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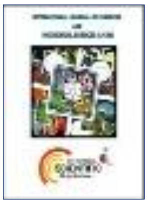

Effect of superabsorbent polymers on the growth and survival of young cork oak plantations in Morocco

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Abstract

Water availability is often the limiting factor for forest regeneration in Morocco. Among the approaches undertaken to mitigate the effects of aridity, thus promoting plant growth is the use of superabsorbent polymers (SAP). While widely used in agriculture, their application in forestry remains limited. Thus, the objective of this study was to evaluate the effect of Stockosorb®500 on the growth and survival of cork oak plantations in the Maamora forest in Morocco. An experiment plot in which two irrigation regimes (normal and limited) were imposed was set up in 2008 for cork oak regeneration. Three treatments consisting of control (T0), 50 g (T1), and 100 g (T2) doses of Stockosorb®500 were implemented on a total of 3600 plants, with periodic inventory to measure their growth parameters. The results showed a greater soil water holding capacity in the amended plots, with up to 96% of the soil water content recorded at a depth of 60 cm in the T2 plots. While the effect of the polymer was unnoticeable in the first year, plant growth was strongly influenced, especially under limited irrigation in subsequent years until 2014. Despite differences in watering frequency, the polymer treatment resulted in nearly identical cork oak growth at the end of the study. Plant survival was not affected by the polymer, although mortality primarily associated with white grub attack was observed. Our results highlight the potential of SAPs to reduce irrigation costs while facilitating forest regeneration, particularly in areas with limited water resources.

Keywords: Plant survival, *Quercus suber*, superabsorbent polymer, water stress

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1. Introduction

Water availability is a major determinant of forest structure and composition in the driest regions of the world, where drought events can have severe impacts on forest dynamics [1]. Forest ecosystems there undergo significant transformation under the combined effects of longstanding human influence and climate change, resulting in soils marked by nutrient deficiency and water scarcity ([2] ; [3]; [4]). The poor soil structure and low organic matter associated with these water-scarce environments directly leads to a reduction in the water-holding capacity of the soil, which impacts vegetative cover and can lead to increased risks of greenhouse gas emissions (5].

In recent decades, the Mediterranean climate has been shaped by increasing temperatures and declining annual precipitation. Current climate projections indicate that this phenomenon of aridification is expected to increase during the 21st century, which could exacerbate existing pressures on water resources and pose a particular threat to forest ecosystems ([6] ; [7] ; [8]). In Morocco, a country that has experienced an average temperature increase of about 0.42°C every decade since the 1960s and a decrease in precipitation of more than 20%, future projections indicate that the aridification trend will continue ([9] ; [10] ; [11]). Indeed, water scarcity will accelerate forest degradation, given its documented character as the main limiting resource for vegetation growth ([12] ; [13]). Among the species expected to be affected is the cork oak (*Quercus suber* L.).

Cork oak forests represent one of the most important ecosystems in Morocco due of their multiple socio-economic and environmental roles. However, their ecosystems have been deteriorating for several decades, notably due to overexploitation through illegal logging, cork harvesting, acorn collection, and overgrazing [14]. Moreover, the natural regeneration of the species is highly uncommon on account of human and environmental factors, requiring intervention through reforestation efforts. However, plantations often fail to meet the goals of reforestation programs due to inappropriate reforestation site preparation techniques and poor morpho-physiological quality of nursery seedlings ([15] ; [16]).

The success of afforestation and reforestation activities depends on the selection of the ideal species for each site, as well as the adoption of appropriate planting strategies and techniques. Seedlings must not only withstand adverse site conditions, but also be able to develop and improve their growth potential ([17] ; [18] ; [19]). Thus, proper planting programs create a demand for the development of technologies involving reduced nursery production costs and good plant performance in the field ([20] ; [21]). One technique that has been increasingly adopted in the cultivation and production of forest seedlings is the use of superabsorbent polymers (SAPs).

SAPs are hydrophilic substances that are capable of absorbing a large volume of water between their macromolecular chains, typically between one hundred and one thousand times their own weight across an osmotic potential gradient between the inside and outside of their membrane [22]. As a consequence, they have been used to promote plant growth in arid soils. Indeed, their application has been shown to improve plant survival by enhancing water use efficiency, nutrient uptake and dry matter production under these harsh drought conditions [23]. This characteristic has led to their use especially in horticulture and agriculture. In forestry, several authors postulate their ability to counteract conditions of low precipitation, high evapotranspiration demand, and low soil water holding capacity, thus facilitating the establishment of forest species following planting ([21] ; [24]). Under dry conditions, SAPs increase water use efficiency, especially in soils with low clay content, due to their repeated uptake of soil water and slow release to plants while reducing edaphic aridity-related plant damage ([25] ; [26] ; [27]).

Studies on the effects of SAPs on the growth and consequently the survival of Moroccan forest species are scarce. Therefore, the main objective of this study is to evaluate the effect of these hygroscopic polymers on the success and growth of oak plantations in the Maamora forest, Morocco. Specifically, the work consisted of: (i) characterizing the experiment site and studying the physical and chemical elements of the soil; (ii) analyzing the effect of two doses (50 g and 100 g) of Stockosorb®500 on the growth parameters of young cork-oak plants under two irrigation regimes; and (iii) evaluating the rate of plant growth between 2009 and 2014.

2. Materials and Methods

2.1. Study area

The Maamora forest is located between 6° and 6° 45' West and 34° and 34° 20' North in Morocco, extending between the cities of Rabat and Kenitra over an area of approximately 132000 ha. The characteristic climate is sub-humid with warm winters in the west and semi-arid with temperate winters in the central and eastern regions of the forest. Mean annual precipitation ranges from 350 to 650 mm and is characterized by a decreasing gradient from west to east of up to 100 mm/year ([28]; [29]), with the wettest months being November and December while the driest are July and August. Mean monthly temperatures range from 12°C (January) to 25°C (July-August), while the maximum and minimum of the coolest and warmest months are 3.5°C and 37°C respectively. Summer drought across the forest often lasts more than two months ([28]; [30]). Geologically, the Maamora forest is composed of a layer of marl and clay from the Miocene, and sand and sandstone from the Pliocene over which lies deposits of the Maamora red clay [31]. The characteristic of the soils is a sandy cover resting on an ancient sandy-clay layer [32] whose horizons are marked by traces of hydromorphy. The dominant plant cover is cork oak, which extends over more than 60,000 ha and is notable for the predominance of low density stands [33]. Significant areas of the forest are made up of forested stands that are mostly composed of eucalyptus, pine, acacia.

2.2. Plant material and SAP

Cork oak seedlings and acorns were obtained from the Centre de Recherche Forestière (Rabat, Morocco). The choice of species was based on its socio-economic and ecological importance, as well as on the state of degradation of current cork oak stands in the forest. The SAP used in this study was Stockosorb®500 in granular form. This hydrophilic hydrogel consists of cross-linked potassium acrylate-polyacrylamide copolymers [22] with an effect lasting several years. Stockosorb®500 is manufactured by Evonik Industries (Germany) and has the ability to retain water in an amount greater than 100 times its volume, thus improving soil structure and preventing it from becoming too wet.

2.3. Characterization of the experiment plot

The characterization of the properties of the experiment site was done based on the physical and chemical elements of the soil. Accordingly, it included the following: (i) analysis of the position/depth of the clay layer using a soil auger; (ii) determination of soil moisture using the gravimetric method; (iii) analysis of soil pH using a pH meter; (iv) analysis of soil carbon using the Walkley-Black method [34] ; and (v) determination of soil calcium content.

2.4. Experiment design

The experiment plot was divided into 2 blocks distinguished by two irrigation regimes. Block 1 was subjected to the normal irrigation treatment, which is based on the recommendations of the Forest Service and includes two waterings of 10 liters each at the time of planting and two more of the same volume during the first summer. In contrast, block 2 was subjected to the treatment involving limited irrigation. This treatment, although identical to the normal irrigation at planting, differs in that only one 10-liter watering is done during the summer. Furthermore, three polymer treatments were implemented as follows: control with no polymer treatment (T0), and Stockosorb®500 at doses of 50 g per plant (T1) and 100 g per plant (T2). These treatments were applied in 3 replications of elementary plots containing 100 plants per plot (Table 1) for a total of 3600 plants.

2.5. Soil preparation and planting

Soil preparation work depends on environmental factors including topography, soil type and depth, rainfall, etc. In this research, where the study area is largely in the plain, three techniques were adopted including: (i) full tillage consisting of clearing, cleaning and deep tillage of 30 to 35 cm; (ii) strip tillage, which involves the same activities as in (i), but in 3 m strips separated by 2 m strips that are not tilled;

and (iii) opening of 0.5×0.5×0.5 m planting holes. Subsequently, planting of the seedlings (2.1 ha) and/or acorns (2.1 ha) was done and consisted of the following: (i) uniform mixing and incorporation of the recommended SAP dose at the bottom of the planting hole; (ii) backfilling of the planting holes and covering the surface with soil (no SAP in the top 5 cm); (iii) planting of the seedling or acorn followed by watering immediately after planting, as well as the following day.

2.6. Evaluation of plant survival and growth rate

Plant growth parameters, including height and circumference, were measured during the study period to determine the growth rate of cork oak under the different treatments. These measurements were taken monthly in the first year and then annually in subsequent years until the end of the study in 2014. Similarly, the rate of plant dieback and mortality was recorded at this frequency.

2.7. Statistical analysis

One-way analysis of variance (ANOVA) was used to investigate the effect of Stockosorb®500 on the survival and growth of cork oak after field plantation. The significant level for statistical analyses was set at $p < 0.05$. All analyses were performed using statistical software.

3. Result

3.1. Description of the physical and chemical elements of the experiment plot

3.1.1. Clay layer

The variation in the position of the clay layer after installation of the experiment plot is shown in Figure 1. In general, it was located between 1.3 m and 1.7 m below the soil surface, with the lowest depths observed in areas that received 50 g of Stockosorb®500 (T1), especially under limited irrigation. On average, the clay layer under normal irrigation in all treatments was no deeper than 1.5 m below the soil surface. On the other hand, under limited irrigation, it was located between the depths of 1.59 m and 1.65 m, observed for the T2 and control treatments, respectively.

3.1.2. Soil moisture

The evolution of soil moisture three months after setting up the experiment in the field is presented in Table 2 and illustrated in Figure 1. By far the highest rates were observed in areas with the application of 100 g (T2) of Stockosorb®500. In fact, up to 96% of the soil moisture content was recorded in samples taken at a depth of 60 cm under this treatment, highlighting increased water retention with increasing polymer content. In general, under treatments T1 and T2, the highest moisture contents were recorded in samples taken at a depth of 20 cm, which has been shown to favor growth of young cork oak. Conversely, the highest rates in the control group were recorded at 1 m below the soil surface, which may be a potential limiting factor for young plant growth in an area dominated by sandy soils.

3.1.3. Soil chemical properties

The results of sample analysis of selected soil chemical properties from the experiment plot are presented in Table 3. For the most part, there was little variation in soil pH with depth. Indeed, with the exception of two (2 and 3) samples taken at the surface where the pH was recorded below 6, it varied between 6.30 and 6.74 from a soil depth of 20 cm to 1 m. This is in the near-neutral range which is characteristic of the forest and has been shown to promote nutrient uptake, thus favoring growth of cork oak. Beyond this range, it has been shown that mineral deficiencies occur, which is detrimental particularly to young plants (Comtois & Légaré, 2004). Soil carbon, which is the primary component of organic matter in the soil, decreases with increasing depth. Indeed, the highest contents were observed at the surface level, ranging from 0.34% to 0.80%, while the lowest were observed at the 1 m depth, where organic matter was as low as 0.07%. Overall, soil carbon was less than 1%, reflecting the poor organic content nature of the experiment plot. Consistent with soil carbon, calcium decreased with depth, ranging on average from 300 meq/100 g at 1 m below ground to 419 meq/100 g at the surface level.

3.2. Effect of Stockosorb®500 on plantation success

The influence of soil amendment with Stockosorb®500 on cork oak growth and survival in the first year was mostly statistically insignificant (Table 5). Nevertheless, the growth of plants resulting from seedlings (as opposed to acorns) was strongly influenced ($p < .01$) by the SAP treatments. Moreover, higher plantation success rates were observed under normal irrigation (Block 1), ranging from 68% to 78.33% (Table 6). Under both irrigation regimes, the treatment with 50 g of SAP resulted in the highest success rates. Consistent with planting success rates, height growth was highest under normal irrigation, with the control treatment resulting in the greatest growth at 51.88 cm. Conversely, under limited irrigation, plants in the control treatment showed the lowest height growth (33.52 cm).

3.3. Evaluation of the growth rate after one year after plantation

The results of the one-way ANOVA to investigate the effect of Stockosorb®500 on the growth of cork oak from 2009 to the end of the study period are presented in Table 7.

Table 1: Design of the experiment representing each irrigation regime (block 1 and block 2)

Replications		
T0	T1	T2
T1	T2	T0
T2	T0	T1

Table 2: Soil moisture (%) by depth in the experiment plot

	T0			T1			T2		
Soil depth (cm)	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
0	3.45	0.80	0.45	0.35	2.20	0.50	10.62	2.97	0.31
20	6.07	4.44	4.50	13.27	4.50	13.66	31.45	73.40	4.90
60	5.92	5.41	6.60	7.97	5.30	6.80	7.58	25.80	96.00
100	9.45	7.00	7.50	12.02	9.02	9.43	13.16	16.90	6.18

Table 3: Chemical properties of the experiment plot by soil depth

Soil depth (cm)	1	2	3	4
		pH		
0	6.70	5.92	5.84	6.28
20	6.40	6.30	6.38	6.48
60	6.30	6.43	6.32	6.58
100	6.40	6.56	6.74	6.58
		Carbon (%)		
0	0.34	0.80	0.70	0.73
20	0.24	0.50	0.47	0.72
60	0.09	0.23	0.35	0.41
100	0.07	0.09	0.18	0.24
		Calcium (meq/100 g)		
0	350	500	450	375
20	300	425	400	325
60	250	400	375	325
100	250	325	325	300

Table 4: Mortality of young cork-oak after plantation

Treatment	Replication	Pest attack	Desiccation
T0	R1	18	10
	R2	10	5
	R3	15	10
T1	R1	22	11
	R2	5	6
	R3	30	4
T2	R1	24	7
	R2	12	3
	R3	15	7

Table 5: Effect of Stockosorb®500 on cork oak one year after plantation

Plantation type		**F**	**p-value**
Seedlings	Growth (height)	5.766	.003**
	Success rate	0.409	.682
Direct seeding	Growth (height)	0.394	.675
	Success rate	0.837	.478

** indicates significant effects at $p < .01$

Table 6: Cork oak growth and success rate after one year of plantation

Irrigation regime	**Treatment**	**Success rate (%)**	**Height growth (cm)**
Normal	T0	71.83	51.88
	T1	78.33	44.70
	T2	68.00	45.32
Limited	T0	47.42	33.52
	T1	56.33	36.57
	T2	55.33	35.00

Table 7: Effect of Stockosorb®500 on cork oak growth between 2009 and 2014

Irrigation regime	**Period**	**F**	**p-value**
Normal	2009 - 2010	5.575	.004**
	2010 - 2011	1.250	.287
	2011 - 2012	1.448	.236
	2012 - 2014	1.631	.197
Limited	2009 - 2010	0.337	.715
	2010 - 2011	5.393	.005**
	2011 - 2012	7.958	.000***
	2012 - 2014	4.883	.005**

** and *** indicate significant effects at $p < 0.01$, and $p < 0.001$, respectively

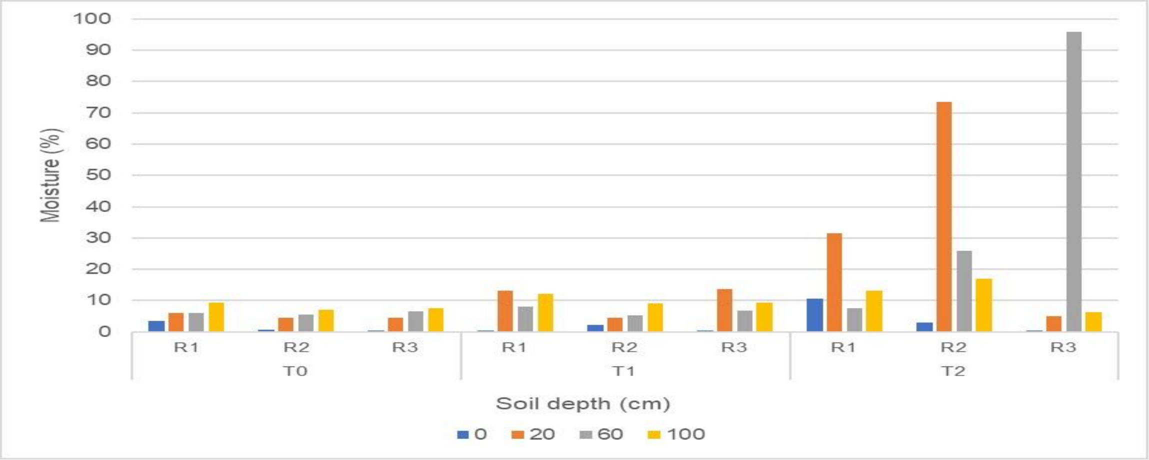

Figure 1: Soil moisture content by depth in the experiment plot under different Stockosorb®500 treatments

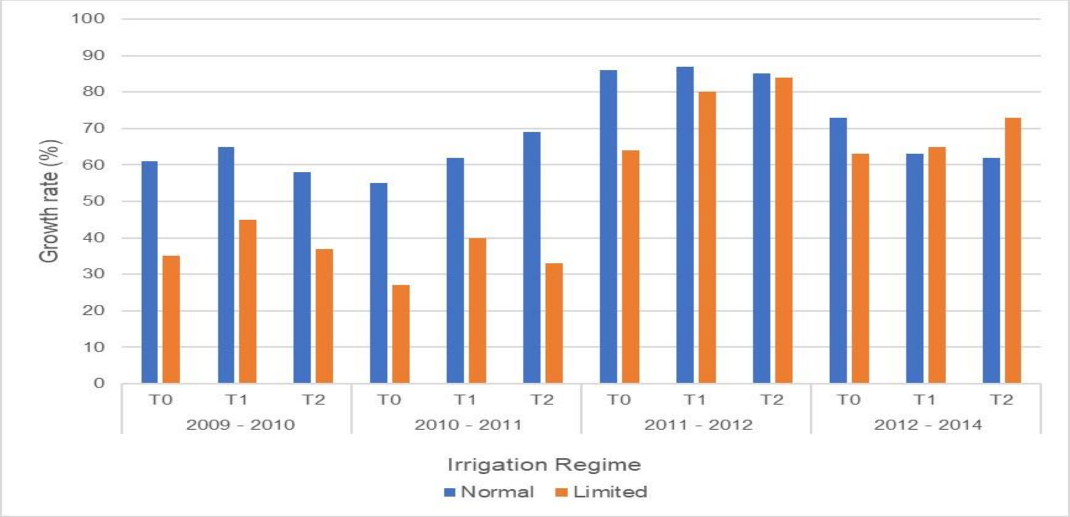

Figure 2: Growth rate of cork oak under different irrigation and Stockosorb®500 treatments between 2009 and 2014

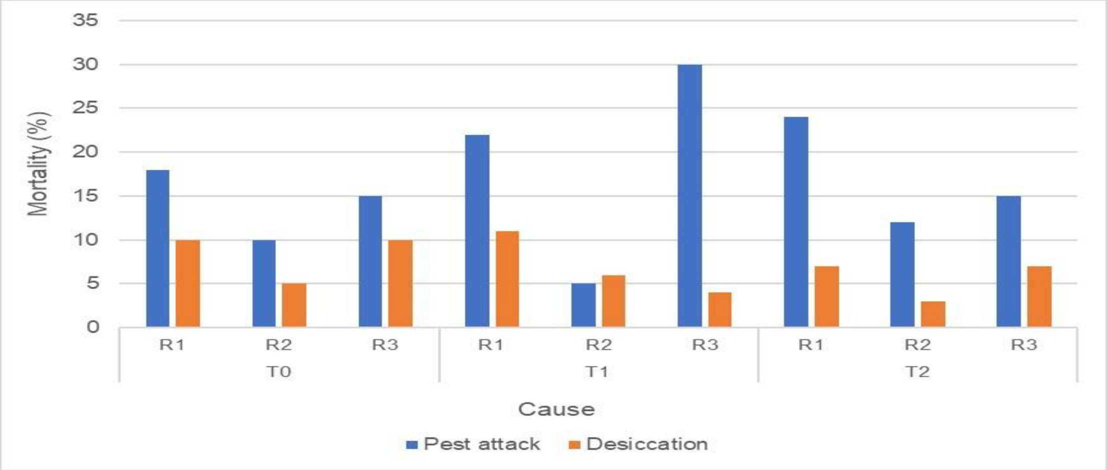

Figure 3: Plant mortality due to pest attack and desiccation under different Stockosorb®500 treatments

The immediate observation is that the polymer strongly influenced growth considerably under limited irrigation compared to normal watering. Indeed, under the normal regime, it appeared to have a significant impact on the growth of cork oak saplings only at the beginning of the study period, which decreased over time, in subsequent years. On the other hand, with the exception of the 2009-2010 period, Stockosorb®500 exhibited a highly significant effect ($p < .01$) on cork oak growth under limited irrigation. The greatest influence ($p < .001$) of the product was observed in the 2011-12 period, as shown by the highest growth rates during the study period (Figure 2). Cork oak growth, particularly for plants under limited irrigation, was slowest in the first half of the study period, one year after planting. In addition, plants in the control treatment units exhibited significantly lower growth rates under limited irrigation compared to plants under normal watering, with twice as high rates observed during 2010-2011. During this period, plants under the 50 g Stockosorb®500 treatment (T1) performed better than plants in units receiving twice the amount (T2) of the polymer. However, in the second half of the study period, the effect of the polymeric amendment was clear, with the highest growth rates under both irrigation regimes observed during 2011-2012. Indeed, plants in the T1 and T2 units exhibited growth rates of up to 80% and 84%, respectively, under limited irrigation, which were only slightly lower (T1) to almost equal (T2) to their corresponding units under normal irrigation. By the end of the study period in 2014, plant growth in the amended units was greater under limited irrigation than in the units under normal irrigation. This was particularly notable for units with the 100 g dose of Stockosorb®500 treatment, where cork oak growth was recorded at 73% under limited irrigation versus 62% under the normal regime.

3.4. *Cork oak mortality*

Figure 3 show the mortality of cork oak seedlings after planting. White grub (*Sphodroxia maroccana*) attacks contributed the most damage, observed mainly in late winter and spring due to heavy rainfall. Indeed, the results of the inventories carried out after the summer period showed that the highest mortality rates of young cork oak plantations reached 30% due to grubs, while desiccation did not contribute to more than 11%. Occasional damage from the pest was also observed in summer when plants were overwatered, which has been shown to promote the emergence of the insect's larvae [35]. On average, the highest mortality rates due to white grub attacks were recorded in the amended T1 and T2 plots at 19% and 17%, respectively, highlighting the influence of increased soil moisture content in providing favorable conditions for pest infestation.

4. Discussion

In Morocco, due to the scarcity and concentration of rainfall at certain times of the year, together with high evaporation rates results in insufficient and irregular supply of water to forest ecosystems. This hinders the regeneration of species, especially in arid and semi-arid regions. Therefore, it is imperative to adopt proper water conservation methods and improve water efficiency as they are essential for plant establishment. In this study, water conservation techniques based on the application of SAP during planting of cork oak seedlings and seeds were used.

In this study, initial observations of the influence of Stockosorb®500 on cork oak growth showed generally insignificant effects under limited irrigation. The minimal effect of SAP was attributed to the unusually wet period in the first year, which would have mitigated the effects of reduced summer watering. However, the effect of the polymer was evident in subsequent years until the end of the study, with the highest growth rates observed in the amended plots. Indeed, plants under limited irrigation were about as productive as plants receiving normal irrigation. This implication is significant in semi-arid and arid Moroccan ecosystems in its potential to reducing irrigation costs in the early establishment of forest species. The effect of Stockosorb, a hygroscopic polymer, in promoting plant growth in water-deficient environments is well documented. Defaa et al. [36] in their study in southern Morocco under arid conditions observed a significant improvement in morphological traits of seedlings despite reducing the watering frequency by half. Similarly, Chebab et al. [37] showed that water content was generally higher in the amended soil, where olive plants with the Stockosorb treatment had the highest water status, higher growth and limited stress. In China, Shao et al. [39] observed better growth of poplar in Stockosorb amended soils. This was attributed not only to improved water availability for plants, but also to water quality due to reduced salt levels associated with their buffering capacity. This capacity is particularly important in arid soils, which are often marked by high salinity levels that inhibit nutrient uptake and increase water loss leading to plant desiccation [40].

Our results showed that Stockosorb®500 had no effect on the survival ability of cork oak seedlings during the study period. This is consistent with the observations of Defaa et al. [36] where the same polymer had no effect on the observed survival rates of argan. However, this is not always the case as shown by Chirino et al. [41] who observed an increase of up to 20% in the survival rate of cork oak under plots amended with Stockosorb®400 compared to plots without application of the polymer. Similarly, the same polymer has been reported to result in increased survival of Aleppo pine [23] and Euphrates poplar ([42] ; [43]) under drought conditions. Such inconsistencies in survival rates can be attributed to factors such as differences in soil properties, specific conditions during planting including watering frequency, SAP size, as well as the plant species [44].

Considerable mortality of cork oak was observed very early in the study, especially in the first year, in direct-seeded plants. This was mainly attributed to attacks by white grubs (*Sphodroxia maroccana*) whose larval growth was observed to increase with increased watering. Thus, the increased moisture content of the soil after application of the SAP may have influenced in the appearance of this pest, given they represented the plots with the highest attacks. This is especially true in dry environments, where a sudden increase in soil moisture has been shown to encourage outbreaks of insect pests, some of which can spend years in a long diapause waiting for favorable conditions [45]. White grubs sever the roots of cork oak seedlings, causing their dieback and eventual death [46]. To counter their impact, preventive management can be done by planting in strips, with alternating planted rows and the preservation of grassy strips. In addition, the application of Chlorpyrifos-based phytosanitary treatments during the filling of the planting hole is done to control the pest. While pest attacks were highest in the amended plots, desiccation mortality was lowest, confirming the potential of SAP to promote water availability and thus limit plant death. Indeed, studies have shown that SAP application protects the root from desiccation, especially after seedling transplanting, by weakening the drop in water potential at the root-soil interface, thereby decreasing the energy required to absorb water from the soil ([47] ; [48] ; [49]).

5. Conclusion

This study highlighted the contribution of SAPs in promoting plant growth by addressing water shortage under semi-arid conditions in Morocco, thus demonstrating their potential application in other similar contexts. The application of Stockosorb®500 mitigated the negative influence of water deficit on the growth and productivity of cork oak. At the same time, it demonstrated its potential for limiting irrigation costs by up to 50%, especially for a region characterized by inherent water shortages, in a predominantly desert country. This particularity of the polymer is related to the considerable absorption of water in the superabsorbent structure and the progressive transfer of the absorbed water to the surrounding soil and plant roots. It can therefore be exploited to facilitate the growth of forest species, especially in degraded areas where plant growth is hampered by water stress induced by aridity. Nevertheless, the use of SAPs represents an additional expense in forest planting activities. Therefore, their application must be evaluated in comparison to other silvicultural interventions that aim to improve plant growth and survival. A comprehensive approach to forest regeneration, incorporating proper planting techniques and planting timing that minimize physiological stress on seedlings, is essential to creating an effective plantation scheme.

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