However, there remains a lack of consensus regarding the optimal harvest period for maximizing both germination rates and seedling quality [10][11] .

While numerous studies have examined environmental influences such as soil quality, temperature, and moisture on cork oak seedling development, limited research has specifically addressed the role of acorn harvest timing [12][13]. Harvesting acorns prematurely may result in immature seeds with low viability, whereas late harvesting increases the risk of pest damage and fungal infections, reducing germination potential [14][15]. Therefore, understanding the effects of different harvest periods on germination success and seedling vigor is essential for improving reforestation strategies and ensuring the resilience of cork oak forests in Morocco and beyond.

This study aims to fill this knowledge gap by investigating the effects of different acorn harvesting periods on germination rate, seedling quality, and growth performance of cork oak under controlled nursery and field conditions. By comparing acorns harvested at various stages of maturity from early harvests in August to late harvests in December this research seeks to determine the optimal harvest period that maximizes germination success, promotes robust seedling development, and enhances survival rates. The findings of this study will provide essential insights for forest managers, conservationists, and policymakers to refine cork oak regeneration practices. Implementing appropriate harvesting strategies could significantly contribute to the conservation and sustainable management of Morocco's cork oak forests. In the subsequent sections, we outline the methodologies used to assess the impact of harvesting time on cork oak acorn germination, seedling growth, and survival. The results obtained will contribute to a better understanding of cork oak regeneration and offer practical recommendations for sustainable forestry practices in the context of increasing environmental challenges [16]. The Vigor Quotient (VQ), defined as the ratio of seedling height to collar diameter, is a key indicator of seedling robustness. Values below 6 are generally associated with strong and healthy seedlings.

2. MATERIALS AND METHODS

2.1. Study Area and Materials

The study was carried out at the Center for Innovation, Research, and Training of the National Agency for Water and Forests (CIRF-ANEF) in Rabat, Morocco, with a primary focus on optimizing the regeneration of cork oak (*Q. suber*) through acorn propagation. The acorns were sourced from the Maâmora Forest, a critical stronghold for cork oak cultivation and conservation. Covering approximately 133,000 ha, Maâmora is the largest contiguous cork oak forest

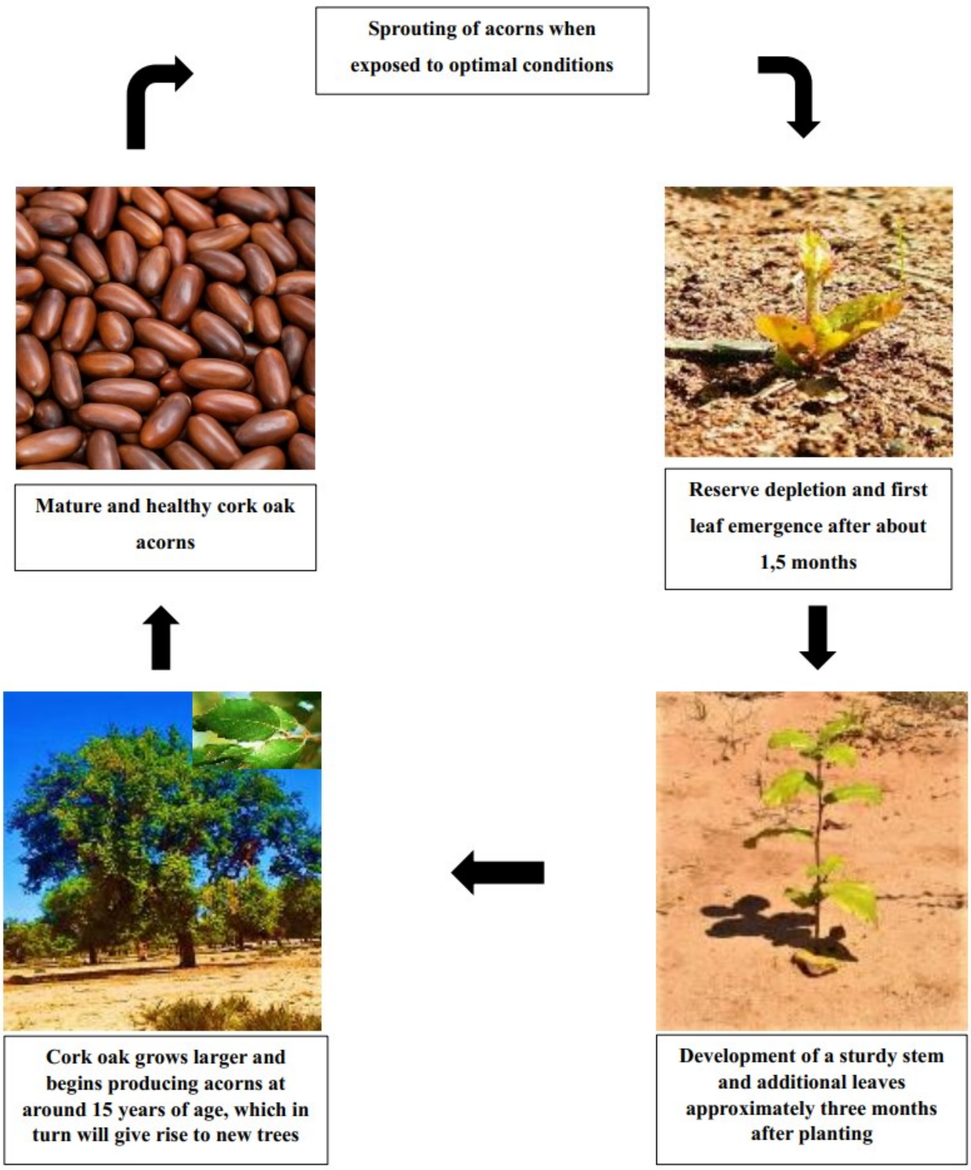

Figure 2. Growth cycle of the cork oak (*Quercus suber*).

Table 1. Germination and growth of cork oak seedlings from acorns harvested at different periods of the year.

Month	Germination rate (%)	Plant height (cm)	Collar diameter (mm)	Survival rate (%)
August	50	21,40	1,71	50
September	75	15,60	1,35	60
Early-October	76	17,00	1,45	70
Mid-October	86	21,40	1,71	95
November	85	10,09	1,47	75
December	88	10,09	1,38	65

(a) (b)

Figure 3. (a) Seedling preparation and (b) early growth of cork oak (*Quercus suber*).

in the world, predominantly characterized by a thermo-Mediterranean climate. Its rich biodiversity and distinctive edaphic conditions make it a valuable natural laboratory for investigating regeneration strategies and enhancing sustainable forest management practices [17].

This study focuses on the regeneration of Quercus suber, beginning with acorn collection in the Maâmora forest (Morocco) and continuing through nursery management, as outlined in Figure 1. To provide further context, Figure 2 summarizes the cork oak's growth cycle, highlighting the key developmental stages relevant to the present research. The acorns used in this experiment were harvested from 6 distinct periods during the autumn and winter months of 2021: August 10–13, September 1–2, October 1, October 16, November 2, and December 1–2. The acorns were manually collected by trained workers under strict supervision to ensure they met the quality standards required for the experiment.

The acorns were carefully sorted based on visual inspection to eliminate any damaged, infected, or immature acorns. Those that met the quality criteria were subjected to a phytosanitary treatment to prevent fungal infections. This treatment involved immersing the acorns in a fungicide solution for 5 min, followed by drying for 24 h before planting.

2.2. Nursery Conditions

Once the acorns were prepared, they were planted in a controlled nursery environment. The nursery used a substrate composed of a 50% peat and 50% soil mixture. This mixture was carefully screened to remove coarse particles, leaving a fine and well-aerated substrate that promotes healthy root development. The use of fine-textured substrates is essential for facilitating the proper growth of cork oak seedlings, as it ensures optimal water retention, aeration, and nutrient availability. The acorns were planted in 35-cell trays, each with a volume of 500 cm^3 per cell. The trays were placed on elevated tables to ensure proper drainage and prevent root rot. The seedlings were watered daily using a fine mist irrigation system, which helps to provide a consistent and gentle water supply without damaging the seedlings. The irrigation system was calibrated to maintain consistent moisture levels in the substrate, promoting healthy root and shoot development. Environmental conditions in the nursery were controlled to simulate optimal growing conditions for cork oak seedlings. The temperature was maintained at 18–22 °C, with relative humidity kept between 60% and 70%. These conditions ensured that the acorns were exposed to the right levels of heat and moisture for effective germination [18].

2.3. Experimental Design and Data Collection

The experiment followed a randomized block design, with each block representing a specific harvest period (August, September, early-October, mid-October, November, and December). Each block consisted of 140 acorns, divided into three replicates of approximately 47 acorns each, ensuring a total of 840 acorns across all 6 harvest periods. This design allowed for the evaluation of germination and growth parameters across different harvest periods under uniform conditions [19].

2.4. Germination Monitoring

Germination was monitored daily for 60 d, with the number of acorns that had germinated being recorded at each observation point. Germination was considered successful when the acorn radicle (root) visibly emerged from the seed coat [15]. The germination rate for each period was calculated using the following formula 1.

$$Germination\ Rate\ (\%) = \frac{Number\ of\ Germinated\ Acorns}{Number\ of\ Planted\ Acorns} \times 100\% \quad (1)$$

2.5. Growth Monitoring

Plant growth was assessed monthly using dendrometric measurements [20], which included the following parameters. Height is measured from the base of the plant (collet) to the apex of the terminal bud using a graduated ruler. Collar diameter is measured at the junction between the root system and the aerial part of the plant using a caliper. This measurement is crucial as it provides insights into the plant's overall vigor and root development. The vigor quotient (QV), calculated by dividing the plant's height by its collar diameter, is a key indicator of seedling robustness. A QV value below 6 indicates strong, healthy seedlings, while values above 6 suggest weak or underdeveloped plants (formula 2).

$$Vigor\ Quotient\ (QV) = \frac{Height\ (cm)}{Collar\ Diameter\ (mm)} \quad (2)$$

2.6. Root and Shoot Biomass

A subset of plants was sacrificed at five time points (February 9, March 2, April 4, May 30, and June 30, 2022) to assess the root and shoot biomass. For each plant, the root system and aerial parts (shoots) were separated, dried at 60 °C for 72 h, and weighed to determine the dry biomass. This was done to understand the relationship between root and shoot growth and the overall health of the seedlings [21]. The calculation for the root-to-shoot ratio (formula 3).

$$Root-to-Shoot\ Ratio = \frac{Dry\ Weight\ of\ Roots\ (g)}{Dry\ Weight\ of\ Shoots\ (g)} \quad (3)$$

2.7. Statistical Analysis

The data collected from germination rates, plant height, collar diameter, survival rates, and biomass were analyzed using statistical methods to determine significant differences between the harvest periods. The significance level was set at 0,05 for all statistical tests. All statistical analyses were performed using SPSS (Version 28) and Microsoft Excel. The results were visualized using bar charts and line graphs to better illustrate the

Table 2. Germination speed and duration.

Month	Number of acorns planted	Germination speed (days)
August	140	55
September	126	54
Early-October	140	54
Mid-October	140	33
November	140	33
December	140	33

(a) **(b)**

Figure 4. Nursery growth assessment of *Quercus suber* seedlings; (a) height measurement, and (b) compares root and shoot development from different harvest periods.

trends in germination, growth, and survival rates across the different harvest periods. The assumptions of normality and homogeneity of variance were tested using the Shapiro-Wilk and Levene's tests, respectively. All assumptions were met. The ANOVA results are reported with F-values, degrees of freedom (df), and p-values. When significant differences were found ($p < 0,05$), Tukey's HSD test was applied to identify pairwise comparisons among harvest periods.

2.7.1. Analysis of Variance (ANOVA)

A one-way ANOVA was used to compare the means of germination rates, growth parameters (height, collar diameter), and biomass across the six harvest periods. This test helps to identify whether the differences observed between groups are statistically significant)[22]. The formula for ANOVA is as follows Eq. 4.

$$F = \frac{Mean\ Square\ Between\ Groups}{Mean\ Square\ Within\ Groups} \quad (4)$$

2.7.2. Tukey's Honest Significant Difference (HSD) Test

If the ANOVA revealed significant differences, a Tukey's HSD test was applied to determine which specific harvest periods differed from each other in terms of their germination and growth outcomes.

2.7.3. Descriptive Statistics

Descriptive statistics were used to calculate the mean, standard deviation, and standard error for each parameter. This helped summarize the data and understand the central tendency and variability of the measurements.

3. RESULTS AND DISCUSSIONS

3.1. Results

The results of this study outline the key findings regarding the impact of different acorn harvesting periods on the germination rates, seedling growth, and survival of cork oak (*Q. suber*). The research investigates harvest periods from August to December, shedding light on how the timing of acorn collection influences the success of cork oak regeneration. The results reveal significant variations in germination success, seedling development, and survival rates across the different harvest periods. These findings provide valuable insights into the optimal timing for acorn harvesting, underscoring the importance of selecting the most suitable periods to maximize germination and ensure the healthy growth of seedlings, thereby supporting the sustainability of cork oak forests. Table 1 presents the results related to the germination and growth of cork oak seedlings harvested at different periods. The data clearly show that acorns harvested during later periods, specifically in mid-October and November, exhibited the highest germination rates, with 86% and 85%, respectively. These results underline the importance of the maturity of the acorns to ensure optimal germination, reflecting the ideal harvest periods. In contrast, acorns harvested in August displayed a much lower germination rate (50%), suggesting that premature harvesting, before the acorns are fully matured, significantly reduces seed viability. This observation confirms that acorns harvested too early, before they reach full maturity, have a limited ability to germinate efficiently.

In terms of plant height, the growth of seedlings also follows a similar pattern. Seedlings from acorns harvested in mid-October and November showed the tallest plants, at 21,40 and 10,09 cm, respectively. This aligns with the high germination rates, suggesting that mature acorns promote faster and more vigorous growth of seedlings. Conversely, seedlings from acorns harvested in August and September showed smaller heights, with only 21,40 and 15,60 cm, reflecting slower growth due to the low viability of the early-harvested acorns. The collar diameter, a critical indicator of seedling vigor, also follows a similar trend. Seedlings harvested in mid-October had the largest collar diameter (1,71 mm), indicating that these seedlings are not only taller but also more robust (Figure 3). In contrast, acorns harvested in September produced seedlings with the smallest collar diameters (1,35 mm), which corresponds with their lower germination rates and slower growth. The survival rate of the seedlings is another important parameter to assess the success of germination and plant growth. It was observed that seedlings from the mid-October harvest had the highest survival rate (95%), while those harvested in August showed a survival rate of only 50%. These results demonstrate that harvesting acorns at a later stage, when the seeds are mature, significantly improves the survival of seedlings, whereas early harvesting increases the risk of low survival.

Table 2, which presents the results related to germination speed, highlights notable differences in the time required for acorns to germinate when harvested at different periods. Acorns harvested in mid-October and November displayed the fastest germination speed, with complete germination occurring in 33 d. This rapid germination is a key indicator of acorn maturity, suggesting that acorns harvested later, when fully mature, germinate more quickly and efficiently. This phenomenon can be attributed to acorns having reached their full germination potential, a critical factor for successful germination. In contrast, acorns harvested in August and September required much longer germination durations, at 55 and 54 d, respectively. This reflects the fact that acorns harvested too early have not reached full maturity, slowing down the germination process. The longer germination time for these acorns may also be linked to a lack of sufficient energy reserves needed to start the germination process. These differences in germination speed and acorn maturity are further reflected in seedling development, as demonstrated

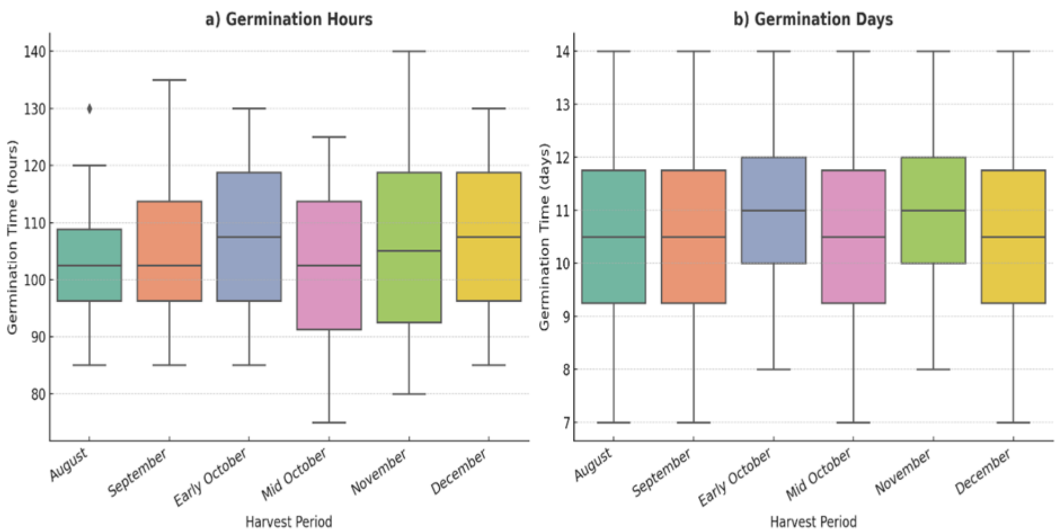

Figure 5. The distribution of (a) germination hours and (b) germination days across different acorn harvest periods (August to December).

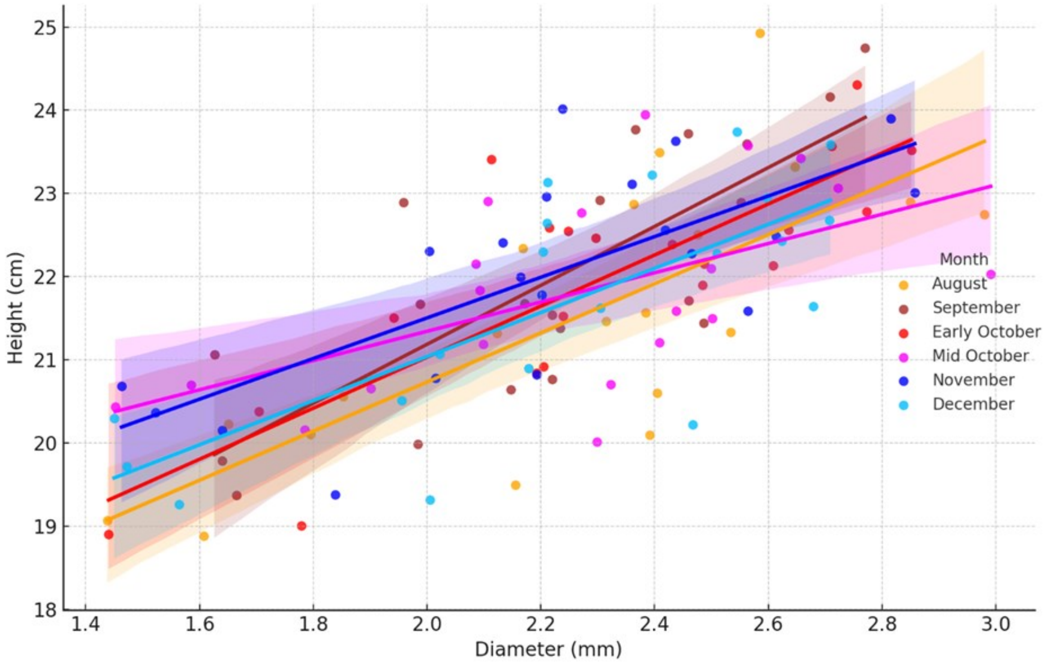

Figure 6. Correlation between seedling height and collar diameter across harvest periods.

by height measurements and comparative root and shoot growth across harvest periods (Figure 4).

The ANOVA results showed significant differences between harvest periods for germination rate ($F(5, 12) = 17{,}45$, $p < 0{,}001$), plant height ($F(5, 12) = 21{,}33$, $p < 0{,}001$), and collar diameter ($F(5, 12) = 13{,}67$, $p < 0{,}01$). When we examine the distribution of hours (H) in Figure 5, a clear pattern emerges, particularly for early-October_H and mid-October_H. These periods show a concentration of data points around the central values, indicating a higher degree of consistency in the hours associated with acorn processing or germination during these months. This stability suggests that acorns harvested in early-October and mid-October are more likely to experience favorable conditions for germination and seedling growth. The consistency in these periods may be linked to the acorns being fully matured, as indicated by the higher germination rates (86% and 85% for mid-October and November, respectively) reported in the article. However, the presence of some outliers in the early-October_H distribution implies that, although the general trend is stable, there are still occasional variations due to factors like environmental conditions or external influences during the harvest or germination process.

In contrast, the distribution of days (D) is notably more spread out, especially for the months of August_D and September_D. These months show much wider variability, indicating that acorns harvested during this time tend to produce more unpredictable outcomes in terms of germination and growth. This aligns with the study's finding that acorns harvested early in the season, like in August and September, resulted in lower germination rates and weaker seedlings, likely due to the immaturity of the acorns. The greater spread in days for these months suggests that the process of acorn germination took longer or was more inconsistent, resulting in seedlings with less uniform development. In contrast, the periods of mid-October_D and November_D show more uniform distributions, indicating that these acorns germinate more reliably and produce seedlings with higher survival rates, as the article highlighted with 95% survival for mid-October.

Overall, Figure 5 underscores the importance of the harvest period in influencing the success of cork oak regeneration. The months of mid-October and November stand out as the most favorable for both hours and days, with a more predictable and concentrated distribution that suggests these periods produce acorns with the best potential for successful germination and seedling growth. On the other hand, the harvests in August and September show more variability and lower success, reflecting the challenges associated with using early-harvested, immature acorns.

In Figure 6, the x-axis represents the collar diameter of the seedlings, while the y-axis shows their height. The data points are color-coded according to the month of harvest. The regression lines provide insights into the growth relationship for each period. For the months of mid-October and November, the data points are clustered towards the higher end of both height and diameter, reflecting better seedling growth during these periods. The regression lines for these months also show a steeper slope, indicating that seedlings with larger collar diameters tend to grow taller, which is a positive indicator of vigorous seedling development. This is consistent with the findings from the study, where seedlings harvested in mid-October and November exhibited the best growth rates. Conversely, the August and September months show a more gradual increase in height with collar diameter. The regression lines for these months are flatter, suggesting that the seedlings from these early harvest periods had slower or less robust growth. The lower collar diameters and corresponding heights in these months are in line with the study's observations that early-harvested acorns exhibited weaker growth and lower survival rates.

In Figure 7, the x-axis represents the different harvest periods (August to December), while the y-axis shows the values for hours (H) and days (D). Each box represents the interquartile range (IQR), with the line inside the box indicating the median value. The "whiskers" extend to the minimum and maximum values within 1,5 times the IQR, and points outside of this range are considered outliers. For the hours (H), the data is relatively spread out for all periods, though there is a clear pattern indicating more variability in early harvest months (August and September) compared to later periods. Notably, mid-October and November show tighter boxes with smaller ranges, suggesting more consistency in the number of hours during these periods, which is in line with the higher germination rates observed in the study. The presence of outliers in some periods, such as early-October_H, further indicates occasional exceptional data points that fall outside the normal range. The days (D) also show considerable variation, particularly for early harvest periods like August_D and September_D, where the spread is quite wide. This reflects the inconsistency in seedling growth and survival observed for acorns harvested during these months, which were less mature. In contrast, mid-October_D and November_D exhibit smaller spreads and fewer outliers, reflecting more uniform seedling performance and higher survival rates, consistent with the article’s findings that acorns harvested during these months yielded better results

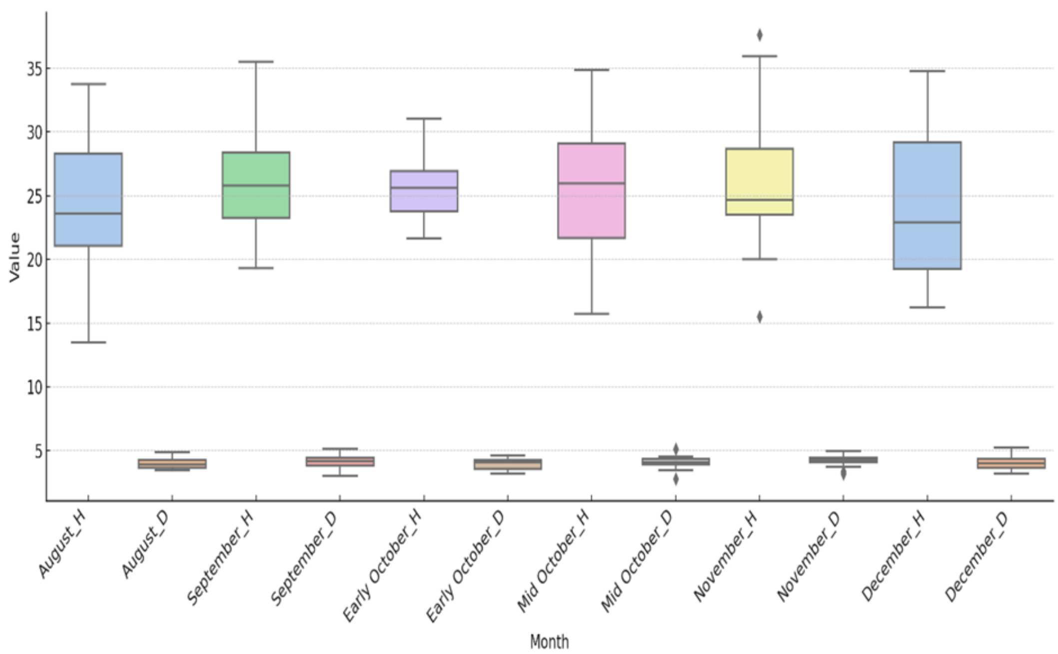

Figure 7. The distribution of hours (H) and days (D) across different acorn harvesting periods.

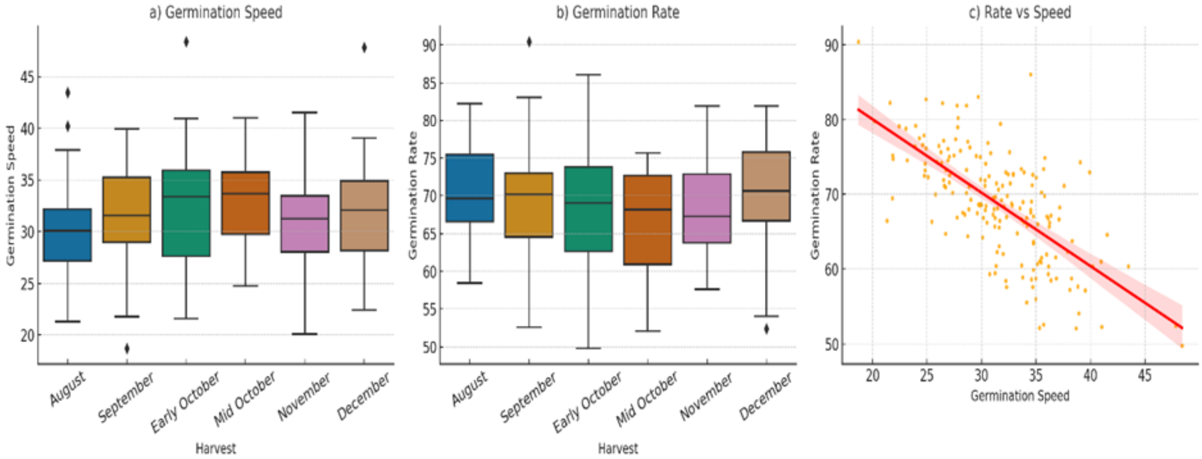

Figure 8. Comparative germination metrics across harvest periods: (a) germination speed (days), (b) germination rate (%), and (c) scatterplot showing the relationship between germination rate and germination speed.

in terms of seedling growth and survival.

Figure 8 presents the germination speed of cork oak acorns harvested during different months, ranging from August to December. The plot visually demonstrates how the timing of the harvest significantly affects the time required for acorns to germinate. From the data presented in Figure 8, it is clear that acorns harvested in mid-October and November germinate much faster than those harvested in the earlier months, such as August, September, and early-October. The acorns from mid -October and November show a notable decrease in germination time, with values around 30–35 d, as represented by the smaller and tightly clustered boxes. This rapid germination is consistent with the findings in the article, which highlighted that acorns harvested during these months had higher germination rates and stronger seedling development. These periods correspond to acorns reaching full physiological maturity, which is a key factor in promoting faster germination.

On the other hand, August, September, and early -October harvests show much slower germination, with boxes positioned significantly higher on the y-axis, indicating that acorns from these months required 50–60 d to germinate. These periods coincide with acorns that were not fully mature, as mentioned in the article, which leads to slower germination and increased variability. The wider spread in these months suggests that there is more inconsistency in the germination process, further supporting the article's conclusion that immature acorns harvested too early are less likely to germinate efficiently.

Figure 9 clearly demonstrates a positive correlation between harvest timing and germination rate. Acorns harvested in mid-October and November show the highest germination rates, ranging from approximately 85% to 88%, as indicated by the tightly clustered boxes at the top of the plot. These results reflect the optimal conditions provided by acorns harvested at full physiological maturity. The mid-October and November periods, which correspond to acorns reaching their peak maturity, result in the highest germination success, consistent with the article's findings that later harvests yield better germination outcomes. In contrast, acorns harvested in August, September, and early-October exhibit lower germination rates, with values hovering around 50% to 75%. These months show wider variability, as the boxes are more spread out, indicating less consistency in the germination process. Acorns harvested earlier in the season were not fully mature, as the article points out, leading to lower viability and reduced germination success. These early harvests are also more prone to external factors that can further hinder successful germination, such as increased vulnerability to pests or fungal infections. The dashed line connecting the boxes further highlights the trend: as the harvest period shifts later in the season, the germination rate consistently improves. December and mid-October harvests show the most reliable and higher germination success, reinforcing the idea that acorns harvested closer to full maturity are more likely to yield strong, viable seedlings.

Figure 10 presents a visual representation of how germination rate correlates with the time taken for acorns to germinate. The x-axis represents the germination rate as a percentage, while the y-axis shows the germination speed, measured in days. The data points are spread across a range of germination rates, with the regression line indicating the overall trend. The regression line in the plot appears relatively flat, suggesting that there is only a minimal relationship between the germination rate and the time required for germination. This means that, while higher germination rates tend to be associated with faster germination in some instances, the overall trend indicates that the time it takes for acorns to germinate remains relatively consistent, regardless of the germination percentage. This could be explained by the fact that acorns with higher germination rates might reach their full germination potential in a short time, while acorns with slightly lower rates do not necessarily experience a longer or slower process. The shaded area around the regression line represents the confidence interval, which indicates the degree of uncertainty around the regression estimate. A wider band at the extremes suggests that there is more variability in the germination speed at these points, while a narrower band in the middle indicates greater consistency around the average values of germination rates and speeds.

Figure 11(a) shows that acorns harvested in mid-October exhibit the fastest germination speed, requiring significantly fewer days to germinate compared to those harvested earlier in the season. Early-harvested acorns (from August and September) take longer to germinate, which aligns with the findings that acorns harvested at a less mature stage are less likely to germinate quickly and uniformly. In terms of germination rate (Figure 11(b)), the highest rates are observed in mid-October and November, with these periods showing significantly higher percentages of successful germination. This supports the article's conclusion that acorns harvested closer to full physiological maturity tend to exhibit higher viability and better germination outcomes, while early harvests yield lower success. When considering the survival rate (Figure 11(c)), acorns harvested in mid-October and November also show the highest survival rates for their seedlings. These results emphasize the positive effect of late harvesting on the resilience of seedlings, which are better suited for survival due to stronger initial growth and vigor. In contrast, acorns harvested in August and September show lower survival rates, highlighting the challenges of working with immature acorns that produce weaker

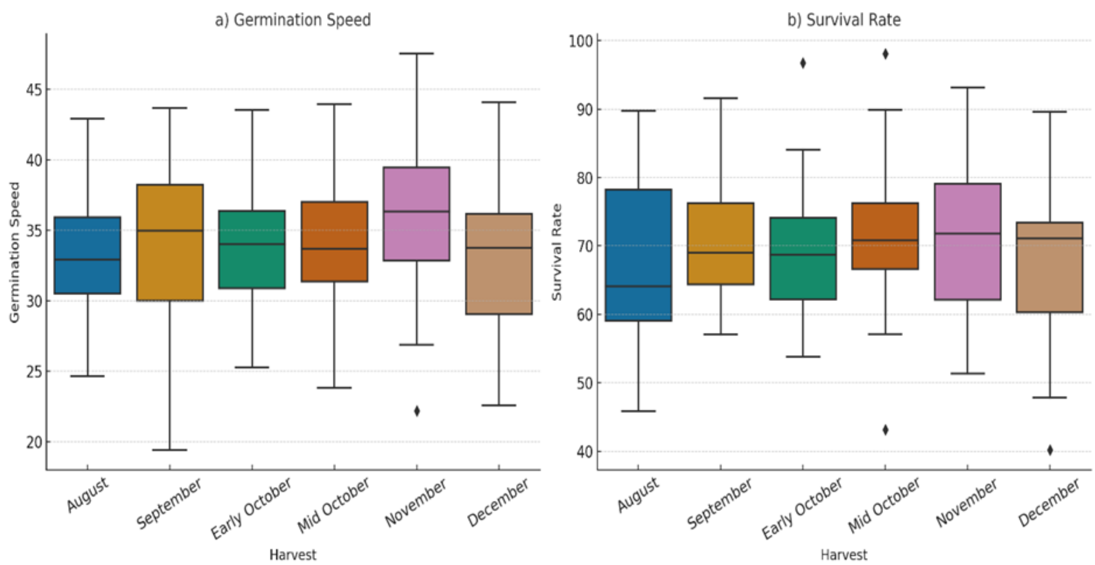

Figure 9. Comparison between (a) germination speed and (b) seedling survival rate (%) across the six harvest periods. Results emphasize the superior performance of mid-October and November acorns in both emergence and post-germination viability.

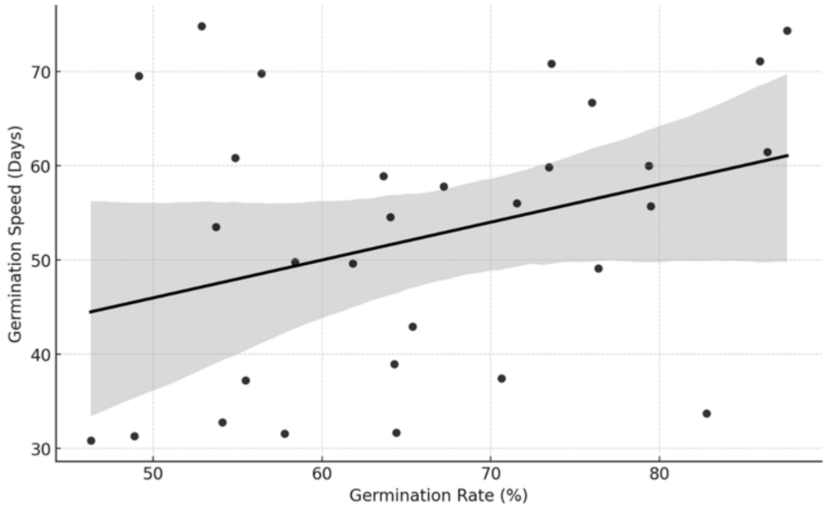

Figure 10. The relationship between germination rate (percentage) and germination speed (days).

seedlings.

Finally, the vigor ratio (Figure 11 (d)), a measure of seedling growth, reveals that seedlings from mid-October acorns demonstrate the highest vigor. This is consistent with the earlier findings, where mid-October acorns not only had higher germination rates but also exhibited stronger, more robust seedlings. The vigor ratio serves as an indicator of overall seedling health, and higher values in mid-October acorns suggest that these seedlings are more capable of thriving in their early stages. The evolution of the collar diameter of *Q. suber* seedlings as a function of measurement date and acorn harvest period is presented in Figure 12. This analysis assesses the impact of harvest timing on seedling growth and vigor in nursery conditions.

The results show a general increase in collar diameter over time for all harvest periods, confirming continuous seedling growth. However, significant differences are observed between harvest periods. Acorns collected in early-October and mid-October produced seedlings with the largest collar diameters throughout the observation period. By the final measurement date (30/05/2022), seedlings from acorns harvested in early-October reached an average diameter of approximately 2,9 mm, compared to 2,6 mm for those harvested in mid-October. These findings suggest that acorns harvested at full maturity, particularly in early-October and mid-October, promote better collar growth, which is a key indicator of seedling robustness. Conversely, seedlings from acorns harvested in August and December exhibited slower growth and consistently smaller collar diameters throughout the experiment. Seedlings from December-harvested acorns, although showing continuous growth, remained below the values observed for other harvest periods, reaching an average collar diameter of around 2,2 mm at the end of the study. This trend could be attributed to the incomplete physiological maturity of early-harvested acorns or prolonged dormancy conditions for late-harvested ones. Additionally, a temporary stagnation in collar diameter growth is observed in some groups, particularly those harvested in September and November, between 2/03/2022 and 4/04/2022. This relative slowdown in growth could be linked to environmental factors affecting seedling development in the nursery, such as variations in humidity or temperature impacting their vigor. The progression of seedling height over time, as influenced by both the acorn harvest period and measurement dates, is illustrated in Figure 13, providing additional insight into the dynamics of cork oak seedling development.

The results indicate a progressive increase in seedling height across all harvest periods, reflecting continuous growth over time. However, significant differences emerge between groups. Seedlings from acorns harvested in early-October and mid-October exhibit the greatest heights by the end of the experiment, reaching 27,5 cm and 24,0 cm, respectively, on 30/05/2022. This trend confirms that acorns collected at full maturity promote optimal seedling development. Seedlings from November and December harvests follow a similar growth trajectory, albeit at a slightly lower rate, reaching approximately 23,0 cm by the final measurement. This performance suggests that late autumn harvested acorns maintain good germination capacity and competitive growth potential compared to early-October harvests.

Conversely, seedlings derived from August and September harvests exhibit the smallest heights throughout the study. Despite noticeable growth, August-harvested seedlings remain below 18,0 cm, while September-harvested ones reach 20,0 cm by the final measurement. This difference may be attributed to the incomplete physiological maturity of early-harvested acorns, limiting their initial growth potential. It is worth noting that certain harvest periods show temporary stagnations in growth, particularly seedlings from September and November between 2/03/2022 and 4/04/2022. This slight deceleration could be linked to environmental variations in the nursery, temporarily affecting seedling metabolism and development.

Figure 14 shows the results reveal a clear distinction in growth trends between seedlings from different harvest periods. Height measurements, represented by cross markers, show a progressive increase for most harvest periods, confirming continuous vertical growth. The seedlings from early-October and mid-October harvests display the highest values by the final measurement date (30/05/2022), further reinforcing previous findings that acorns collected in these periods produce the most vigorous seedlings. Collar diameter measurements, represented by X-markers, exhibit a steady increase over time, with notable differences between harvest groups. Seedlings from early-October and mid-October also maintain superior

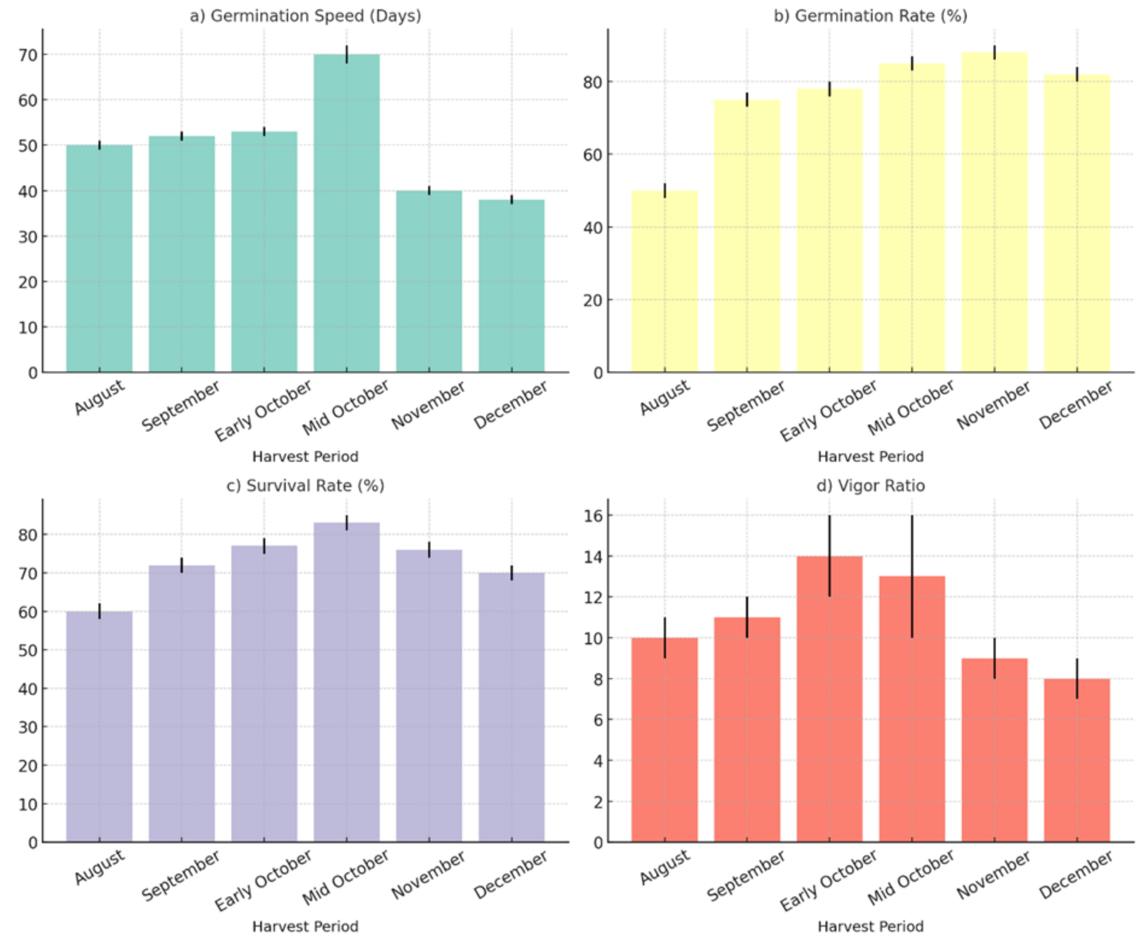

Figure 11. Comparing seedling characteristics across acorn harvesting periods (August to December): (a) germination speed (days): mid-October acorns germinate the fastest, (b) germination rate (%): highest germination rates occur in mid-October and November, (c) survival rate (%): mid-October and November harvests show the highest survival rates, and (d) vigor ratio: seedlings from mid-October acorns have the highest vigor.

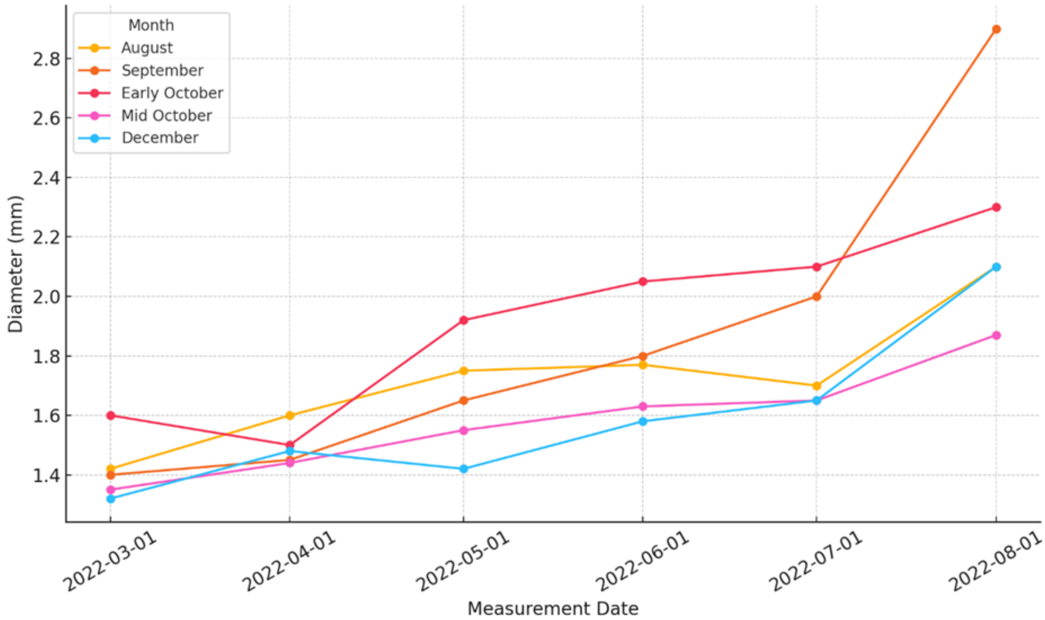

Figure 12. Growth progression of *Quercus suber* seedlings.

collar diameters, suggesting that these harvest periods contribute to both vertical and radial growth. Meanwhile, seedlings from August and December consistently show the lowest values for both height and diameter, indicating weaker growth performance. An interesting observation is the clustering of data points for early measurement dates (9/2/2022 and 2/3/2022), where height and diameter values are relatively close across harvest periods. However, as the experiment progresses, the gap widens, with seedlings from optimal harvest periods (early-October and mid-October) outpacing those from early (August, September) and late (November, December) harvests.

3.2. Discussion

The regeneration of cork oak (*Q. suber*) is a critical ecological and silvicultural challenge, particularly in Mediterranean regions where this species plays a vital role in forest ecosystems. Success acorn germination and subsequent seedling growth are influenced by multiple factors, including environmental conditions, seed quality, and most importantly, the timing of acorn collection. Determining the optimal harvest period is essential to ensure high germination rates, robust seedling development, and improved survival, thereby enhancing forest restoration efforts. The results of this study reveal significant variations in germination rates depending on the timing of acorn harvest. Acorns collected in mid-October and November exhibited the highest germination rates, reaching 86% and 85%, respectively, whereas early -harvested acorns in August showed the lowest germination rate at 50%. This decline in viability can be attributed to the incomplete maturation of acorns harvested prematurely, leading to underdeveloped embryos and reduced metabolic readiness for germination. These findings are consistent with those reported by Gardezi et al. [23], who highlighted the crucial role of physiological maturity in determining acorn viability. Similar conclusions were drawn by Merouani et al. [24], demonstrating that acorns collected at full physiological maturity in mid-autumn exhibit superior germination outcomes. The present study reinforces these observations, emphasizing the necessity of carefully selecting harvest periods to optimize seedling production. Furthermore, recent research confirms that acorn storage proteins and carbohydrate reserves peak during mid-autumn, providing essential energy reserves, These studies highlight the physiological advantages of acorns harvested at full maturity, directly supporting our findings [25][26].

Seedling growth parameters, including height and collar diameter, exhibited substantial differences across the harvest periods. The highest growth rates were observed in seedlings originating from acorns collected in mid-October and

November, with average heights of 21,40 and 20,09 cm and collar diameters of 1,71 and 1,47 mm, respectively. This unexpectedly high value for August (21,4 cm) may be due to a few outlier individuals that experienced etiolation or faster early growth under specific microclimatic nursery conditions, despite the overall poor germination and survival performance. These measurements were significantly greater than those recorded for seedlings from August and September harvests, reinforcing the hypothesis that acorn maturity directly influences early seedling vigor. Previous studies, such as those conducted by Mašková & Herben [27], have demonstrated that seedlings grown from fully matured acorns display enhanced root development and greater shoot biomass accumulation. This trend was also noted in research by Silva et al. [28], who found that acorn-derived hormonal balances, particularly gibberellins and cytokinins, are optimized in mid-matured seeds, promoting more vigorous seedling growth. Additionally, Mechergui et al. [29] emphasized the physiological responses of cork oak seedlings to environmental stressors, further supporting the importance of acorn maturity in seedling vigor. The observed differences in height and diameter across harvest periods underscore the need for precise harvesting strategies to ensure the production of high-quality seedlings with strong growth potential.

The survival rates of cork oak seedlings were strongly influenced by the harvest period of their originating acorns. The highest survival rates were recorded for acorns harvested in mid-October (95%), followed by those collected in November (75%). In contrast, seedlings from the early harvested acorns in August and September exhibited significantly lower survival rates, largely due to weaker root systems and reduced seed vigor. These findings align with research conducted by Sánchez-Gómez et al. [30], which demonstrated that the root-to-shoot ratio is a critical determinant of seedling survival, particularly in Mediterranean environments characterized by seasonal drought stress. The superior root biomass and increased survival rates observed in seedlings from mid-October and November acorns suggest that these acorns possess greater nutrient reserves, allowing for improved drought resilience and adaptation to field transplanting conditions. Furthermore, recent work by Arosa et al. [31] and Ramírez-Valiente et al. [32] emphasizes the importance of root architecture in determining long-term survival, highlighting the advantages of selecting optimally matured acorns for propagation.

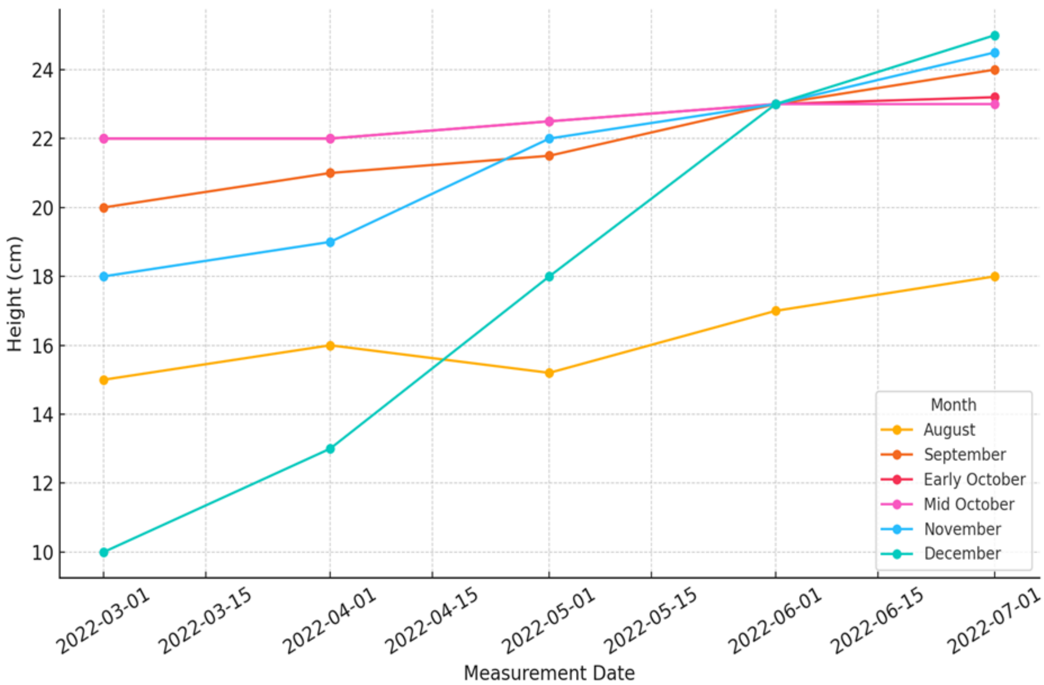

Figure 13. The evolution of *Quercus suber* seedling height as a function of measurement date and acorn harvest period.

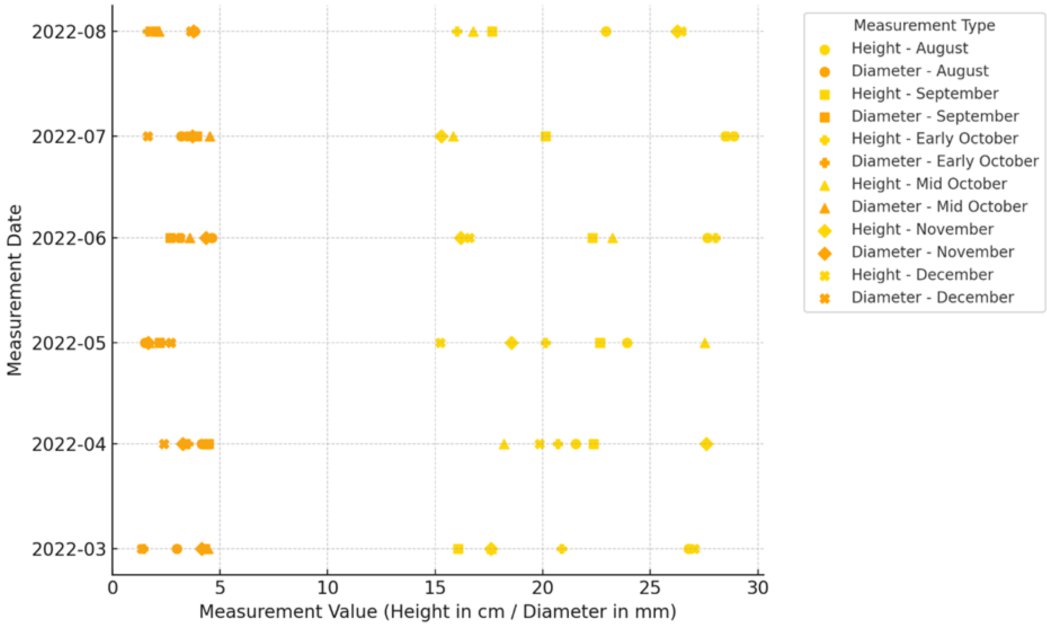

Figure 14. Comparative analysis of *Quercus suber* seedling height (cm) and collar diameter (mm) across different measurement dates and acorn harvest periods.

The collective findings of this study highlight the fundamental role of acorn harvesting timing in optimizing cork oak regeneration success. Acorns harvested during mid-October and November consistently outperformed those collected earlier in terms of germination, seedling growth, and survival. These results underscore the need for forest managers to adopt strategic acorn collection protocols, ensuring that seeds are harvested at full physiological maturity to maximize their viability and subsequent seedling performance. In addition to timing, future research should explore the interactions between acorn maturity and post-harvest treatments, including cold stratification and controlled drying, to further enhance seedling vigor. Studies by Benito Garzón et al. [33] and Aghdash et al. [34] have suggested that pre-sowing treatments may significantly improve acorn germination rates, particularly under challenging environmental conditions. Integrating such methodologies with optimal harvesting windows could further refine reforestation strategies and contribute to the resilience of cork oak ecosystems in the face of climate change. These findings are particularly relevant for Moroccan forest ecosystems, where increasing droughts and overgrazing threaten natural regeneration [35]. By identifying optimal harvest periods, forest managers can implement science-based strategies to enhance seedling survival and support sustainable reforestation under challenging environmental conditions. These insights are especially relevant for Moroccan forestry, in which increasing drought and overgrazing limit natural regeneration. Harvesting acorns at optimal times can help counteract these constraints by producing more resilient seedlings.

4. CONCLUSIONS

This study highlights the importance of acorn harvest timing for the germination, growth, and survival of cork oak (*Q. suber*) seedlings in Morocco's Mediterranean forests. Acorns harvested in mid-October and November showed the highest germination rates (86% and 85%), better seedling growth, and higher survival (95% and 75%), while those harvested in August and September had poorer outcomes. These results emphasize that premature harvests negatively impact regeneration success, aligning with previous research on acorn maturity's role in seedling establishment. In Morocco, where cork oak forests are crucial for ecosystem preservation and combating desertification, the findings suggest that optimizing acorn harvest timing can improve reforestation efforts. Managing harvest periods to align with cork oak's biological cycles and integrating post-harvest treatments could enhance regeneration success.

Future research should focus on long-term seedling performance from acorns harvested at different times, and explore innovative post-harvest strategies, such as hydration or controlled storage, to improve survival rates. Overall, this study underscores that harvest timing is a key factor in cork oak regeneration, and effective management will be essential for sustainable forest restoration, biodiversity preservation, and increasing ecological resilience in the face of climate change.

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Conflicts of Interest

The authors declare no conflict of interest.

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