Heliyon 10 (2024) e39974

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Reducing drought vulnerability of forest soils using Xanthan gum-based soil conditioners

Jasna Smolar [a,*], Barbara Fortuna [a], Janko Logar [a], Alessandro Sorze [b], Francesco Valentini [b], Matej Maček [a], Boštjan Pulko [a]

[a] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, 1000, Ljubljana, Slovenia
[b] Department of Industrial Engineering and INSTM Research Unit, University of Trento, Via Sommarive 9, 38123, Trento, Italy

ARTICLE INFO

Keywords:
Soil conditioners (SCs)
Xanthan gum (XG)
Forest soils
Soil water retention curve (SWRC)
Hydraulic conductivity
Seed germination
Plant growth

ABSTRACT

Climate change increases the frequency and severity of droughts in many parts of Europe, thereby affecting the availability of water resources. Therefore, preserving the soil water content is essential for maintaining forest diversity and plant vitality. To improve soil hydraulic properties and reduce drought vulnerability, three xanthan-gum-based soil conditioners (SC_R, SC_CG, and SC_ZZC) were developed under the European ONEforest project. These soil conditioners (SCs), including oxide ash and cellulose fibres of different lengths, differ in their filler properties. This study evaluated the performance of these soil conditioners in forest soils in Slovenia (S1), Spain (S2), and Germany (S3). Water absorption, water retention, hydraulic conductivity, seed germination, and plant growth in the untreated soils and mixtures were analysed.

The results showed a 53 %–100 % increase in water absorption with high dosage of SCs (1.7 % of dry SC per dry soil mass). The addition of SCs also significantly improved the water retention capacity of the treated soils within a suction range of 0–100 kPa, which is advantageous for maintaining adequate water availability for plant growth. The effect of SCs on unsaturated hydraulic conductivity varies depending on the soil type. For example, at a similar suction, the unsaturated hydraulic conductivity of mixtures with soils S2 and S3 can be more than an order of magnitude lower than that of untreated soils S2 and S3. In contrast, mixtures with soil S1 showed unsaturated hydraulic conductivity similar to that of the untreated soil. In the seeding experiment, plants in treated soils survived for up to 8 d without watering compared to those in untreated soils, with survival linked to the initial water content of the mixtures. These findings suggest that soil conditioners reduce drought vulnerability by improving water retention and regulating water loss. However, the optimal dosage should be adjusted according to different soil types and local environmental conditions.

* Corresponding author.
E-mail addresses: jasna.smolar@fgg.uni-lj.si (J. Smolar), barbara.fortuna@fgg.uni-lj.si (B. Fortuna), janko.logar@fgg.uni-lj.si (J. Logar), alessandro.sorze@unitn.it (A. Sorze), francesco.valentini@unitn.it (F. Valentini), matej.macek@fgg.uni-lj.si (M. Maček), bostjan.pulko@fgg.uni-lj.si (B. Pulko).

https://doi.org/10.1016/j.heliyon.2024.e39974
Received 8 August 2024; Received in revised form 29 October 2024; Accepted 29 October 2024
Available online 30 October 2024

1. Introduction

Trees and other forest plants play crucial roles in mitigating the effects of climate change on forest ecosystems. The absence of vegetation directly exposes forest soils to the adverse effects of rainfall events [1] and drying due to direct sunlight, thereby disrupting the natural water balance. Furthermore, the stability of a slope surface (erosion resistance), which often comprises well-drained and low-cohesion soil, depends on the mechanical reinforcement offered by trees and plant roots in the soil, as well as on the soil water retention characteristics [2–7]. Ni et al. [8] and Ng et al. [9] developed advanced numerical models to quantify the effect of root hydromechanical reinforcement on slope stability.

Root distribution is influenced by the climatic regime and the ability of the soil to retain water, which is especially vital in regions where plant growth occurs under conditions with relatively limited water availability [3]. The application of biopolymers with water superabsorbent properties has shown promising results in terms of enhancing soil water retention capacity, thus mitigating the vulnerability of forest soils to drought [4,10–12]. Biopolymers not only improve the soil water retention capacity but also promote the germination and growth of vegetation [4,13]. Consequently, they contribute to creating a suitable and stable environment for plant and tree growth [4,10,12–15].

Numerous studies have illustrated that the addition of biopolymers, with xanthan gum (XG) prevailing among them, alters the geotechnical properties of treated soil and effectively reduces the potential for soil erosion [16–25]. Among the different biopolymers used for soil treatment, XG stands out because of its efficiency, availability in large quantities, and low price [26]. Moreover, the XG-treated soil can absorb large amounts of water during the rainy season and slowly release water during the dry season. Thus, XG treatment of soil plays a vital role in the preservation of soil water content and in improving vegetation growth and survival [27,28]. In addition to the beneficial effects of biopolymers on soil hydraulic properties, Zhang et al. [11] and Tariq et al. [13] emphasised the importance of optimising their dosage. Excessive use of biopolymers can lead to soil hardening at low water content and a reduction in soil porosity at high water content. Both can be unfavourable for seed germination and plant growth. The formation of a dry crust on treated soil can prevent water infiltration and evaporation, as well as the penetration of sprouts to the surface. Reduced soil porosity may restrict the availability of the oxygen necessary for root system development and growth. Therefore, when determining a suitable treatment procedure, the interactions between each polymer and the soil type should be considered. In a recent study [29] plant growth tests were performed using clayey soil treated with different XG dosages. The results revealed a significant peak in germination percentage and coverage of the plants in the soil treated with 2 % of XG (per dry soil mass). For cases with higher dosages of XG, the growth indicators were even lower than those of untreated soil, leading to the conclusion that 2 % of XG is the upper limit for clay treatment.

Although the saturated hydraulic properties of both treated and untreated soils have been extensively studied [11,26,30,31], unsaturated hydraulic properties have received far less attention [32], despite their greater importance under field conditions [33].

Al-Darby [34] investigated the impact of hydrophilic type of biopolymer Jalma gel at concentrations of 0.2 %, 0.4 %, and 0.8 % on the soil water retention curve (SWRC) of sandy soil. These findings suggest that the available water content increased exponentially and the saturated hydraulic conductivity decreased exponentially with increasing amount of Jalma gel. Previously, Mustafa et al. [35] determined that for a loamy sand soil, achieving a 50 % reduction in water penetrability is crucial to curb deep percolation losses while simultaneously maintaining an adequate infiltration rate through the soil. Consequently, Al-Darby's study recommended an optimal dosage of 0.4 % Jalma gel. This dosage successfully reduced deep percolation losses while maintaining satisfactory infiltration and water retention characteristics.

Tran et al. [4,36] used up to 1.0 % XG (to the dry mass of soil) to treat a sand-clay mixture. The experimental results show that the use of XG can improve the water-holding capacity of soil and control the rate of water loss from the soil under desaturation conditions.

Chang et al. [10] demonstrated that in the case of inorganic silty loam (ML), treatment with 0.5 % (to the mass of dry soil) of β-glucan and XG, proved to be a promising countermeasure for various aspects of desertification. These treatments were also effective in improving soil erosion resistance, retaining soil water content, and promoting cultivation. A notable improvement in the soil water retention capacity was also reported by Wang et al. [12] for low plasticity clay (CL) treated with 0.5 %–2.0 % per dry soil mass of XG, gellan gum, and guar gum and by Mohawesh and Durner [37] for sandy soil treated with 0.5 % of Luqua-sorb hydrogel.

Liao et al. [38] conducted a 120d experiment on sandy loam treated with different dosages of synthetic polyacrylamide and acrylic acid-based hydrogels. They found that these superabsorbent polymers substantially reduced the unsaturated hydraulic conductivities of treated soil samples, especially in the early stages.

Ng et al. [32] investigated the effects of biopolymers on the gas permeability of compacted clay with various densities and water contents. They found that the gas permeability of the biopolymer-treated compacted clay intended for landfill cover systems was consistently lower than that of untreated clay, regardless of the specimen density or water content. This reduction in gas permeability was attributed to the biopolymers, gellan and xanthan gum, which reduced larger soil pores and clogged smaller pores. Additionally, biopolymers absorb water and hydrate and further clog the soil pores. Such a decrease in gas permeability can disrupt the balance of air and water in the pores of forest soils, potentially leading to an imbalanced air-water cycle that may adversely affect plant growth and development.

Zhang et al. [31] highlighted the importance of understanding changes in the SWRC as a biopolymer-treated soil transitions from a saturated to an unsaturated state. Drying alters the water retention capacity of biopolymer-treated soils. Hydrogels, which can retain bound water for extended periods, gradually release water under extremely dry conditions, thereby increasing the cross-sectional area for water movement. Because field soils to which hydrogels are to be applied are often water-limited and remain in an unsaturated state, further studies must be conducted on the impact of hydrogel applications on unsaturated hydraulic conductivity [33].

This study primarily aimed to conduct a comprehensive assessment of the effect of newly developed XG-based soil conditioners (SCs) on the hydraulic properties of various forest soils, with a particular focus on the behaviour of SC-treated soils under unsaturated conditions. The uniqueness of the XG-based SCs developed within the ONEforest project frame is the enhanced XG matrix with oxide ash and cellulose fillers of various fibre lengths. Therefore, we focused on identifying how different fillers influence the effectiveness of SCs in soil treatment.

After the development of SCs [39], investigation of their rheological properties, initial basic application in soil conditioning [15] and influence of SCs on the geotechnical properties (drained shear strength, compressibility and hydraulic conductivity) of treated soils in a saturated state [40], the present study represents a follow-up research focused on the efficacy of SCs in enhancing soil hydraulic characteristics in saturated and unsaturated states.

To illustrate the efficacy of SCs in enhancing soil hydraulic characteristics in saturated and unsaturated states, three different forest soil types sourced from various European locations were utilised. The water retention characteristics of both the untreated and treated soils were analysed across a wide suction range using Hyprop and WP4-T devices (METER group). The saturated hydraulic conductivity was measured using a falling head permeameter (oedometer), whereas the unsaturated hydraulic conductivity was estimated from Hyprop measurements. Additionally, the influence of SCs on the seed germination and plant growth was investigated under laboratory conditions.

2. Materials

2.1. Soils

Laboratory investigations were conducted on three types of soil from different forest areas in Europe: Ljubelj in the Alpine part of Slovenia (S1), Catalonia, northeastern Spain (S2), and Heldburg, Germany (S3). By utilising these diverse forest soils, the influence of inherent soil properties on the interactions of soils with different SCs treatments was assessed.

Although the samples were collected from the soil layer beneath the fresh organic layer on the surface, they still contained a small amount of older and partially decomposed organic matter. The organic content of soil S1 was 8.2 % by mass per dry matter (DM), whereas S2 and S3 had organic contents ranging from 1.8 % to 5.2 % DM.

Prior to the laboratory investigations, thesoil samples were manually cleared of small tree branches, needles, and leaves. Fig. 1 illustrates the cleared soil samples, and Table 1 summarises their index properties. A more comprehensive description of the geotechnical properties of soils, including laboratory test methods, can be found in Ref. [40].

2.2. Soil conditioners

Three types of XG-based SCs with various types of fillers were investigated. The SCs were selected based on their performance during the development phase and initial application testing [15,39]. Table 2 summarises the properties of the fillers used in the preparation of SCs. The fillers were mixed with 4 % XG-water solution at the dosage of 2 %. The mixing operations were performed using a Dispermat® F1 mixer (VMA-Getzmann Gmbh, Reichshof, Germany), operating at 5000 rpm for 15 min, until a homogeneous mixture without lumps was obtained. After mixing, the SCs were dried in an oven at 50 °C for 72 h and ground in a Piovan® RN166/1 granulator (Piovan SpA, Venice, Italy) for 3 min. Detailed descriptions of the development and properties of SCs can be found in Refs. [15,39].

Fig. 2 depicts the SCs in three representative states: dry product (a), hydrogel after saturation (b), and thin crust of SCs after drying at room temperature (c) where it can be seen that after drying the hydrogel forms very stiff and fragile dry crust.

2.3. Soil treatment procedure

The forest soils were treated with both low (L) and high (H) doses of the soil conditioner SC_R, whereas SC_CG, and SC_ZZC were applied solely at high doses. A high dosage of SC corresponded to 1.7 % of dry SC per dry soil mass, whereas a low dosage corresponded to 0.4 % of dry SC per dry soil mass. The four mixtures listed in Table 3 were prepared and investigated for each soil type. Therefore, 12

Fig. 1. Investigated soils after removing older and partially decomposed organic particles.

Table 1
Index properties of the different soil types.

Soil Type		S1	S2	S3
Natural water content, w (%)		43	10	18
Particle density, ρ_s (g/cm^3)		2.52	2.59	2.56
Liquid limit, w_L (%)		67	31	26
Plastic limit, w_P (%)		41	15	13
Particle size distribution (%)	**> 2.0 mm**	3.81	3.17	1.20
	0.063–2.0 mm	13.12	39.03	36.38
	< 0.063 mm	83.07	57.80	62.42

Table 2
Composition of different fillers in soil conditioners [15,40].

SC label	Filler type	Cellulose content (%)	Oxide ash content (%)	Average fibre length (µm)	Aspect ratio
SC_R	Arbocell R	>99	0.5	200–300	9.9
SC_CG	Cellugrün	80	15	1400	31.1
SC_ZZC	Arbocell ZZC 500	80	15	400	8.8

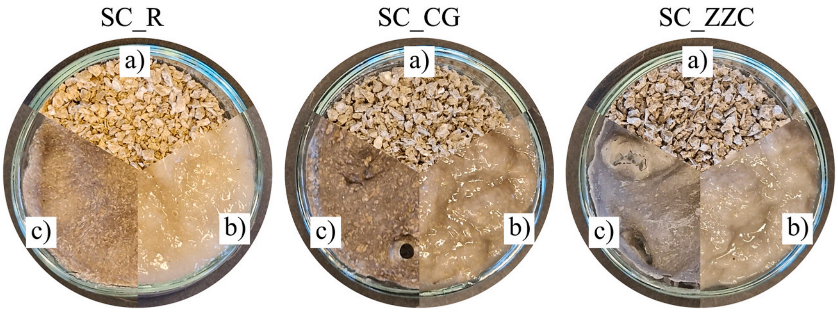

Fig. 2. The soil conditioners in (a) dry state, (b) saturated state - hydrogel and (c) dry crust resulting from the air drying of the hydrogel.

Table 3
Investigated mixtures [40].

Soil	Soil Conditioners	Dosage	Mixture Label
S*	SC_R	low, L, 0.4 %	S*+SC_R L
	SC_R	high, H, 1.7 %	S*+SC_R H
	SC_CG	high, H, 1.7 %	S*+SC_CG H
	SC_ZZC	high, H, 1.7 %	S*+SC_ZZC H

S*—represents the identification number of the soil (S1, S2, and S3).

mixtures were included in this study.

Mixtures of selected soil and SCs for the determination of water absorption w_A were prepared using dry soil ($T_{drying} = 45$ °C) and dry SC. Prior to mixing, both the dry soil and SC were ground to achieve a maximum particle diameter of 0.355 mm. For other laboratory investigations, soils were used in their natural state, preserving their natural water content and grain size distribution (Table 1), and mixed with dry SCs. Each specimen was prepared from a fresh mixture.

3. Methods

Laboratory investigations of untreated soils and mixtures were conducted following standard procedures for determining soil properties or by employing methods recommended by the manufacturers of the devices used. Owing to the unique properties of mixtures influenced by soil conditioners SCs, certain adjustments were made to the preparation of the specimens and test methods. As mandated by the standards, detailed descriptions of the deviations from the test methods are provided below.

3.1. Gravimetric water content

The gravimetric water content was determined by drying soils and mixtures to a constant mass in a ventilated drying oven maintained at 45 °C. The drying temperature was selected based on the proposal of the standard for soils containing organic matter [41].

3.2. Water absorption

Water absorption tests were performed on untreated soils and mixtures using an Enslin–Neff device. The standard [42] recommends a dry specimen mass of 1.0 g for specimens with water absorption lower than 100 %, whereas for specimens with water absorption equal or higher than 100 %, the suggested initial mass of dry specimen is 0.2 g. Due to the difficulty in preparing a homogeneous representative mixture with a mass of 0.2 g, tests were conducted on specimens with a dry mass of 1.0 g even in cases where the water absorption exceeded 100 %. Following the recommendations of the standard, water absorption was assessed after 24 h ($w_{A\ 24h}$). At least two test replicates were conducted for each untreated soil sample and mixture. To assess the effect of the initial mass of the dry specimens on the test results, tests for randomly selected mixtures (S1+SC_R H, S2+SC_ZZC H and S3+SC_CG H) were repeated using specimens with an initial dry mass of 0.2 g.

Because of extremely high water absorption of SCs alone, water absorption tests using the Enslin-Neff device could not be conducted. Consequently, an adapted method was used to determine the water absorption of the SCs, as shown in Fig. 3. A dry filter paper of known mass was positioned inside a Petri dish of known mass and connected to a water basin using a filter paper strip. After the saturation of the filter paper, the masses of the saturated filter paper and Petri dish was determined. Approximately, 1.0 g of the dry specimen of SCs, soil, or mixture was carefully placed on a saturated filter paper. The water-absorption capacities of the specimens were determined by weighing them at various intervals during the absorption process. The test was terminated if no discernible difference was found in the mass between two consecutive weightings, indicating that the absorption process had reached a stable state. Additionally, the water content of each specimen was measured at the end of the test.

To validate the test results, the adapted method was also used for water absorption tests of the untreated soil S2 and its mixtures.

3.3. Soil water retention curve (SWRC)

Soil water retention curves (SWRCs) were determined using the Hyprop evaporation method device (for matric suctions up to approximately 100 kPa) and a dew point potentiometer WP4-T (for total suctions exceeding approximately 300 kPa). Investigations were conducted following the manufacturer's instructions [43,44] and adhering to standard procedures [45].

The Hyprop device involves measurements of matric suction at two depths (1.25 cm and 3.75 cm) within a specimen with the diameter of 8 cm and height of 5 cm. The time-dependent evaporation rate was obtained by the automated weighing of the initially saturated specimen. The changes in weight were assumed to be equal to changes in water mass. This means that biodegradation during the investigation, lasting for at least one month, was not considered. The water retention values were estimated from the average gravimetric water content and average pressure measured during drying of the specimen using two tensiometers.

Specimens were prepared from untreated and treated soils (mixtures). Homogeneous mixtures were prepared from soil at natural water content with the addition of dry SC and were slightly compacted into the Hyprop mould. The specimens in the mould were then saturated by immersion in water up to four-fifths of their height. Volume changes were minimised by placing porous discs on the upper and lower surfaces of the specimens and applying a weight of 10 kPa to the top during the saturation process. After saturation was completed, tensiometers mounted on the Hyprop device were pushed into the specimen and measurements were started. To provide quasi-steady-state conditions (constant flux and hydraulic gradient over the time interval), the evaporation rate was reduced by covering the specimens with a perforated plastic bag of a known mass.

In the high suction range, the SWRC was measured using a potentiometer WP4-T. The potentiometer WP4-T was calibrated each day before regular measurements using standard solution of 0.5 M KCl. Measurements were conducted on the remaining portion of the sample (soil or mixture) prepared for the specimens investigated using the Hyprop device. Using drippers, the sample was wetted to a water content at or slightly below full saturation. The first specimen was prepared and the total suction was measured. The samples were then slowly dried stepwise at room temperature (22°) and the specimens were taken at various drying intervals. Prior to conducting the measurements, the prepared specimens were tightly sealed in special plastic containers for at least 24 h to ensure that the water content and suction were equilibrated.

3.4. Saturated hydraulic conductivity

The saturated hydraulic conductivity (k_{sat}) was measured using a falling-head permeameter [46]. These tests were conducted at the end of the 25 kPa loading stage as part of the incremental loading oedometer tests [40].

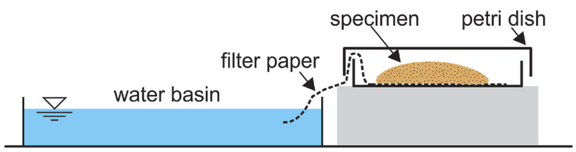

Fig. 3. Schematic representation of the set up for adapted water absorption test.

3.5. Unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity (k_{unsat}) of the soils and mixtures was derived from the data measured using a Hyprop device. Unsaturated hydraulic conductivity reflects the ability of the soil to transport water from the wet bottom to the top of the specimen, where water evaporates. Based on the loss of mass per time interval and the difference in pressures measured with tensiometers, the water flux and unsaturated hydraulic conductivity were determined according to the simplified evaporation method presented in Refs. [47–49]. The calculations were performed using LABROS Soilview and Soilview-Analysis Software [50] and were based on the following assumptions: (1) changes in hydraulic conductivity within the specimen during the measurement time interval were negligible; (2) the flux at a depth of 2.5 cm within the specimen was half of the total flux and could therefore be calculated from the total evaporative soil water volume difference in the time interval; and (3) the vertical distributions of water content and suction were linear throughout the entire column.

$$k_{unsat}\left(\overline{\overline{s_i}}\right) = \frac{q_i/2}{1 - \Delta s_i/(\gamma_w \Delta z)}, \tag{1}$$

where $\overline{\overline{s_i}}$ is the mean suction (in kPa) of the two consecutive time steps (i, i-1) at two depths, defined by positions of the tensiometers within the specimen z_1 and z_2 ($\overline{\overline{s_i}} = (s_{1,i} + s_{2,i} + s_{1,i-1} + s_{2,i-1})/4$). The Δs_i is the difference between the tensiometer readings ($\Delta s_i = (s_{2,i} - s_{1,i} + s_{2,i-1} - s_{1,i-1})/2$), γ_w unit weight of water and Δz is determined as $\Delta z = z_2 - z_1$. The water flux is denoted as q_i ($q_i = (m_i - m_{i-1})/((t_i - t_{i-1})\rho_w A)$), where m_i is the mass of specimen at time t_i, A is cross-section area of the specimen, and ρ_w is water density).

3.6. Plant growth

Seeding experiments were conducted to assess the effects of SCs on seed germination and plant growth. Christmas wheat (Fig. 4, left) was selected for the seeding experiment because of the expected fast germination and growth rates. The investigation was carried out in laboratory conditions with temperature of 19–24 °C and a relative air humidity between 40 and 60 %. Specimens of untreated soils with natural water content and mixtures with high dosages of different SCs were placed in plastic containers. Seventy-eight seeds were evenly distributed across the surface of the soil or mixture within each container (Fig. 4, right) and covered with approximately 1 cm thick layer of soil or mixture. The specimens were subsequently watered with tap water. Two parallel experiments were performed:

(1) Specimens with the same initial water content: Each untreated soil specimen was watered until it could no longer absorb water. The amount of added water was determined by weighing the specimens. The mixtures were watered with the same amount of water as the untreated soil.
(2) Saturated specimens: Each specimen was watered until it could no longer absorb water. Excess water either exited the bottom or was stagnant on the surface (referred to as saturated specimens).

During the experiment, seed germination and plant growth were monitored using photographs. The gravimetric water content was calculated from the measured mass of the specimens at different time intervals and the final dry mass. Saturated specimens were watered once more after 7 d, whereas specimens prepared with the same initial water content were watered upon initial germination and then twice more.

Fig. 4. Christmas wheat seeds (left) and seeds placed in mixture of soil S2+SC_R H before covering the seeds with approx. 1 cm thick layer of mixture (right).

4. Results

4.1. Water absorption

Fig. 5 shows the water absorption capacity of the SCs granules determined using the adapted method illustrated in Fig. 3. For an improved overview of the results and easier traceability, the point measurements are connected by curves. Water absorption rates were virtually equal for all three types of SCs. The final water absorption was achieved after 145 h and exceeded 1500 %. Measured values fall within the same range as those reported by Sorze et al. [39], who conducted investigations on dry specimens exposed to constant humidity (RH = 80 %) and temperature (25 °C) for 100 h.

The water absorptions of the soils and mixtures with an initial dry mass of 1.0 g per specimen are summarised in Table 4. Further details are provided in Ref. [40]. At least two test repetitions were conducted for each soil or mixture, and the average of the measurements after 24 h was considered the water absorption ($w_{A\ 24\ h}$).

For mixtures with a high dosage of SCs, $w_{A\ 24\ h}$ was generally close to or higher than 100 % (Table 4). Consequently, tests on mixtures S1+SC_R H, S2+SC_ZZC H and S3+SC_CG H were conducted also on specimens with an initial dry mass of 0.2 g, as recommended by the standard. Regardless of the initial dry mass of the specimens, the measured water absorption was within the same range (Table 4; values in parentheses). This confirmed that the water absorption capacity obtained with an initial dry mass of the specimen 1.0 g was reliable for the investigated specimens.

The efficiency of SCs depends on their dosage and the soil type. A low dosage of SCs resulted in 7–8 % relative increase in $w_{A\ 24\ h}$ compared to the $w_{A\ 24\ h}$ of untreated soils S1 and S2, whereas for S3, the increase was 24 %. A high dosage of SCs was least effective in the case of soil S2, where 51–54 % increase in w_A was observed regardless of the type of SC. On the contrary, a high dose of SCs was most effective in the case of soil S3, where the $w_{A\ 24\ h}$ of mixtures ranged from 82 % (SC_R) to 102 % (SC_ZZC) higher than $w_{A\ 24\ h}$ of the untreated soil.

Fig. 6 depicts a comparison of the results obtained through both the standard procedure (solid bars) and the adapted test method (hatched bars) for untreated soil S2 and its mixtures with SCs. The tests were conducted on specimens with an initial dry mass of 1.0 g. The adapted test method showed reduced water absorption for untreated soil compared with the standard Enslin-Neff test method. However, for the mixtures, the results obtained using the two methods were comparable.

4.2. SWRC

The Soil Water Retention Curves (SWRCs) for untreated soils and mixtures are depicted in Fig. 7. The data obtained from the Hyprop device are represented by a solid line, whereas the WP4-T device results are illustrated by scatter plots.

Specimens from the mixtures and the corresponding untreated soils were prepared with comparable initial dry densities. Table 5 presents the initial dry densities and the dry densities of the specimens from the untreated soils and their mixtures after saturation and swelling. Owing to swelling during saturation, the specimens from the mixtures exhibited lower dry densities and higher water contents than those from the untreated soils at the start of the test. Similar behavior is also expected under field conditions, because the vertical stress will generally be lower than that applied during the saturation of specimens in the laboratory (10 kPa). Thus, the measured SWRCs are valid for describing the effect of SCs on water retention capacity.

The lowest measured suctions of the soil and its mixtures varied, depending on the initial saturation of the specimens. For both soils S1 and S2 and their mixtures, the achieved initial saturation of specimens was higher than 90 % (often exceeding 95 %). However, for specimens from mixtures with S3, achieving an initial saturation higher than 70 % (S3 + SC_R H) and 85 % (S3 + SC_ZZC H) was unattainable, even after exposing the specimens to water for up to 7 d. The saturation time was limited to 7 d owing to the presence of organic matter in the mixtures. The prolonged saturation time, and in the case of mixtures with S3, the lower initial saturation achieved, can be attributed to the XG contained in the SCs. Upon contact with water, XG forms a viscous hydrogel that coats soil particles and blocks pores within the soil matrix, as reported by Wang et al. [12]. This led to a significant reduction in water flow through the treated soil specimens.

Fig. 7 shows that the drying curves of specimens from mixtures in the low-suction range (<100 kPa) consistently occupied higher positions compared to the SWRCs of untreated soils. This consistent upward shift implied an enhancement in the water retention

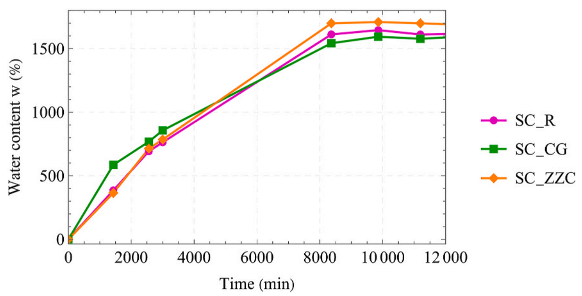

Fig. 5. Determination of water absorption capacities of the three types of SCs using the adapted method.

Table 4
Water absorption of specimens from soils and mixtures with the initial dry mass of 1.0 g (0.2 g). *representing the identificatory number of the respective soil.

Soil	S1	S2	S3
Specimen		$w_{A\ 24\ h}$ (%)	
S*	88	68	50
S*+SC_R L	95	73	62
S*+SC_R H	158 (126)	105	91
S*+SC_CG H	145	103	100 (112)
S*+SC_ZZC H	135	105 (93)	101

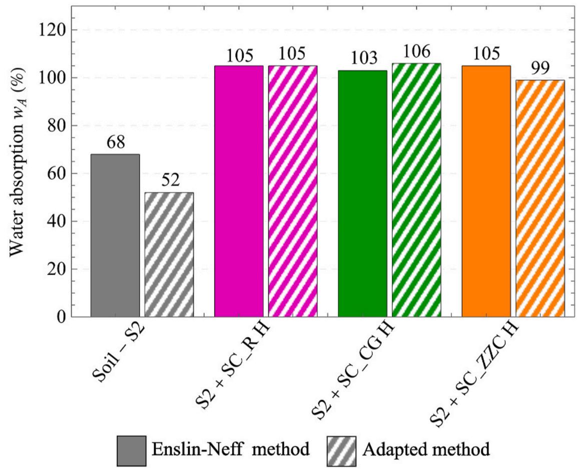

Fig. 6. Comparison of water absorption capacities of untreated soil S2 and its mixtures determined using the Enslin-Neff test method and the adapted method (1.0 g of the specimen).

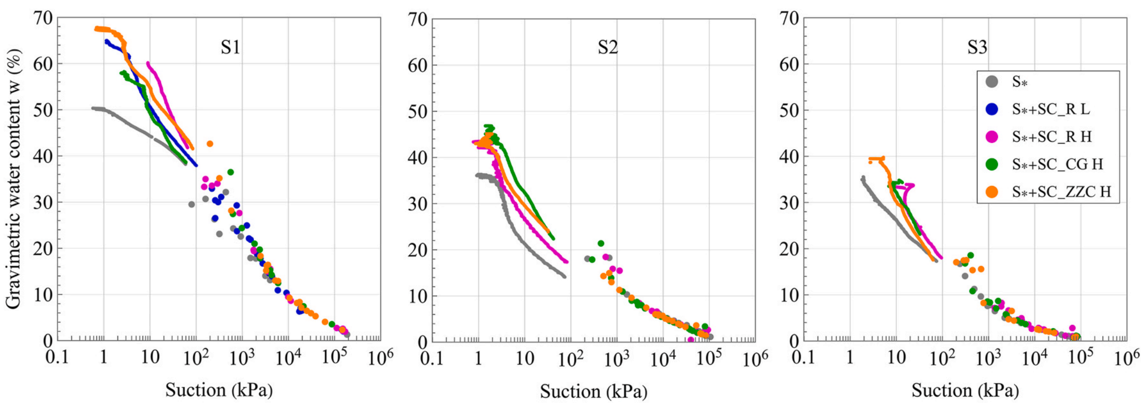

Fig. 7. SWRCs for untreated soils S1 to S3 and their mixtures.

Table 5
Initial and post-saturation dry densities of specimens from untreated soils and their mixtures. *representing the identificatory number of the respective soil.

Soil	S1	S2	S3
Specimen		$\rho_{d\ initial}/\rho_{d\ post\text{-}saturation}$ (Mg/m^3)	
S*	1.04/1.04	1.29/1.29	1.20/1.20
S*+SC_R L	1.04/0.94	not investigated	not investigated
S*+SC_R H	1.04/0.95	1.29/1.14	1.22/1.14
S*+SC_CG H	1.05/0.96	1.28/1.11	1.21/1.18
S*+SC_ZZC H	1.05/0.91	1.29/1.14	1.22/1.18

characteristics of the treated specimens within a particular suction range. In addition, the results obtained for the S1 mixture with two different dosages of SC_R indicated that the water retention capacity of the mixtures increased with increasing SC content. Some improvement in the water retention capacity was also observed in the middle suction range (100 kPa–2000 kPa). In this suction range, the distinctions between SWRCs of soil and mixtures are minimal, potentially stemming from various factors such as the presence of SCs, inhomogeneity of specimens, or the declared accuracy of the WP4-T device, specified at ± 100 kPa for suctions below 1000 kPa. When the suction exceeded 2000 kPa, which was higher than the permanent wilting point [51], the water retention capacity of the mixtures showed no noticeable difference compared with the untreated soils.

4.3. Hydraulic conductivity

Fig. 8 presents both the saturated hydraulic conductivity measured using a falling head permeameter (solid rectangles) and the unsaturated hydraulic conductivity calculated from the Hyprop measurements (empty circles) of untreated soils and mixtures. Irrespective of the soil type and saturated hydraulic conductivity of the untreated soils, the introduction of a high dosage of SCs resulted in saturated hydraulic conductivity values ranging from 10^{-9} m/s to 10^{-10} m/s. This implies a reduction in the saturated hydraulic conductivity by two to four orders of magnitude compared to that of untreated soils.

Although the influence of biopolymers on the saturated hydraulic conductivity has been well investigated, data on the unsaturated hydraulic conductivity of forest soils treated with biopolymers are lacking. Unsaturated hydraulic conductivity is primarily influenced by the water content or matric suction of the soil. In addition, it is contingent on the structure and connectivity of the pore spaces within the soil matrix. As illustrated in Fig. 8, the unsaturated hydraulic conductivity generally decreased with increasing matric suction and was generally lower than the saturated hydraulic conductivity. Notably, for the untreated soils, this decrease was more pronounced than that for the mixtures. Untreated soil S1 and its mixtures exhibited comparable k_{unsat} values for higher matric suction, whereas untreated soils S2 and S3 showed higher values of k_{unsat} than their mixtures for the same matric suction. There were no notable differences between the mixtures of different types of SCs with soil S1, whereas in the case of the soils S2 and S3, the influence of the type of SC was visible. The results indicated that SCs affected both the saturated and the unsaturated hydraulic conductivity in various types of soils, with no discernible influence attributable to the specific type of SCs used.

4.4. Seed germination, plant growth and vegetation viability under drought conditions

Figs. 9–11 illustrate the average gravimetric water content measured in the specimens prepared from various soils and mixtures with a high dosage of SCs during the investigation of seed germination, plant growth, and wilting in the drying phase. For each mixture, two separate graphs were plotted: (1) for specimens with the same initial water content corresponding to the water retention capacity of untreated soil, and (2) for initially saturated specimens watered until the soil or mixture could not absorb water. The germination and wilting points are marked with circles and diamonds, respectively. Germination and wilting points were determined based on the first seeds to germinate and the first plants to wilt. Photographs of the initial states of the specimens (during 1st watering), seed germination, and wilting are included in the Supplementary File (Appendix A).

Regardless of the soil type and mixture, germination in specimens with the same initial water content began within 3 or 4 d of seeding. However, for the saturated mixtures S1+SC_R H, S3+SC_CG H, and S3+SC_ZZC H, the germination time was extended from 5 to 8 d. In contrast, for the other saturated specimens, the germination time remained within 3–4 d. Upon watering, a thin layer of hydrogel formed on the surfaces of the saturated specimens from mixtures. However, upon air-drying, the mixture on the surface transformed into a rigid crust, impeding the penetration of sprouts during the initial stages of growth. Watering at distinct time intervals, represented by the vertical dashed blue lines in Figs. 9–11, resulted in the crust becoming wet and soft.

The germination rate and plant growth depend on the type of soil and, in the case of mixtures, on the type of SCs and the initial water content. Fig. 12 illustrates that, under similar laboratory conditions and care, untreated soil S3 exhibited the lowest germination rate and plant growth, whereas untreated soils S1 and S2 demonstrated comparable results.

Fig. 13 illustrates the plant growth and germination rates in the untreated soil S3 and its mixtures prepared with the same initial

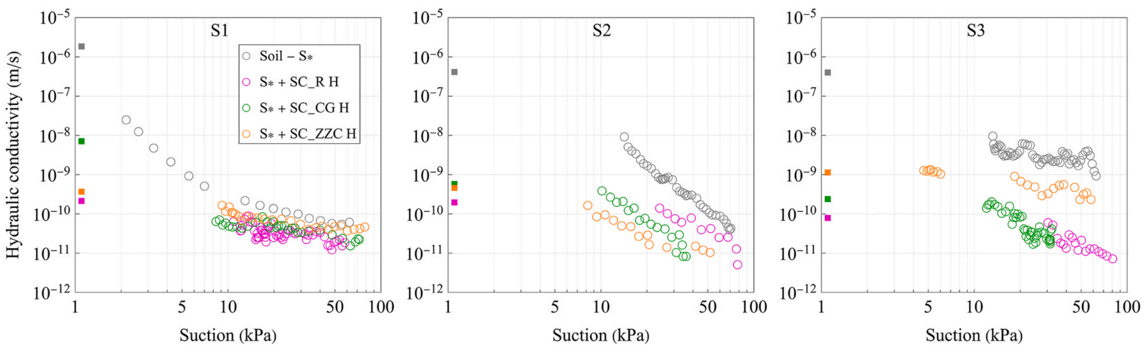

Fig. 8. Saturated and unsaturated hydraulic conductivity for untreated soils S1, S2 and S3, and mixtures with high dosages of SCs.

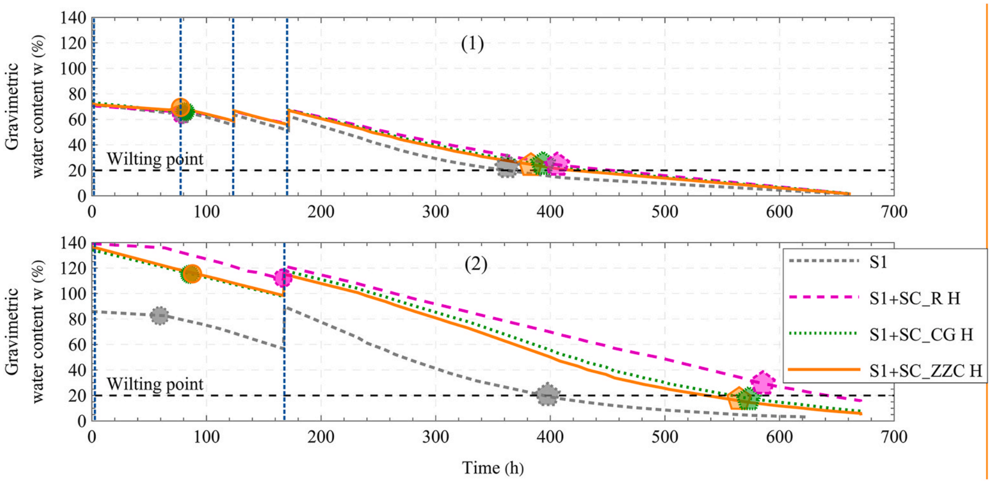

Fig. 9. Gravimetric water content of soil S1 and mixtures with high dosage of SCs during seed germination (circles), plant growth and wilting during drying (diamonds): (1) specimens with the same initial water content and (2) initially saturated specimens.

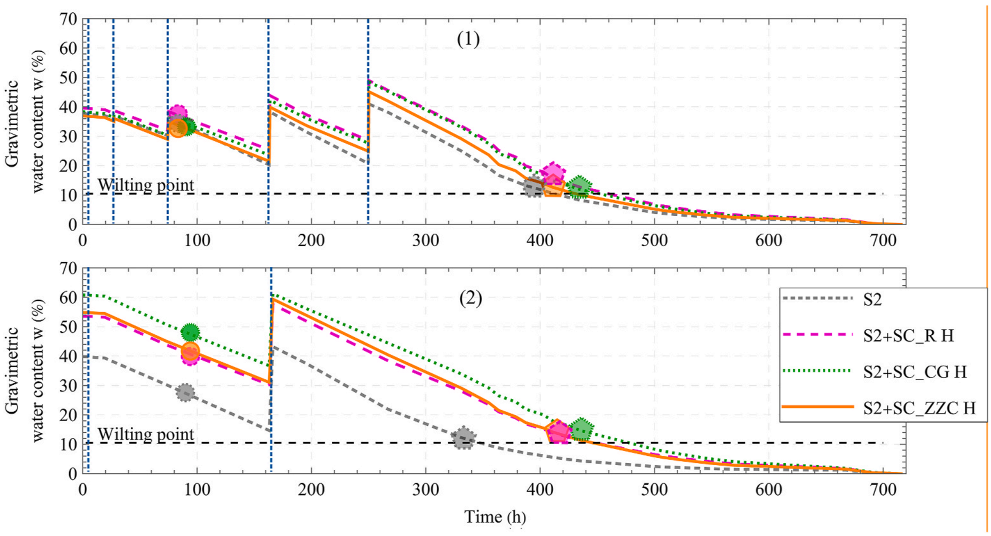

Fig. 10. Gravimetric water content of soil S2 and mixtures with high dosage of SCs during seed germination (circles), plant growth and wilting during drying (diamonds): (1) specimens with the same initial water content and (2) initially saturated specimens.

water content (1) and in a saturated initial state (2), 187 h after seeding. Specimens with the same initial water content (1) showed a favourable effect of SCs, resulting in higher plant growth than in an untreated soil. However, excluding the mixture with SC_R H, the influence of SCs in the initially saturated specimens was less favourable, as evidenced by reduced seed germination and consequently poorer plant growth. Whereas the initially saturated mixture S3+SC_ZZC H exhibited fewer promising results, the saturated mixtures of soils S1 and S2 with the same soil conditioner (Fig. 14) showed more favourable outcomes. Fig. 15 shows plants grown in mixtures prepared from soils S2 and S3 with SC_R and SC_CG at 267 h post-seeding and watering to the same initial water content (1). Plants in the soil S3 mixtures display diminished height compared with those in the S2 mixtures, irrespective of the SC type.

During the non-watering phase, plants that germinated in the treated soils survived longer than those that germinated in the untreated soils. The specimens that were saturated at the beginning of the test and had the largest water supply showed the best plant survival (Figs. 9–11, diamonds). Interestingly, the wilting point was identified at a gravimetric water content corresponding to a suction of approximately 1500 kPa, which has been reported as the permanent wilting point [51]. Water content at suction 1500 kPa was approximately 20–23 % for S1 and its mixtures, 11 % for S2 and its mixtures, and 6–8% for S3 and its mixtures (Fig. 7). Figs. 9–11 (black horizontal dashed line) show that these water content values correspond well with the empirically assessed wilting points during the experiment.

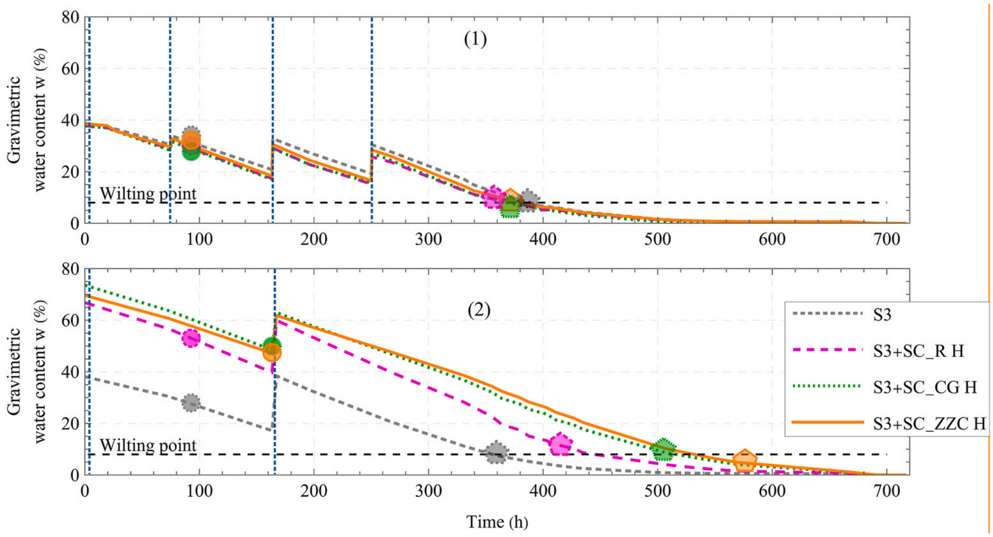

Fig. 11. Gravimetric water content of soil S3 and mixtures with high dosage of SCs during seed germination (circles), plant growth and wilting during drying (diamonds): (1) specimens with the same initial water content and (2) initially saturated specimens.

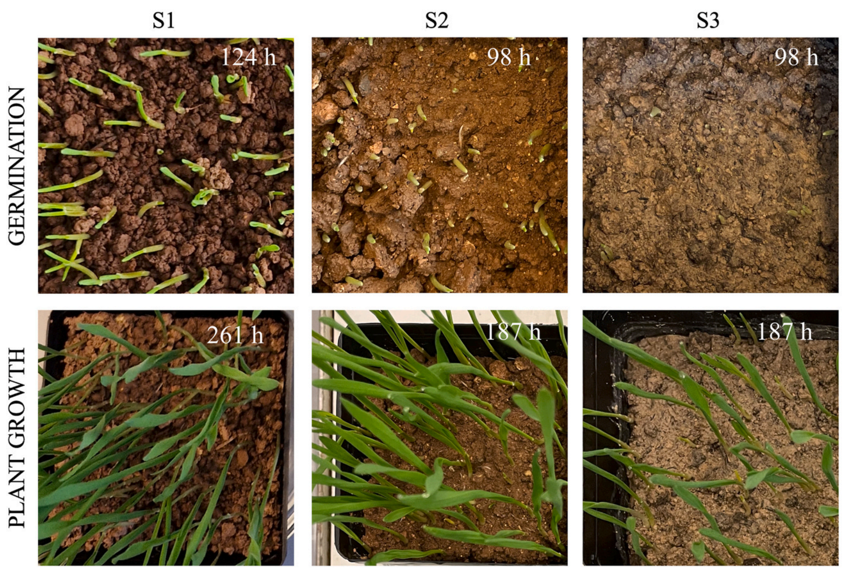

Fig. 12. Germination and growth of Christmas wheat in different types of untreated soils with denoted time after seeding.

5. Discussion

In this study, we investigated the use of xanthan-gum-based SCs to improve drought resilience in forest soils. The results showed clear improvements in water absorption and water retention capacities in the SC-treated soils, which are crucial for maintaining soil moisture and supporting plant growth during drought. Water absorption capacity increased by 53 %–100 % depending on soil type and SC dosage, while the most substantial enhancements in water retention occurred at suctions below 100 kPa. Although the investigated soils were fine-grained, their liquid and plastic limits and grain size distributions varied. Soil S1, which was classified as silt with sand, had the highest liquid and plastic limits, water absorption, and fines content. Consequently, the water absorption and retention capacities of mixtures containing S1 were the highest. By examining these diverse forest soils, we demonstrated that the inherent properties of each soil type significantly influenced the mixture characteristics. Given the lack of prior research on the application of biopolymers to forest soils, exploring multiple soil types is essential to gain a comprehensive understanding of the effects of SCs.

These findings are consistent with previous research indicating that biopolymers, such as xanthan gum, enhance soil water absorption and retention [4,10,11,28,29,31,52–54]. Regardless of the soil type and the properties of the additives used, the soil conditioners were the most effective in the lower suction range (<100 kPa). Some improvement in water retention capacity was also

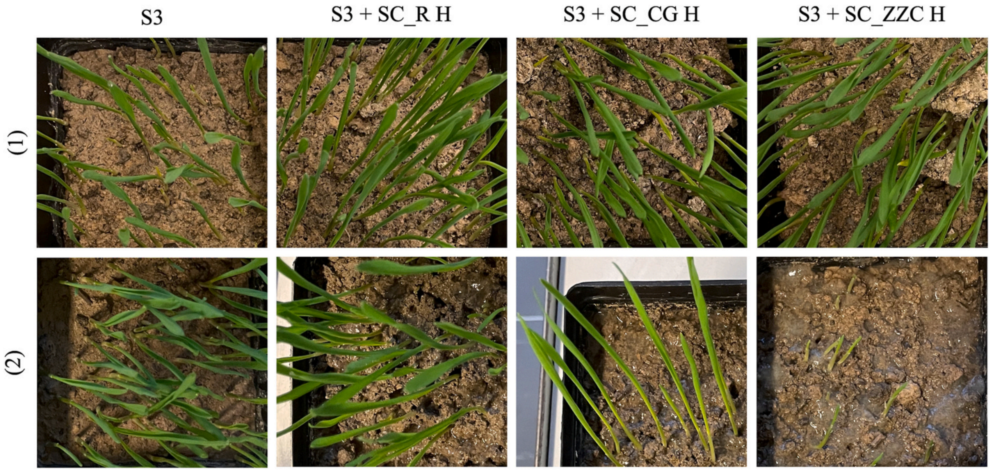

Fig. 13. Influence of the SCs on the growth of Christmas wheat on example of soil S3 for specimens with the (1) same initial water content and (2) initially saturated specimens. Photos were taken 187 h after seeding.

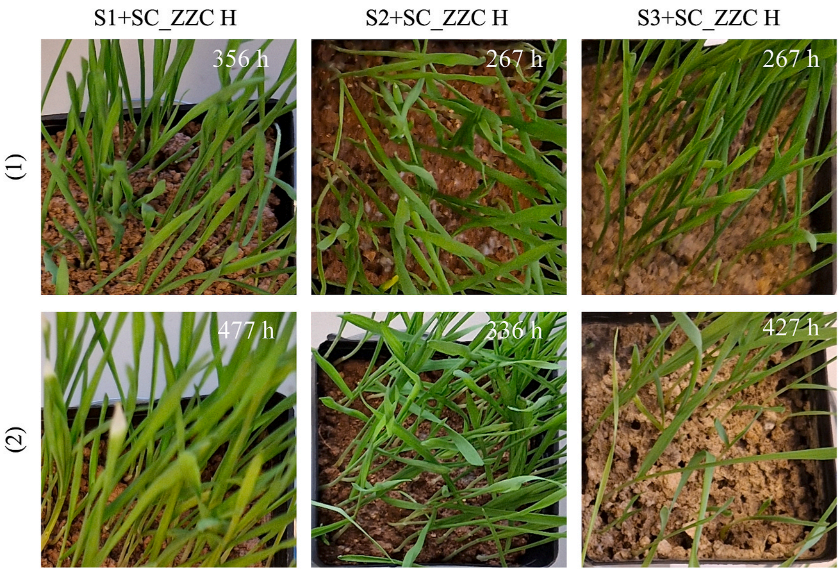

Fig. 14. Growth of Christmas wheat in mixtures of soils S1, S2 and S3 with high dosage of SC_ZZC for specimen with the (1) same initial water content and (2) initially saturated specimens with denoted time after seeding. Pictures were taken at the peak of the plant growth.

observed in the suction range between 100 kPa and 2000 kPa, although the effect was less pronounced [53]. Enhanced water retention in treated soils increased the availability of water to plant roots under drought conditions.

Moreover, this study highlights the impact of SCs on hydraulic conductivity. The treated soils exhibited lower saturated hydraulic conductivity than the untreated soils, which is consistent with previous studies [27,55,56]. In forests and other natural settings, the achievement and maintenance of soil saturation is infrequent and typically has a short duration. Therefore, the unsaturated hydraulic conductivity of the topsoil is a crucial parameter for studying water flow in the vadose zone [57–59]. In addition to providing water for plants and trees, the unsaturated zone also provides oxygen and nutrients to the plant roots [60]. Determining the unsaturated hydraulic conductivity is challenging, and measured data are scarce [61]. Although a direct comparison with literature data is not possible, the results indicate that SCs affect unsaturated hydraulic conductivity, with no discernible influence attributable to the specific type of SC used. For soils S2 and S3, the unsaturated hydraulic conductivity of mixtures was lower than that of the untreated soils, suggesting that SCs can effectively reduce water loss through evaporation and deep percolation.

The benefits of SCs also extend to plant growth under drought conditions, as demonstrated by the survival of plants in treated soils lasting up to eight days longer during non-watering phases. This observation is supported by Tran et al. [4] and Tariq et al. [13], who demonstrated that biopolymers can improve soil moisture availability and promote plant growth. However, upon air drying, the mixture on the surface can transform into a rigid crust, impeding sprout penetration during the initial stages of growth. Wang et al.

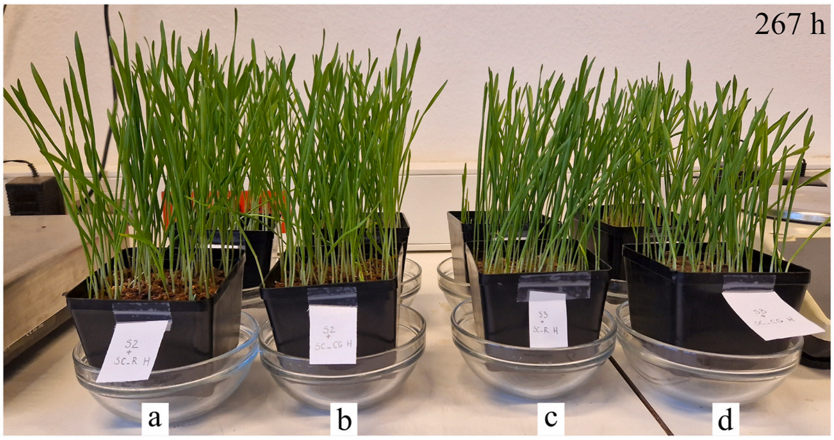

Fig. 15. Height of Christmas wheat in the mixtures of (a) S2+SC_R H, (b) S2+SC_CG H, (c) S3+SC_R H and (d) S3+SC_CG H at the peak of the plant growth. Specimens from the same soil were prepared at the same initial water content.

[12] reported the formation of a dry crust on the surface of XG-treated soil and its effect on sprout penetration during the early growth stages.

The observed behaviour of the mixtures stems primarily from the hydrogel nature of xanthan gum, which forms upon contact with water. Thus, the influence of the filler property in the SCs on the properties of the mixtures was not recognised.

Despite these advantages, careful consideration is necessary when determining the dosages of SC under specific conditions [11,13]. The dosage cannot be accurately predicted based solely on intrinsic soil properties such as grain size distribution, liquid and plastic limits, or water absorption. Local climatic conditions, including precipitation and evaporation, as well as the intended purpose of use must also be factored into dosage decisions.

The SCs developed under the ONEforest project are in granular form, making them easy to apply in practice. Based on laboratory-scale production methods [15,39], the estimated cost is approximately 20–25 €/kg. This is comparable to the prices of similar commercially available products, suggesting the potential for scalable technology [40]. Similar to commercial products, the developed dry SCs can be mixed directly into the soil at the tree-planting site, focusing on the root zone, where moisture retention and nutrient uptake are critical.

Future studies should focus on long-term field studies to validate these findings and explore how SCs interact with various soil types and microbial communities to provide deeper insight into their mechanisms of action [62].

6. Conclusions

Laboratory tests on three untreated soils (S1, S2, and S3) and their mixtures with xanthan-gum-based SCs (SC_R, SC_CG, and SC_ZZC) yielded the following key conclusions:

(1) Soils treated with SCs exhibited higher water absorption than untreated soils. While dosage and soil type influenced absorption, SC type had no effect.
(2) When the suction was less than 100 kPa, the water retention capacity of the SC-treated soil was notably higher than that of the untreated soil. SC type was not identified as an influential factor. The improvement in water retention capacity is favourable for providing available water for plant growth.
(3) SCs reduced the saturated hydraulic conductivity in all soils by two to four orders of magnitude, owing to pore clogging from swelling. Under unsaturated conditions, the impact of SCs varies. In soil S1, the effect is smaller than that in soils S2 and S3, where SC-treated soils have lower unsaturated conductivity.
(4) During the non-watering phase, plants grown from seeds sown in treated soils generally had longer survival rates than those grown in untreated soils, with the best survival observed in specimens that were initially saturated and had the highest water supply.

CRediT authorship contribution statement

Jasna Smolar: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Barbara Fortuna:** Writing – original draft, Visualization, Investigation, Data curation. **Janko Logar:** Writing – review & editing, Funding acquisition. **Alessandro Sorze:** Writing – review & editing, Resources, Methodology, Investigation. **Francesco Valentini:** Writing – review & editing, Resources, Methodology, Investigation. **Matej Maček:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Boštjan Pulko:** Methodology, Resources, Supervision, Writing – review & editing.

Data availability statement

Data are available upon reasonable request to the corresponding author.

Funding

The study has been funded by the European Union's Horizon 2020 Research and Innovation Program within the project ONEForest: A Multi-Criteria Decision Support System for Common Forest Management to Strengthen Forest Resilience, Harmonize Stakeholder Interests, and Ensure Sustainable Wood Flows (Grant Agreement No.: 101000406) and by the research program P2-0180 (B) Water Science and Technology, and Geotechnical Engineering: Tools and Methods for Process Analyses and Simulations, and Development of Technologies, supported by the Slovenian Research Agency.

Declaration of competing interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Acknowledgments

The authors express their gratitude to ONEforest partners University of Freiburg for providing the soil samples from Germany and to CTFC for providing the soil samples from Catalonia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e39974.

References

[1] P. Borrelli, L.A. Sandia Rondón, B. Schütt, The use of Landsat imagery to assess large-scale forest cover changes in space and time, minimizing false-positive changes, Appl. Geogr. 41 (Jul. 2013) 147–157, https://doi.org/10.1016/j.apgeog.2013.03.010.
[2] J.J. Roering, K.M. Schmidt, J.D. Stock, W.E. Dietrich, D.R. Montgomery, Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range, Can. Geotech. J. 40 (2) (Apr. 2003) 237–253, https://doi.org/10.1139/t02-113.
[3] G.B. Chirico, M. Borga, P. Tarolli, R. Rigon, F. Preti, Role of vegetation on slope stability under transient unsaturated conditions, Procedia Environ. Sci. 19 (2013) 932–941, https://doi.org/10.1016/j.proenv.2013.06.103.
[4] A.T.P. Tran, I. Chang, G.-C. Cho, Soil water retention and vegetation survivability improvement using microbial biopolymers in drylands, Geomech. Eng. 17 (5) (Apr. 2019) 475–483, https://doi.org/10.12989/GAE.2019.17.5.475.
[5] R. Chen, J.W. Huang, Z.K. Chen, Y. Xu, J. Liu, Y.H. Ge, Effect of root density of wheat and okra on hydraulic properties of an unsaturated compacted loam, Eur. J. Soil Sci. 70 (3) (May 2019) 493–506, https://doi.org/10.1111/ejss.12766.
[6] J. Ni, S. Liu, Y. Huang, Y. Gao, Temperature and plant root effects on soil hydrological response and slope stability, Comput. Geotech. 174 (Oct. 2024) 106663, https://doi.org/10.1016/j.compgeo.2024.106663.
[7] T. Xiao, P. Li, W. Fei, J. Wang, Effects of vegetation roots on the structure and hydraulic properties of soils: a perspective review, Sci. Total Environ. 906 (Jan. 2024) 167524, https://doi.org/10.1016/j.scitotenv.2023.167524.
[8] J.J. Ni, A.K. Leung, C.W.W. Ng, W. Shao, Modelling hydro-mechanical reinforcements of plants to slope stability, Comput. Geotech. 95 (Mar. 2018) 99–109, https://doi.org/10.1016/j.compgeo.2017.09.001.
[9] C.W.W. Ng, Q. Zhang, J. Ni, Z. Li, A new three-dimensional theoretical model for analysing the stability of vegetated slopes with different root architectures and planting patterns, Comput. Geotech. 130 (Feb. 2021) 103912, https://doi.org/10.1016/j.compgeo.2020.103912.
[10] I. Chang, A.K. Prasidhi, J. Im, H.-D. Shin, G.-C. Cho, Soil treatment using microbial biopolymers for anti-desertification purposes, Geoderma 253–254 (Sep. 2015) 39–47, https://doi.org/10.1016/j.geoderma.2015.04.006.
[11] J. Zhang, J. Liu, Y. Cheng, T. Jiang, D. Sun, M. Saberian, Water-retention behaviour and microscopic analysis of two biopolymer-improved sandy soils, Construct. Build. Mater. 403 (Nov. 2023) 133202, https://doi.org/10.1016/j.conbuildmat.2023.133202.
[12] S. Wang, X. Zhao, J. Zhang, T. Jiang, S. Wang, J. Zhao, Z. Meng, Water retention characteristics and vegetation growth of biopolymer-treated silt soils, Soil Tillage Res. 225 (Jan. 2023) 105544, https://doi.org/10.1016/j.still.2022.105544.
[13] Z. Tariq, D.N. Iqbal, M. Rizwan, M. Ahmad, M. Faheem, M. Ahmed, Significance of biopolymer-based hydrogels and their applications in agriculture: a review in perspective of synthesis and their degree of swelling for water holding, RSC Adv. 13 (35) (2023) 24731–24754, https://doi.org/10.1039/D3RA03472K.
[14] E. Collado, M. Piqué, J. Coello, J. de-Dios-García, C. Fuentes, L. Coll, Close-to-nature management effects on tree growth and soil moisture in Mediterranean mixed forests, For. Ecol. Manag. 549 (Dec. 2023) 121457, https://doi.org/10.1016/j.foreco.2023.121457.
[15] A. Sorze, F. Valentini, J. Smolar, J. Logar, A. Pegoretti, A. Dorigato, Effect of different cellulose fillers on the properties of xanthan-based composites for soil conditioning applications, Materials 16 (23) (Nov. 2023) 7285, https://doi.org/10.3390/ma16237285.
[16] A.F. Cabalar, H. Canakci, Direct shear tests on sand treated with xanthan gum, Proc. Inst. Civ. Eng. - Ground Improv. 164 (2) (May 2011) 57–64, https://doi.org/10.1680/grim.800041.
[17] A.F. Cabalar, M. Wiszniewski, Z. Skutnik, Effects of xanthan gum biopolymer on the permeability, odometer, unconfined compressive and triaxial shear behavior of a sand, Soil Mech. Found. Eng. 54 (5) (Nov. 2017) 356–361, https://doi.org/10.1007/s11204-017-9481-1.
[18] A.F. Cabalar, M.H. Awraheem, M.M. Khalaf, Geotechnical properties of a low-plasticity clay with biopolymer, J. Mater. Civ. Eng. 30 (8) (Aug. 2018) 04018170, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002380.
[19] H. Dehghan, A. Tabarsa, N. Latifi, Y. Bagheri, Use of xanthan and guar gums in soil strengthening, Clean Technol. Environ. Policy 21 (1) (Jan. 2019) 155–165, https://doi.org/10.1007/s10098-018-1625-0.
[20] Y.-M. Kwon, I. Chang, M. Lee, G.-C. Cho, Geotechnical engineering behavior of biopolymer-treated soft marine soil, Geomech. Eng. 17 (5) (Apr. 2019) 453–464, https://doi.org/10.12989/GAE.2019.17.5.453.

[21] Y.-M. Kwon, J.-H. Moon, G.-C. Cho, Y.-U. Kim, I. Chang, Xanthan gum biopolymer-based soil treatment as a construction material to mitigate internal erosion of earthen embankment: a field-scale, Construct. Build. Mater. 389 (Jul. 2023) 131716, https://doi.org/10.1016/j.conbuildmat.2023.131716.
[22] A. Soldo, M. Miletić, Study on shear strength of xanthan gum-amended soil, Sustainability 11 (21) (Nov. 2019) 6142, https://doi.org/10.3390/su11216142.
[23] S.P. Singh, R. Das, Geo-engineering properties of expansive soil treated with xanthan gum biopolymer, Geomechanics Geoengin. 15 (2) (Apr. 2020) 107–122, https://doi.org/10.1080/17486025.2019.1632495.
[24] A. Soldo, M. Miletić, M.L. Auad, Biopolymers as a sustainable solution for the enhancement of soil mechanical properties, Sci. Rep. 10 (1) (Jan. 2020) 267, https://doi.org/10.1038/s41598-019-57135-x.
[25] P. Bagheri, I. Gratchev, M. Rybachuk, Effects of xanthan gum biopolymer on soil mechanical properties, Appl. Sci. 13 (2) (Jan. 2023) 887, https://doi.org/10.3390/app13020887.
[26] I. Chang, et al., Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices, Transp. Geotech. 24 (Sep. 2020) 100385, https://doi.org/10.1016/j.trgeo.2020.100385.
[27] A. Mendonça, P.V. Morais, A.C. Pires, A.P. Chung, P.V. Oliveira, A review on the importance of microbial biopolymers such as xanthan gum to improve soil properties, Appl. Sci. 11 (1) (Dec. 2020) 170, https://doi.org/10.3390/app11010170.
[28] T. Berninger, N. Dietz, Ó. González López, Water-soluble polymers in agriculture: xanthan gum as eco-friendly alternative to synthetics, Microb. Biotechnol. 14 (5) (Sep. 2021) 1881–1896, https://doi.org/10.1111/1751-7915.13867.
[29] J. Wan, Z. Tang, Y. Liu, H. Xiao, H. Wang, Study on the improvement of clay properties by xanthan gum and its application on ecological slope protection engineering, Environ. Technol. (Mar. 2023) 1–14, https://doi.org/10.1080/09593330.2023.2186271.
[30] O.O. Ojuri, V. Ramdas, E.A. Aderibigbe, C.G. Williams, S. Ramchuran, H. Al-Nageim, Improving strength and hydraulic characteristics of regional clayey soils using biopolymers, Case Stud. Constr. Mater. 17 (Dec. 2022) e01319, https://doi.org/10.1016/j.cscm.2022.e01319.
[31] J. Zhang, J. Liu, A review on soils treated with biopolymers based on unsaturated soil theory, Polymers 15 (22) (Nov. 2023) 4431, https://doi.org/10.3390/polym15224431.
[32] C.W.W. Ng, P.S. So, S.Y. Lau, C. Zhou, J.L. Coo, J.J. Ni, Influence of biopolymer on gas permeability in compacted clay at different densities and water contents, Eng. Geol. 272 (Jul. 2020) 105631, https://doi.org/10.1016/j.enggeo.2020.105631.
[33] T.A. Adjuik, S.E. Nokes, M.D. Montross, O. Wendroth, The impacts of bio-based and synthetic hydrogels on soil hydraulic properties: a review, Polymers 14 (21) (Nov. 2022) 4721, https://doi.org/10.3390/polym14214721.
[34] A.M. Al-Darby, The hydraulic properties of a sandy soil treated with gel-forming soil conditioner, Soil Technol. 9 (1–2) (May 1996) 15–28, https://doi.org/10.1016/0933-3630(95)00030-5.
[35] M.A. Mustafa, A.M. Al-Omran, A.S. Shalaby, A.M. Al-Darby, Horizontal infiltration of water in soil columns affected by a gel-forming conditioner, Soil Sci. 145 (5) (1988) [Online]. Available: https://journals.lww.com/soilsci/fulltext/1988/05000/horizontal_infiltration_of_water_in_soil_columns.2.aspx.
[36] T.P.A. Tran, G.-C. Cho, C. Ilhan, Water retention characteristics of biopolymer hydrogel containing sandy soils, Hue Univ. J. Sci. Earth Sci. Environ. 129 (4A) (Apr. 2020), https://doi.org/10.26459/hueuni-jese.v129i4A.5652.
[37] O. Mohawesh, W. Durner, Effects of bentonite, hydrogel and biochar amendments on soil hydraulic properties from saturation to oven dryness, Pedosphere 29 (5) (Oct. 2019) 598–607, https://doi.org/10.1016/S1002-0160(17)60426-0.
[38] R. Liao, W. Wu, S. Ren, P. Yang, Effects of superabsorbent polymers on the hydraulic parameters and water retention properties of soil, J. Nanomater. 2016 (2016) 1–11, https://doi.org/10.1155/2016/5403976.
[39] A. Sorze, F. Valentini, A. Dorigato, A. Pegoretti, Development of a xanthan gum based superabsorbent and water retaining composites for agricultural and forestry applications, Molecules 28 (4) (Feb. 2023) 1952, https://doi.org/10.3390/molecules28041952.
[40] B. Fortuna, J. Logar, A. Sorze, F. Valentini, J. Smolar, Influence of xanthan gum-based soil conditioners on the geotechnical properties of soils, Appl. Sci. 14 (10) (May 2024) 4044, https://doi.org/10.3390/app14104044.
[41] ISO, ISO 17892-1:2014, Geotechnical Investigation and Testing — Laboratory Testing of Soil Part 1: Determination of Water Content.
[42] DIN, DIN 18132:2012-04, Soil, Testing Procedures and Testing Equipment - Determination of Water Absorption.
[43] Decagon Devices, Inc., WP4T Operators Manual, 2003, Version 2.1.
[44] METER Group, in: HYPROP 2, vols. 18263–02, METER Group, 2023 [Online]. Available: https://metergroup.com/products/hyprop-2/hyprop-2-support/.
[45] ASTM, ASTM D6836-02, Standard test methods for determination of the soil water chararcteristic curve for desorption using a hanging column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge (2008) e2.
[46] ISO, ISO 17892-11, Geotechnical Investigation and Testing — Laboratory Testing of Soil Part 11: Permeability Tests, 2019.
[47] A. Peters, W. Durner, Simplified evaporation method for determining soil hydraulic properties, J. Hydrol. 356 (1–2) (Jul. 2008) 147–162, https://doi.org/10.1016/j.jhydrol.2008.04.016.
[48] A. Peters, W. Durner, A simple model for describing hydraulic conductivity in unsaturated porous media accounting for film and capillary flow, Water Resour. Res. 44 (11) (Nov. 2008), https://doi.org/10.1029/2008WR007136, 2008WR007136.
[49] U. Schindler, W. Durner, G. Von Unold, L. Müller, Evaporation method for measuring unsaturated hydraulic properties of soils: extending the measurement range, Soil Sci. Soc. Am. J. 74 (4) (Jul. 2010) 1071–1083, https://doi.org/10.2136/sssaj2008.0358.
[50] METER Group, LABROS Soilview-Analysis for Hyprop, vols. 18422–04, METER Group, 2023 [Online]. Available: https://metergroup.com/products/hyprop-2/hyprop-2-support/.
[51] R. Shortt, A. Verhallen, P. Fisher, Monitoring soil moisture to improve irrigation decisions, in: Ministry of Agriculture, Food and Rural Affairs, Ontario, Jun. 2011.
[52] B. Narjary, P. Aggarwal, A. Singh, D. Chakraborty, R. Singh, Water availability in different soils in relation to hydrogel application, Geoderma 187–188 (Oct. 2012) 94–101, https://doi.org/10.1016/j.geoderma.2012.03.002.
[53] B. Rattan, K.V. Dhobale, A. Saha, A. Garg, L. Sahoo, S. Sreedeep, Influence of inorganic and organic fertilizers on the performance of water-absorbing polymer amended soils from the perspective of sustainable water use efficiency, Soil Tillage Res. 223 (Sep. 2022) 105449, https://doi.org/10.1016/j.still.2022.105449.
[54] J. Zhang, Z. Meng, T. Jiang, S. Wang, J. Zhao, X. Zhao, Experimental study on the shear strength of silt treated by xanthan gum during the wetting process, Appl. Sci. 12 (12) (Jun. 2022) 6053, https://doi.org/10.3390/app12126053.
[55] A. Bouazza, W.P. Gates, P.G. Ranjith, Hydraulic conductivity of biopolymer-treated silty sand, Geotechnique 59 (1) (Feb. 2009) 71–72, https://doi.org/10.1680/geot.2007.00137.
[56] S. Anandha Kumar, E.R. Sujatha, Assessing the potential of xanthan gum to modify in-situ soil as baseliners for landfills, Int. J. Environ. Sci. Technol. 19 (11) (Nov. 2022) 10613–10624, https://doi.org/10.1007/s13762-021-03721-4.
[57] X. Li, L.M. Zhang, D.G. Fredlund, Wetting front advancing column test for measuring unsaturated hydraulic conductivity, Can. Geotech. J. 46 (12) (Dec. 2009) 1431–1445, https://doi.org/10.1139/T09-072.
[58] M. Homolák, V. Pichler, W.A. Jury, J. Capuliak, J. O'Linger, J. Gregor, Unsaturated hydraulic conductivity estimation of a forest soil assuming a stochastic-convective process, Soil Sci. Soc. Am. J. 74 (1) (Jan. 2010) 292–300, https://doi.org/10.2136/sssaj2009.0200.
[59] J.-P. Wang, P.-Z. Zhuang, J.-Y. Luan, T.-H. Liu, Y.-R. Tan, J. Zhang, Estimation of unsaturated hydraulic conductivity of granular soils from particle size parameters, Water 11 (9) (Aug. 2019) 1826, https://doi.org/10.3390/w11091826.
[60] C. Dirksen, Unsaturated Hydraulic Conductivity, vol. 5, Wageningen Agricultural University, Netherlands, 1990.
[61] I. Vogeler, S. Carrick, L. Lilburne, R. Cichota, J. Pollacco, J. Fernández-Gálvez, How important is the description of soil unsaturated hydraulic conductivity values for simulating soil saturation level, drainage and pasture yield? J. Hydrol. 598 (Jul. 2021) 126257 https://doi.org/10.1016/j.jhydrol.2021.126257.
[62] Y. Sun, et al., Organic fertilization enhances the resistance and resilience of soil microbial communities under extreme drought, J. Adv. Res. 47 (May 2023) 1–12, https://doi.org/10.1016/j.jare.2022.07.009.