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THE EFFECTS OF RAINWATER-HARVESTING V-SHAPED MICROCATCHMENTS AND PLANT-SUPPORTIVE AMENDMENTS ON SOIL MOISTURE AND EARLY ESTABLISHMENT OF *FRAXINUS ANGUSTIFOLIA* VAHL. UNDER SEMI-ARID MEDITERRANEAN CONDITIONS

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ABSTRACT

This study assessed the effectiveness of V-shaped rainwater-harvesting micro catchments and selected plant-supportive amendments on soil moisture dynamics, survival, and early growth performance of narrow-leaved ash (*Fraxinus angustifolia* Vahl.) during three consecutive growing seasons (2022–2024) in western Türkiye. By the end of the first growing season, mean seedling survival was approximately 63% across treatments. However, complete mortality (100%) occurred in conventional terrace control plots by the second growing season, indicating plantation failure under this method. In contrast, V-shaped micro catchments maintained survival rates of 65% in the second year and 57% after three years. Volumetric soil water content (0–20 cm) measured during the peak drought period (July–September) was consistently higher in micro catchments than in terrace controls. In September 2024, soil moisture in the micro catchment control (C-V) reached 8.17% at the upper position and 5.88% at the lower position, compared to 3.83% and 1.53%, respectively, in terrace plots. Relative diameter increment (RDI) differed significantly among treatments ($p < 0.0001$), with the straw-based lignocellulosic superabsorbent polymer increasing stem diameter growth by approximately 40% compared with other micro catchment treatments. Relative height increment (RHI) was up to 2.3 times greater in micro catchment plots than in terrace controls. These findings demonstrate that integrating structural rainwater harvesting with wood- and plant-derived water-retaining amendments substantially enhances soil water availability, seedling survival, and early stem growth of *F. angustifolia*, thereby improving hardwood plantation establishment and resilience under semi-arid Mediterranean environments.

KEYWORDS: Rainwater harvesting, V-shaped micro catchments, *Fraxinus angustifolia* Vahl., soil moisture, lignocellulosic polymer.

INTRODUCTION

Climate change is intensifying soil water limitations in arid and semi-arid regions by increasing evaporative demand and altering precipitation regimes, thereby amplifying drought stress during the critical establishment stage of woody perennial vegetation (Allen et al. 2010; Choat et al. 2012; Seidl et al. 2014). In Mediterranean-type environments, prolonged summer dry periods frequently reduce near-surface soil moisture to levels that constrain early growth and substantially increase seedling mortality risk (Breshears et al. 2005; Lindner et al. 2014). These impacts are particularly pronounced in the Mediterranean Basin, where increasing pressure on water resources is driving the spatial expansion of drought-affected areas (FAO 2019; Feng and Fu 2013; Türkeş et al. 2020; Bağçacı et al. 2021).

Afforestation provides essential ecosystem services, including biodiversity conservation, improvement of soil and microclimatic conditions, and stabilization of hydrological processes. Beyond these ecological functions, afforestation also contributes to the sustainability of wood production systems. In Türkiye, afforestation efforts are predominantly implemented in arid and semi-arid regions, frequently on degraded or post-fire landscapes. Under such conditions, species selection must account for site-specific ecological constraints and socio-economic expectations, as long-term establishment success and sustainable stand development largely depend on this decision (Cortina et al. 2011; Çalışkan and Boydak 2017; Doelman et al. 2020). In these water-limited environments, enhancing on-site retention of incoming precipitation and improving soil water availability are critical prerequisites for sustainable forest establishment and long-term wood production. *Fraxinus angustifolia* Vahl. is a mechanically valuable hardwood species characterized by high density and superior compressive strength. Its anatomical structure confers wood properties suitable for strength-demanding applications, thereby enhancing its industrial relevance (Çota et al. 2025). Ensuring successful establishment of this species is therefore not only significant from an ecological restoration perspective but also strategically important for sustaining long-term, high-value hardwood production under increasingly water-limited conditions.

Rainwater harvesting (RWH) has re-emerged as an effective in-situ water management strategy that captures, concentrates, and conserves precipitation within the root zone, thereby enhancing plant-available water and reducing runoff losses in dryland systems (Critchley and Siegert 1991; Oweis and Taimeh 1996; Tados et al. 2021). Among RWH techniques, micro catchment systems are particularly suitable for afforestation due to their low maintenance requirements and capacity to increase soil moisture at the microsite scale. V-shaped micro catchments represent a practical configuration that directs overland flow toward planting points and may prolong soil moisture availability during summer drought (Critchley and Siegert 1991). However, runoff concentration alone may not fully alleviate water stress in degraded or coarse-textured soils where limited storage capacity and high evaporative losses restrict sustained moisture retention (Oweis and Taimeh 1996). Under such conditions, complementary approaches that enhance soil water retention and root–soil interactions may be necessary to translate improved infiltration into durable establishment success.

In this context, plant-supportive amendments such as arbuscular mycorrhizal inoculation, superabsorbent polymers, and Osmo protectants have attracted increasing attention due to their potential to enhance plant performance under water-limited conditions (Smith and Read 2010; Birhane et al. 2012; Kumari et al. 2015). Mycorrhizal fungi improve effective root surface area and nutrient acquisition, while lignocellulosic-based superabsorbent polymers derived from wood and plant materials can increase soil water retention within the root zone. Osmo protectants such as glycine betaine and proline contribute to cellular osmotic adjustment under dehydration stress. Although these approaches have been widely evaluated under controlled experimental conditions, field-based evidence quantifying the interactive effects of micro catchment-based rainwater harvesting and plant-supportive amendments on soil moisture dynamics and early establishment of woody species under semi-arid Mediterranean conditions remains limited (Tubeileh et al. 2006). This knowledge gap constrains the development of integrated, field-tested strategies for improving afforestation success in drought-prone environments.

Therefore, this study quantifies the effects of V-shaped rainwater-harvesting micro catchments on dry-season soil moisture dynamics and evaluates whether selected plant-supportive amendments (mycorrhiza, superabsorbent polymer, and Osmo protectants) provide additional benefits for early establishment of *Fraxinus angustifolia* under semi-arid field conditions. By assessing seedling survival, relative diameter increment, and relative height increment over three consecutive growing seasons, this research aims to provide empirical evidence for enhancing in-situ soil water availability and improving the long-term establishment potential of high-value hardwood stands in water-limited Mediterranean environments.

MATERIAL AND METHODS

The experiment was conducted at three sites within the İzmir Regional Directorate of Forestry in western Türkiye: Karaburun and Ödemiş (İzmir province) and Yuntdağı (Manisa province) (Fig. 1). The sites represent semi-arid Mediterranean conditions typical of afforestation areas in the region and differ in elevation, slope, aspect, and soil properties. Geographic coordinates were 38°25′00″ N, 26°31′14″ E (Karaburun), 38°10′17″ N, 28°07′33″ E (Ödemiş), and 38°50′53″ N, 27°24′31″ E (Yuntdağı). Elevation ranged from 130 m to 650 m (Tab. 1).

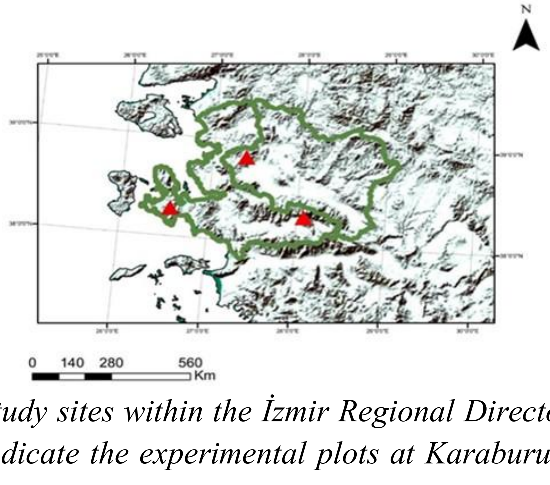


Fig. 1: Location of the study sites within the İzmir Regional Directorate of Forestry, western Türkiye. Red triangles indicate the experimental plots at Karaburun, Ödemiş, and Yuntdağı.

Tab. 1: Site-specific topographic and soil characteristics of the experimental locations.

Study sites	Coordinates	Elevation (m)	Aspect	Slope (%)	Soil			
					Texture	pH	OC (%)	$\mathrm{ECx10^{-3}}$ (mS/cm)
İzmir-Karaburun	38°25'0.40"K 26°31'14.19"D	130	North	9	Clay loam	8,11	1,52	0,03
İzmir-Ödemiş	38°10'16.80"K 28° 7'33.29"D	200	West	21	Sandy clay loam	6,38	0,25	0,027
Manisa-Yuntdağı	38°50'52.68"K 27°24'30.64"D	650	East	6	Clay loam	6,67	1,48	0,048

Before planting, composite soil samples were collected from the 0–20 cm layer at each site. Soil texture was determined according to USDA classification, pH was measured in a 1:2.5 soil–water suspension, electrical conductivity (EC) with a conductivity meter, and organic carbon (OC) using the Walkley–Black method. Climatic conditions were characterized using long-term meteorological records (1938–2024) from nearby stations. Thornthwaite climate diagrams indicated a pronounced water-deficit period from April to mid-October, largely overlapping with the growing season (Fig. 2).

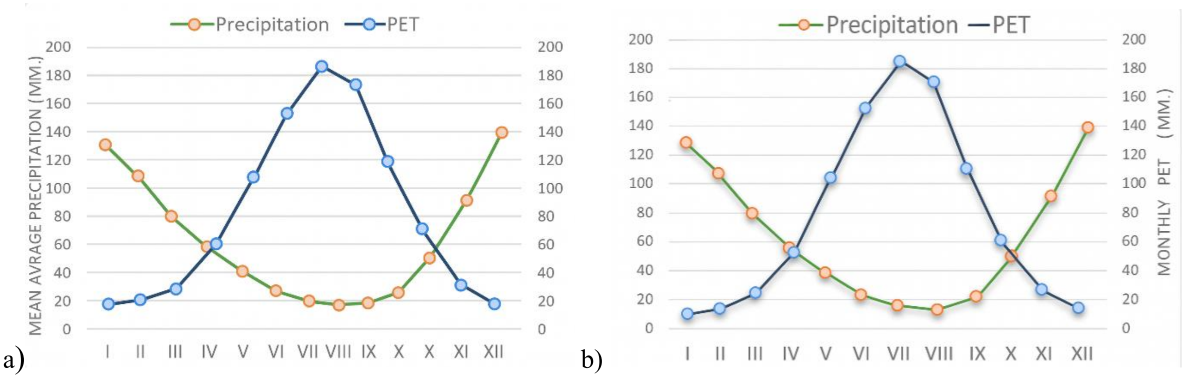
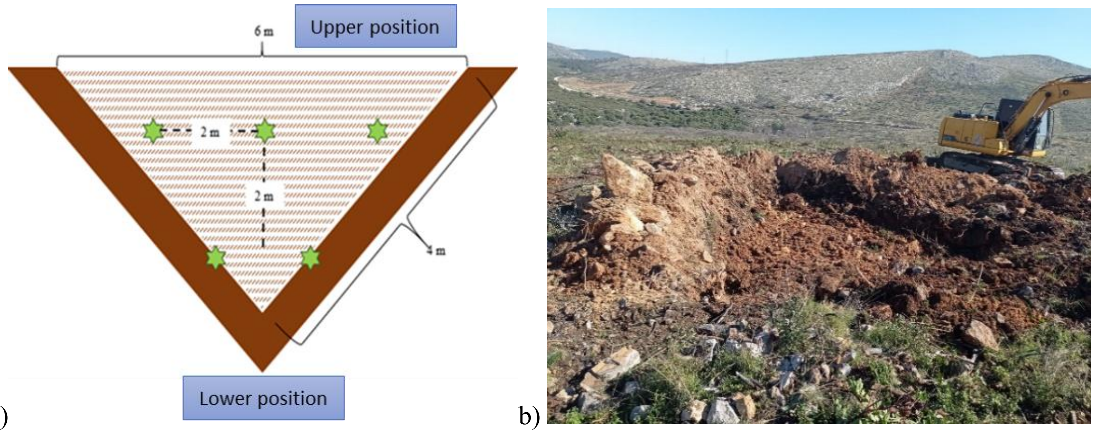


Fig. 2: a) Thornthwaite climate diagram of İzmir, b) Thornthwaite climate diagram of Manisa.

Three-year-old containerized seedlings (3+0) of narrow-leaved ash (*Fraxinus angustifolia* Vahl.) were obtained from the Balıkesir Forest Nursery (Cicek et al. 2007). Seedlings were grown in 1.3 L containers filled with a substrate composed of soil (60%), peat (20%), scoria (10%), and leonardite (10%). At planting in February 2022, mean seedling height and root collar diameter were approximately 131 cm and 13 mm, respectively, and no significant differences were observed among experimental units.

In addition to rainwater-harvesting micro catchments, three plant-supportive treatments were evaluated: *Arbuscular mycorrhizal* inoculation, a superabsorbent polymer, and a foliar Osmo protectant. The mycorrhizal treatment consisted of a commercial *Arbuscular mycorrhizal* inoculum (RhizoMyx®, Novozymes) applied as a root drench at planting following Toprak (2016). The superabsorbent polymer treatment involved application of a straw-based polymer (Natural Aquatic®) at a rate of 50 g per seedling mixed into the planting pit. The Osmo protectant treatment consisted of a glycine betaine-based product (Greenstim®) applied foliarly as a 0.5% solution four times per growing season (June–September) according to Küçük (2013) and Hozman (2016).

The experiment was established using a randomized complete block design (RCBD) with three blocks representing spatial variability in site conditions. For comparison, buror terrace plots representing conventional planting practice were constructed using the same excavation equipment. Within each block, six treatment units were arranged: micro catchment control (C-V), mycorrhiza (M), polymer (P), Osmo protectant (O), polymer + Osmo protectant (PO), and terrace control (C-A). Each treatment unit consisted of 12 V-shaped micro catchments arranged in three rows and four columns, resulting in a total of 180 micro catchments across the experiment, in addition to terrace control plots. Microcatchments were spaced 2 m apart in all directions, with 5 m buffer zones between treatment units. Five seedlings were planted in each micro catchment: two seedlings at the lowest runoff-concentration point (lower position/apex) and three seedlings at the upper position, spaced at 2 m intervals (Fig. 3a–b). In total, 900 Fraxinus angustifolia seedlings were planted in micro catchments and 144 seedlings were planted in terrace control plots.



a) b)

Fig. 3: a) Top-view schematic layout of the V-shaped micro catchment indicating upper and apex (lower) planting positions. b) Field construction of the V-shaped micro catchment.

Volumetric soil water content was measured using time domain reflectometry (TDR). Measurements were taken in the 0–20 cm soil layer at fixed points located approximately 20 cm from the base of each seedling. Within micro catchments, soil moisture was recorded at two topographic positions, namely the lower position (apex) and the upper position (upslope). Measurements were carried out monthly during the dry season (July–September) in each growing season (2022–2024). The same measurement protocol was applied in terrace control plots.

Seedling survival was assessed at the end of each growing season. Root collar diameter (RCD) and shoot height (SH) were measured at planting and after three growing seasons. Relative diameter increment (RDI) and relative height increment (RHI) were calculated following Hunt (1990):

$$\mathrm{RDI}=\frac{\ln(\mathrm{RCD}_2)-\ln(\mathrm{RCD}_1)}{t} \quad (1)$$

$$\mathrm{RHI}=\frac{\ln(SH_2)-\ln(SH_1)}{t} \quad (2)$$

where: RCD_1 and SH_1 are root collar diameter (mm) and shoot height (cm) at planting, RCD_2 and SH_2 are the corresponding values at the end of the third growing season, and t is the time between measurements (years).

Data were analysed according to the randomised complete block design representing site-level differences in climatic water deficit. Treatment effects on growth and soil moisture were evaluated by ANOVA. Normality and homogeneity of variances were tested using the Shapiro–Wilk and Levene tests, respectively, and data were log-transformed when necessary. For soil moisture, ANOVAs were conducted separately for each sampling month and topographic position (lower vs. upper). When treatment effects were significant, means were compared using Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$. All analyses were performed using SAS software (SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Survival rates

At the end of the first growing season, seedling survival did not differ significantly among treatments ($p > 0.05$), with an overall mean of approximately 63% (Fig. 4). From the second growing season onward, treatment effects became significant ($p = 0.0377$) and were primarily driven by the contrast between micro catchment-based planting and conventional terracing.

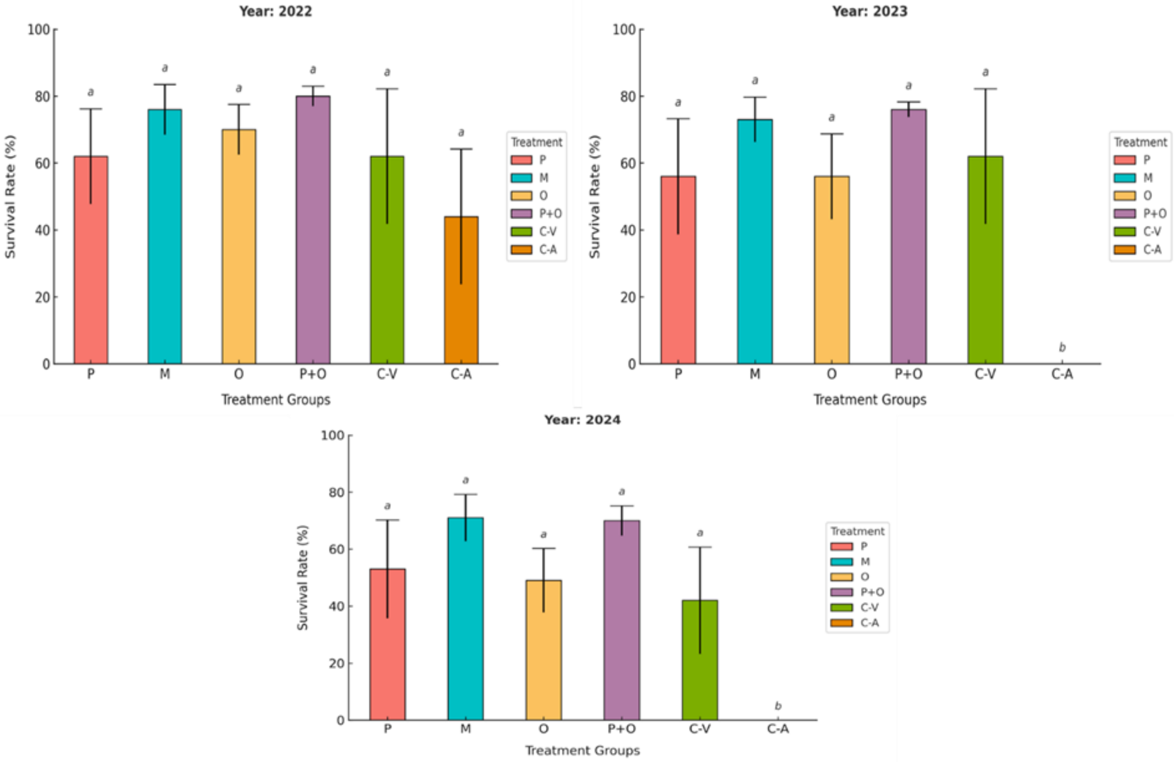


Fig. 4: Survival (%) of narrow-leaved ash (Fraxinus angustifolia Vahl.) seedlings during the 2022–2024 growing seasons (means ± SE). Bars sharing the same letter do not differ significantly (α = 0.05, Tukey's HSD). Treatments: control under conventional planting (C-A), micro catchment without additional treatment (C-V), micro catchment with mycorrhiza (M), polymer (P), Osmo protectant (O) and polymer + Osmo protectant (PO).

All seedlings in the conventional terrace control (c-a) died by the second growing season, indicating complete plantation failure under this method. In contrast, seedlings planted in V-shaped micro catchments maintained survival of 65% in the second season and 57% by the end of the third season (Fig. 4). Overall, micro catchment-based rainwater harvesting prevented the total mortality observed under conventional planting over the three-year period.

Seedling survival differed markedly among planting methods over the three-year study period. Although no significant differences were detected during the first growing season, clear divergence emerged thereafter. Seedlings established on buror terraces declined rapidly and reached complete mortality by the second growing season, indicating plantation failure under prolonged summer drought. In contrast, micro catchment-based treatments-maintained survival above 55% after three growing seasons, demonstrating substantially greater resilience under semi-arid Mediterranean conditions.

Comparable trends were reported by Aydın et al. (2025), who found that rainwater-harvesting systems particularly Negarim micro catchments significantly improved seedling survival relative to buror terrace and pit planting. In their study, survival of Quercus cerris increased by more than 50% compared with conventional methods, while Pinus pinea seedlings in Negarim systems showed survival approximately one-third higher than buror terraces and nearly twofold greater than pit planting.

While their results reflected first-year responses, the present study demonstrates that the hydrological advantage of micro catchments can persist over multiple growing seasons. The contrast between sustained survival above 55% in V-shaped micro catchments and complete mortality in buror terraces underscores root-zone water availability as the primary constraint governing early plantation success under recurrent summer drought. Similar survival benefits of water-harvesting structures have been documented across drought-prone regions (Critchley and Siegert 1991; Lancaster 2019; Bayen et al. 2016).

Relative diameter growth and relative height growth

Relative diameter increment (RDI) differed significantly among treatments ($p < 0.0001$; Fig. 5). In the first growing season, the micro catchment control (C-V) exhibited the highest RDI, with mean values approximately three times greater than the average of the other treatments. By the second season, all micro catchment-based treatments clearly outperformed the conventional terrace control (C-A), where complete mortality had already occurred, and C-V remained significantly higher than the amended micro catchment treatments except polymer (P). By the third growing season, polymer (P) produced the highest RDI, with relative diameter growth 40% greater than that of the other micro catchment treatments (Fig. 5), indicating a strong benefit of combining in-situ rainwater harvesting with a water-retaining amendment under persistent drought.

Relative height increment (RHI) did not differ significantly among treatments during the first growing season; however, from the second season onward, differences became highly significant ($p < 0.0001$; Fig. 6). All microcatchment-based treatments exhibited higher RHI than the conventional terrace control (C-A), consistent with the complete mortality observed in C-A. By the end of the third season, the microcatchment control (C-V) showed the greatest height response among microcatchment treatments, with mean RHI approximately 2.3 times higher than the mean of the amended microcatchment treatments (Fig. 6). This suggests that, for height growth, the microcatchment structure alone provided a highly favourable microsite, even when additional amendments were applied in other treatments.

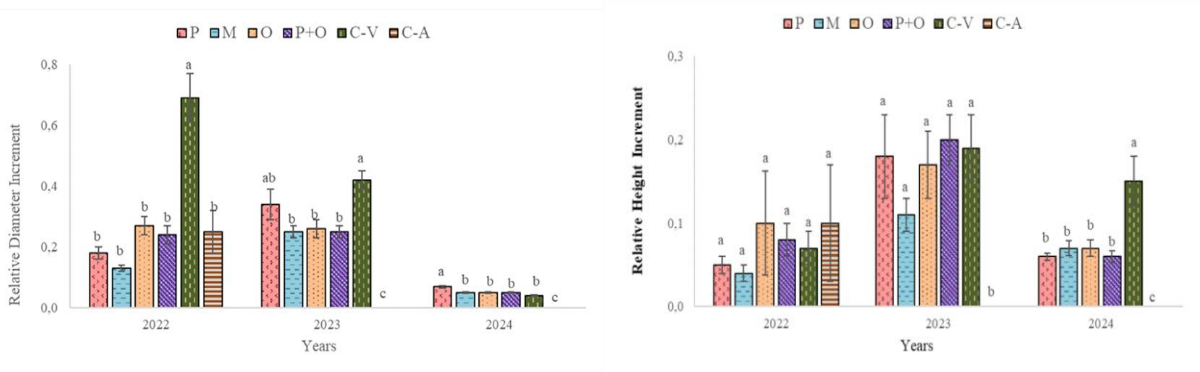


Fig. 5: Relative diameter increment (RDI) and relative height increment (RHI) of narrow-leaved ash (Fraxinus angustifolia Vahl.) seedlings at the end of each growing season (means ± SE). Bars sharing the same letter do not differ significantly (α = 0.05, Tukey's HSD). Treatments: control under conventional planting (C-A), microcatchment without additional treatment (C-V), microcatchment with mycorrhiza (M), polymer (P), Osmo protectant (O) and polymer + Osmo protectant (PO).

Seedling growth responses further highlighted the advantages of microcatchment-based planting. Seedlings established within micro catchments showed greater stem diameter and height increments than those on buror terraces, where growth ceased following complete mortality. Similar quantitative patterns were reported by Aydın et al. (2025), who found that *Quercus cerris* seedlings in Negarim micro catchments exhibited 51% greater diameter increment than those on buror terraces and 93% greater increment than pit planting, with height increment increasing by 44% and 54%, respectively. *Pinus pinea* likewise showed the highest diameter growth under Negarim systems. These findings corroborate that runoff concentration at the microsite scale enhances structural growth beyond improving survival alone.

Among the amendments, the superabsorbent polymer produced the strongest diameter response, consistent with previous reports of improved growth under water-retaining materials in water-limited environments (Olguín-Hernández et al. 2023; Hasan et al. 2024). Mycorrhizal inoculation and Osmo protectant treatments also supported growth, reflecting enhanced water acquisition and physiological buffering under drought (Smith and Read 2010; Wang et al. 2019; Navarro and Morte 2024; Kumari et al. 2015). Overall, sustained root-zone moisture under microcatchment conditions appears to promote early biomass accumulation and stand development in semi-arid Mediterranean environments.

Soil moisture

Across all three years (2022–2024), volumetric soil water content differed significantly among treatments at both the lower (apex/outlet) and upper (upslope) positions within V-shaped micro catchments ($p < 0.05$; Tabs. 3–5). To reflect the sampling design, analyses were conducted separately by year, sampling month (July–September), and microtopographic position. In 2022, soil moisture was generally higher at the lower position than at the upper position, indicating downslope concentration of water within the micro catchments. The microcatchment control (C-V) consistently showed the highest soil moisture at both positions, whereas the conventional terrace control (C-A) showed the lowest values across months (Tab. 2). Treatments receiving mycorrhiza, polymer, Osmo protectant, or polymer + Osmo protectant typically showed intermediate values and frequently overlapped in significance groups.

Tab. 2: Soil moisture (%) at upper and lower positions in V-shaped micro catchments (2022).

Treatment	July Upper	July Lower	August Upper	August Lower	September Upper	September Lower
P	2.47±0.8 bc	1.85±0.65 ab	1±0.73 b	1.32±0.86 b	4.52±0.88 bc	3.05±0.83 b
M	3.61±1.12 ab	3.28±0.98 ab	2.52±1.27 ab	2.63±1.31 ab	5.42±1.34 ab	4.66±1.27 ab
O	3.49±0.95 abc	2.98±0.97 ab	2.43±1.23 ab	1.88±1.07 ab	5.67±1.14 ab	4.74±1.18 ab
P+O	3.27±1.01 bc	2.3±0.84 ab	2.39±1.29 ab	2±1.08 ab	5.01±1.27 b	3.57±1.15 b
C-V	5.08±1.48 a	5.2±1.57 a	3.76±1.9 a	3.96±1.98 a	6.96±1.71 a	6.71±1.86 a
C-A	1.75±0.27 c	1.56±0.3 b	1.22±0.4 b	1.22±0.4 b	2.83±0.41 c	2.83±0.41 b

Note: Values are means ± SE. Different lowercase letters indicate significant differences among treatments within the same month and position (Tukey's HSD, $p < 0.05$).

In 2023, a similar pattern was observed. Soil moisture tended to remain higher at the lower position, and C-V again produced the highest values at both positions, while C-A consistently remained the driest treatment (Tab. 3). Soil moisture generally increased towards September without changing the overall ranking among treatments.

Tab. 3: Soil moisture (%) at upper and lower positions in V-shaped micro catchments (2023).

Treatment	July Upper	July Lower	August Upper	August Lower	September Upper	September Lower
P	5.4±0.4 a	3.8±0.4 a	5.7±0.6 a	4.8±0.6 a	8.9±0.9 bc	5.8±0.8 bc
M	5.5±0.6 a	3.3±0.6 ab	6.1±1.2 a	4.5±1.0 a	9.8±1.3 ab	7.8±1.2 ab
O	5.5±0.7 a	4.0±0.7 a	5.9±1.1 a	5.5±1.2 a	10.1±1.1 ab	7.5±1.2 bc
P+O	5.6±0.8 a	4.2±0.7 a	5.9±1.0 a	5.3±1.0 a	9.4±1.3 b	6.8±1.0 bc
C-V	6.8±1.3 a	4.2±1.3 a	7.1±1.7 a	5.0±1.4 a	11.4±1.7 a	9.5±1.9 a
C-A	3.0±0.2 b	2.1±0.3 b	3.0±0.4 b	2.1±0.2 b	7.2±0.4 c	5.5±0.5 c

Note: Values are means ± SE. Different lowercase letters indicate significant differences among treatments within the same month and position (Tukey's HSD, $p < 0.05$).

In 2024, treatment differences were again significant and followed the same hierarchy as in previous years. Across sampling months and positions, soil moisture remained higher in micro catchments than in the conventional terrace control, and the lower position remained wetter than the upper position (Tab. 4). The consistent multi-year separation between C-V and C-A confirms that V-shaped micro catchments effectively concentrate and retain soil water during the dry season under the study conditions.

Soil moisture dynamics provide a clear explanation for the observed treatment differences. Across all three growing seasons, volumetric soil water content within micro catchments remained consistently higher than in buror terrace plots, particularly during peak summer drought. Comparable hydrological advantages of rainwater-harvesting systems have been documented in semi-arid environments (Ma et al. 2024; Rojano-Cruz et al. 2023). Aydın et al.

(2025) further reported that mean growing-season soil moisture in Negarim micro catchments exceeded that of buror terraces by 31% and pit planting by 65%, with this ranking maintained throughout the dry season.

Tab. 4: Soil moisture (%) at upper and lower positions in V-shaped micro catchments (2024).

Treatment	July Upper	July Lower	August Upper	August Lower	September Upper	September Lower
P	3,83±0,42b	2,49±0,42b	4,54±0,59a	3,32±0,43a	5,74±0,74b	3,63±0,53b
M	3,98±0,63ab	2,65±0,64ab	4,93±1,16a	3,81±0,95a	6,64±1,11ab	4,28±0,97ab
O	4,01±0,65ab	2,67±0,66ab	4,7±1,13a	3,49±0,93a	6,89±0,90ab	4,59±0,74ab
P+O	4,11±0,77ab	2,83±0,75ab	4,74±1,02a	3,52±0,87a	6,22±1,03b	3,97±0,84b
C-V	5,3±1,25a	4,01±1,23a	5,3±1,16a	4,08±0,95a	8,17±1,46a	5,88±1,27a
C-A	1,65±0,14c	0,67±0,09c	2,09±0,31b	0,84±0,19b	3,83±0,25c	1,53±0,19c

In the present study, higher moisture levels at the lower (apex) position of V-shaped micro catchments confirm effective runoff concentration and enhanced root-zone infiltration. These findings demonstrate that structural rainwater-harvesting systems create sustained soil moisture advantages that translate into improved early establishment and growth under semi-arid Mediterranean conditions.

By contrast, Çerçioğlu et al. (2025) observed that although wood-based mulching increased soil organic matter under similar regional conditions, short-term gains in volumetric soil moisture were not significant, indicating that surface amendments alone may provide more limited hydrological benefits than structural runoff-concentrating designs.

Beyond early establishment, successful survival and growth of *Fraxinus angustifolia* in marginal semi-arid sites also carry long-term silvicultural implications. As a mechanically valuable hardwood species with compressive strength values exceeding 50 N/mm² (Çota et al. 2025), ensuring its establishment under drought-prone conditions supports not only ecological rehabilitation but also future structural and economic potential.

CONCLUSIONS

This three-year field experiment demonstrates that plantation success under semi-arid Mediterranean conditions is primarily constrained by root-zone water availability during the summer drought period. Complete mortality observed in buror terrace plots by the second growing season contrasts sharply with the sustained survival recorded in V-shaped micro catchments, where survival declined from approximately 63% in the first year to above 55% after three growing seasons. These findings indicate that conventional site preparation methods may be insufficient under recurrent drought stress, whereas microcatchment-based rainwater harvesting provides a stabilizing hydrological advantage that enhances long-term establishment success.

Volumetric soil water content remained consistently higher within micro catchments throughout the monitoring period, particularly during peak summer drought, and was directly associated with superior relative diameter and height growth. The greatest diameter increment was observed under superabsorbent polymer application, suggesting that integrating structural rainwater harvesting with water-retentive soil amendments can further stimulate cambial activity and early biomass accumulation. Collectively, the results quantitatively confirm the causal linkage between soil moisture availability, seedling survival, and early growth performance under water-limited conditions.

Increasing drought frequency and intensity under climate change are already reducing afforestation success rates in semi-arid landscapes, leading to higher rehabilitation demands and potential losses in future wood production. In this context, microcatchment-based rainwater harvesting represents a practical, scalable, and structurally effective microsite water-management strategy for improving early plantation performance of hardwood species. The integration of such structural water-conserving approaches will be critical for sustaining afforestation and rehabilitation efforts under projected climatic aridity.

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