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Preparation of a Biogel by Immobilizing *TERIA S* Bacterial Cells on CMC-Based Hydrogel and Its Effect on the Germination of *Ferula Tadshikorum* Seeds

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Abstract Currently, the demand for medicinal plants is steadily increasing; therefore, their use as a source of raw materials has significant economic potential. A number of medicinal plants are endemic, and they can serve as valuable sources for the development of biopharmaceuticals with global market relevance. However, environmental changes, depletion of macro- and microelements in soils, and, most importantly, water scarcity negatively affect agricultural crops, including medicinal plants. These factors reduce the yield and biological activity of pharmacologically important compounds. In this study, an eco-friendly hydrogel was synthesized using carboxymethylcellulose (CMC) derived from cellulose waste. The hydrogel is biodegradable, non-polluting to soil, and possesses high water retention capacity. Its physicochemical properties were investigated, and pore sizes were determined using scanning electron microscopy (SEM) along with elemental composition analysis. *TERIA S* bacterial cells were immobilized within the hydrogel pores. To confirm immobilization, the obtained biogel was incubated at 50 ℃ for 10 days, followed by cultivation in nutrient medium, yielding positive results. The resulting biogel was further applied for encapsulation of *Ferula tadshikorum* seeds to evaluate its effect on germination, growth, and development. Experimental results showed that seeds encapsulated in the biogel demonstrated higher germination rates, enhanced root system activity, and improved uptake of essential nutrients such as phosphorus, potassium, calcium, silicon, sulfur, and nitrogen. Furthermore, this approach reduced the plant's water demand, promoted growth and development, increased resistance to phytopathogens, and improved both yield and quality of the medicinal plant. Field experiments were conducted on rain-fed lands in the Surkhandarya region.

Keywords Hydrogel, Biogel, Immobilization, *TERIA S*, *Ferula tadshikorum*, Seed germination, Biotechnology, Medicinal plants

1. Introduction

Currently, global climate change, rapid population growth, and the expansion of agricultural activities have led to a sharp increase in the demand for water resources. According to the World Health Organization and the United Nations Economic Commission for Europe, more than 70% of the world's freshwater consumption is used in agriculture, particularly for irrigation purposes [1]. At the same time, reserves of drinking and irrigation water are steadily declining, which poses serious threats to food security, ecosystem stability, and human health [2]. Water scarcity is especially acute in semi-arid and arid regions. Under such conditions, the rational use of water in agriculture, particularly in the cultivation of medicinal plants, the application of effective agrotechnical practices, and the development of new biotechnological approaches have become urgent tasks [3].

Reducing the water demand of plants while preserving or even enhancing their medicinal properties is one of the most important scientific directions. In particular, hydrogels derived from cellulose, bacterial biopreparations, and biogel technologies are considered innovative solutions that enable the successful cultivation of medicinal plants under limited water supply. Such approaches contribute to sustainable productivity by retaining soil moisture for extended periods, protecting plants from stress conditions, and improving nutrient uptake [4]. From this perspective, cultivating medicinal plants such as *Ferula tadshikorum* using biogel technologies not only ensures ecological sustainability and

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water conservation but also plays a vital role in meeting the demand for pharmaceuticals while protecting the environment. Over the past 30 years, extensive scientific developments have focused on the synthesis of hydrogels and their application in agriculture. The term "hydrogel" originates from the Greek words "hydro" (water) and "gel" (a substance between solid and liquid states), meaning "water-containing gel." It was first introduced in the 1960s by Otto Wichterle and Drahoslav Lim, who succeeded in creating a crosslinked polymer—hydrogel—based on poly(2-hydroxyethyl methacrylate) (polyHEMA), capable of absorbing water [5].

Natural hydrogels contain biopolymers such as cellulose, starch, alginate, chitosan, and gelatin, which are considered environmentally safe due to their biodegradability. These hydrogels are suitable for use in sustainable agricultural practices [7]. For instance, cellulose-based hydrogels have been shown to increase soil water retention and improve crop productivity. Similarly, chitosan-based hydrogels, derived from crustacean shells, are widely applied due to their antimicrobial activity and biodegradability, making them effective in protecting plants against harmful microorganisms [8]. However, natural hydrogels typically exhibit lower mechanical strength and water retention capacity compared to synthetic hydrogels, limiting their application under complex agroecological conditions [9,10].

In Uzbekistan, the biology and natural reserves of plants belonging to the genus *Ferula* have been studied by U. Rakhmonqulov (1981; 1999), S. Meliboev (1985), Kh. Nishonboeva (1972), I.U. Muqumov (1993), and Kh. Rakhmonov (2017), as well as O. Avalboev (2020). The chemical and pharmacological properties of *Ferula* species were investigated by A.I. Saidkhodjaev (1984), G.K. Nikonov (1971), and V.M. Mlikov (1998), while pharmacological effects were assessed by Rakhimov (2007). According to U. Rakhmonqulov (1999) and S. Meliboev, more than 20 species of *Ferula* have been identified in natural reserves. In Uzbekistan, M.A. Khalkuziyeva (2022) carried out studies on the prospects of establishing *Ferula tadshikorum* plantations in rain-fed lands, while A.E. Sharipov (2025) also contributed to research in this field.

At present, in-depth investigation of the ontogenetic biological characteristics of these species, the establishment of plantations for resin (gum) production, and the rational use of existing natural habitats remain among the most pressing scientific and practical tasks.

2. Materials and Methods

In the course of this study, a hydrogel was synthesized based on carboxymethyl cellulose (CMC). To investigate the microstructural and morphological characteristics of the synthesized hydrogel, Scanning Electron Microscopy (SEM) was employed. This method enabled the determination of pore size, shape, and distribution within the hydrogel matrix. However, since SEM operates under vacuum conditions and uses an electron beam, direct observation of hydrogels with high moisture content was not feasible. Therefore, specific sample preparation steps were performed prior to SEM analysis.First, the hydrogel samples were thoroughly dried using one of two methods: vacuum drying or lyophilization (freeze-drying). For SEM analysis, lyophilization was considered the most suitable method, as it removed water while preserving the microstructure of the hydrogel. In this process, hydrogel samples were frozen at −20 ℃ to −80 ℃ and then subjected to sublimation in a freeze-dryer [11]. As a result, water crystals sublimated without damaging the structural integrity of the hydrogel.

The dried samples were cut into small pieces (approximately 5–10 mm) and mounted on SEM stubs. Since hydrogels are dielectric materials and non-conductive, their surfaces were coated with a conductive layer of gold (Au), platinum (Pt), or palladium (Pd) using a sputter-coating apparatus. The metal coating thickness was approximately 5–10 nm, which ensured uniform electron beam distribution and improved image resolution.

The coated samples were placed in the SEM chamber. The accelerating voltage, one of the main operating parameters, was adjusted within the range of 5–20 kV. Additional parameters such as focus, brightness, contrast, and spot size were optimized according to image quality. After proper calibration, high-resolution SEM images were obtained, allowing for the characterization of pore diameters, internal structural uniformity, and bacterial cell localization within the hydrogel [12]. These analyses provided critical insights into the physicochemical and morphological properties of the hydrogel. In the subsequent experiments, Teria-S biofertilizer bacteria were immobilized within the CMC-based hydrogel. For this purpose, 100 ml of Eschbi nutrient medium was inoculated with 2.0 ml of Teria-S biofertilizer and cultivated under deep fermentation for three days. The resulting suspension was then introduced into hydrogel samples at concentrations of 1.0%, 2.0%, and 3.0%, followed by incubation for 12 to 60 hours under shaking conditions (180 rpm) at 30–32 ℃. The prepared biogel was then used for encapsulation of Ferula tadshikorum seeds. As the experimental object, Ferula tadshikorum—a highly valuable and widely cultivated medicinal plant—was selected due to its economic significance. F. tadshikorum is a perennial, monocarpic hemicryptophyte with a taproot system. The upper part of the root forms a thickened rhizome, measuring 30–40 cm in length, with a basal neck diameter ranging from 25 to 40 cm. The plant is characterized by a strong garlic-like odor, and its rhizome serves as a reservoir of organic compounds and water. The stem height can reach up to 2.5 m. Experimental studies were conducted in the territories of "Qiziriq" and "Boysun" state forestry enterprises in Surkhandarya region, where biogels were applied to F. tadshikorum plants and plantations were established. The average annual temperature in these regions is approximately 16–18 ℃. During the coldest months (January–February), minimum temperatures may fall to −13 ℃, while maximum values range from +3 to +6 ℃. In summer (July), maximum temperatures reach +33–35 ℃, occasionally exceeding +40 ℃. In April, average temperatures are +16 ℃ (day) and +7 ℃ (night). Rainfall is scarce in August, with average temperatures of +28/+16 ℃. Annual precipitation is about 400–460 mm, with the wettest period occurring from February to April (77–86 mm per month), while summer precipitation is minimal (~5 mm). Snowfall occurs from November to March, with the highest levels recorded in January (~54 mm).The propagation of F. tadshikorum using biogel technology was studied in these conditions, with emphasis on its biomorphological characteristics. For determining morphological traits and phenological phases, the methods of I.N. Beydeman (1974) and G.E. Shulz (1966) were applied.

3. Results and Discussion

Using carboxymethyl cellulose (CMC) derived from cellulose waste, an environmentally friendly hydrogel was synthesized. This hydrogel is biodegradable, non-polluting to soil, and exhibits a high water-retention capacity. For synthesis, 6 g of CMC and 2 g of polyvinyl alcohol (PVA) were dissolved in 100 ml of distilled water. The mixture was stirred on a magnetic stirrer at 90 ℃ until complete dissolution was achieved. After stirring, the solution was placed in a −40 ℃ freezer for 24 hours. Upon removal, the frozen samples were thawed, and the freeze–thaw cycle was repeated several times to enhance gel formation. After the final thawing, the samples were incubated in a thermostat at 20 ℃ for 24 hours.

Following incubation, the physicochemical properties of the hydrogel were investigated. The water absorption capacity was determined using the gravimetric method. It was found that 1 g of hydrogel could absorb approximately 220–280 ml of water under laboratory conditions, demonstrating its strong hydrophilic nature.

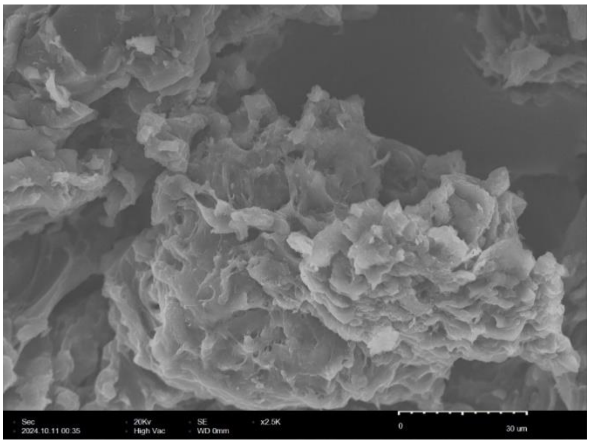


Figure 1. *SEM image of the hydrogel synthesized from carboxymethyl cellulose (CMC) at 20 kV, ×2.5k magnification, within a 30 μm scale range*

In the subsequent stage, the morphology of the hydrogel was studied using Scanning Electron Microscopy (SEM). The analysis revealed the porous architecture of the hydrogel, while elemental composition was determined through energy -dispersive X-ray (EDX) analysis (Figure 1). These structural and compositional features confirmed the suitability of the synthesized hydrogel for biological immobilization and agricultural applications.

Microstructural Morphology Analysis of the Hydrogel

To investigate the microstructural morphology of the hydrogel, Scanning Electron Microscopy (SEM) was employed. Figure 1 presents a high-resolution SEM image of the hydrogel synthesized from carboxymethyl cellulose (CMC). As can be seen, the hydrogel sample exhibits a characteristic porous structure with noticeable inorganic formations and surface depressions. The presence of pores within the hydrogel structure directly contributes to its water absorption and retention capacity. Moreover, such a porous network provides a favorable environment for the immobilization of bacterial cells within the hydrogel matrix.For SEM analysis, the hydrogel sample was initially frozen at temperatures ranging from −20°C to −80°C, followed by lyophilization using a vacuum dryer. The dried hydrogel fragments were mounted onto a metal stub and sputter-coated with a thin layer (5–10 nm) of gold (Au) to ensure uniform electron distribution and improved image resolution. The analysis was performed at an accelerating voltage of 20 kV under high-vacuum conditions with a magnification of ×2500.

This morphological analysis revealed that the hydrogel possesses an inorganic-like surface structure characterized by depressions and pores of varying sizes. Such features are critical for defining the physicochemical properties of the hydrogel, particularly its ability to retain water and serve as a carrier for biological cells. Furthermore, the homogeneous distribution of the internal structure highlights its potential as an efficient biomatrix for microbial immobilization.

Elemental composition of the hydrogel synthesized from CMC was further examined using Energy Dispersive X-ray Spectroscopy (EDS) integrated with the SEM system.

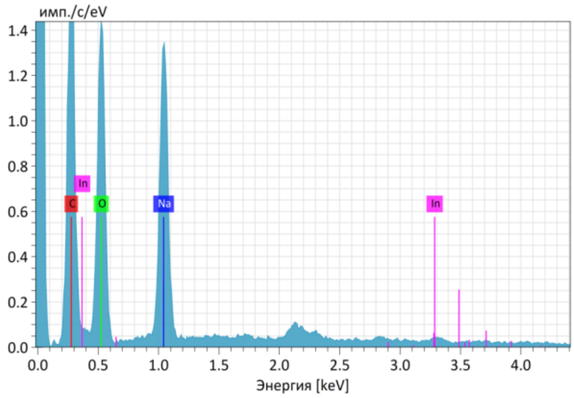
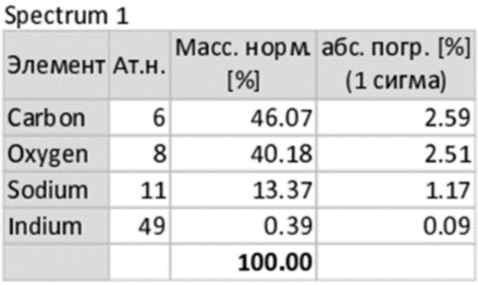


Figure 2. *EDS spectrum of the hydrogel synthesized from CMC (SEM-EDS analysis). The spectrum clearly shows the characteristic energy peaks corresponding to C, O, Na, and In elements, confirming the organic and hydrophilic nature of the material*

According to the spectral analysis, the hydrogel contains four major elements: carbon (C), oxygen (O), sodium (Na), and indium (In). The mass composition indicates that carbon accounts for 46.07%, oxygen for 40.18%, sodium for 13.37%, and indium for 0.39%. This elemental ratio confirms the predominance of organic components, particularly starch derivatives (CMC), within the hydrogel structure.

Table 1. *Quantitative elemental composition of the hydrogel*



Spectrum 1

Элемент	Ат.н.	Масс. норм. [%]	абс. погр. [%] (1 сигма)
Carbon	6	46.07	2.59
Oxygen	8	40.18	2.51
Sodium	11	13.37	1.17
Indium	49	0.39	0.09
		100.00	

The high proportion of carbon and oxygen corresponds to the starch chains forming the main polymer matrix of the hydrogel. The presence of sodium confirms the involvement of sodium-based reagents (e.g., NaOH or sodium monochloroacetate) during hydrogel synthesis. The trace amount of indium is most likely attributed to instrumental contamination or a specific characteristic of the analytical equipment.

Overall, the elemental composition results confirm that the hydrogel is a polymer material with an organic base and contains hydrophilic groups. These groups directly contribute to its ability to absorb and retain water. The CMC-based hydrogel, being derived from natural sources, possesses hydrophilic functionalities that make it highly suitable for applications as a water-retaining material and as a carrier for biological cells.Taking advantage of this property, the immobilization of *Teria-s* bacterial cells onto the hydrogel matrix was performed. For this purpose, the adsorption of *Teria-s* biofertilizer onto the hydrogel was carried out. Specifically, 100 mL of Ashby nutrient medium was prepared, to which 2.0 mL of *Teria-s* biofertilizer was added, followed by submerged cultivation for 3 days. The resulting suspension was then added to biogel samples of 1.0%, 2.0%, and 3.0% concentrations and incubated at 30–32 ℃ on a shaker at 180 rpm for 12–60 hours. After the incubation period, the number of *Teria-s* cells immobilized within the biogel was quantified using a Goryaev chamber. The obtained experimental results are presented in Table 2.

The obtained results clearly demonstrate that in the 1.0% hydrogel, the immobilized bacterial density remained around 3.5×10^4 CFU/mL throughout the 12–60 h incubation period. In contrast, significantly higher values were recorded in the 2.0% and 3.0% hydrogel samples. As shown in Table 2, the 2.0% hydrogel achieved an immobilization level of 5.5×10^4 CFU/mL after 60 h, while the 3.0% hydrogel reached 8.0×10^4 CFU/mL during the same period. These findings indicate that the 3.0% hydrogel concentration is the most effective for immobilizing *Teria-s* bacterial cells. To further evaluate the viability of the immobilized *Teria-s* cells, experiments were conducted using CMC-based biogels. After the immobilization process, the thermal stability of the bacteria was tested by incubating the hydrogel samples at 50 ℃ for 10 days in a thermostat. Following this treatment, the survival rate of the bacteria was assessed. For viability testing, the immobilized hydrogel samples were subjected to a desorption process in sterilized distilled water, during which the bacterial cells were gently released into the medium. The resulting suspension was plated onto GRA (glycerol–raffinose–agar) medium and incubated at 37 ℃ for 24 h. Bacterial growth intensity was taken as the primary indicator of viability. The experiment showed that bacteria retained in the biogel matrix remained highly viable even after drying and thermal treatment. In contrast, control samples (bacteria kept in sterile distilled water) exhibited much lower growth activity, indicating reduced tolerance to thermal stress. Furthermore, the higher number of colonies observed after desorption confirmed that the porous structure of the hydrogel provided protective microenvironments for the cells. Overall, the biogel matrix effectively shielded *Teria-s* bacteria from harmful external factors and preserved their biological activity, demonstrating its potential as a reliable carrier system for microbial immobilization.

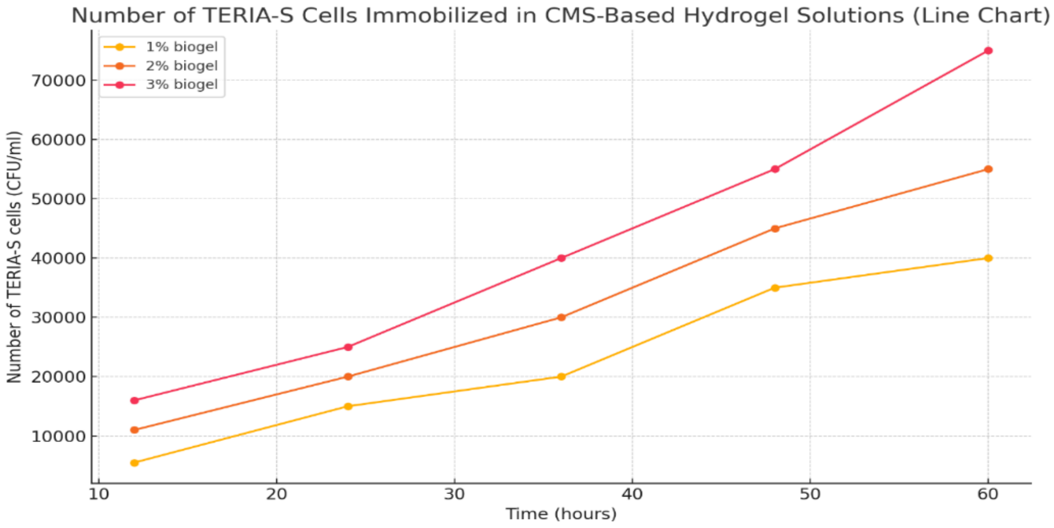


Table 2. *Number of* **Teria-s** *cells immobilized in the hydrogel at different incubation times (12–60 h), (CFU/mL)*

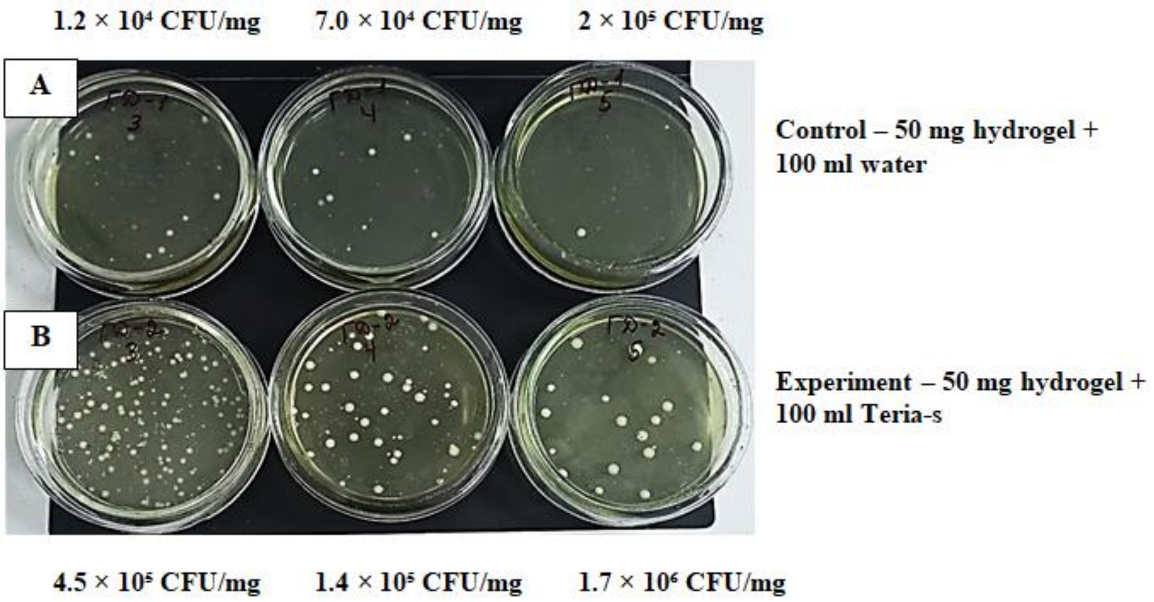


Figure 3. *Viability of TERIA-S bacteria: A – bacteria in the biogel composition; B – sample placed in sterile distilled water as a control*

TERIA-S bacteria were immobilized into a hydrogel synthesized on the basis of CMC, resulting in the formation of a biologically active biogel. In order to evaluate the practical effectiveness of this biogel, the prospects of creating plantations through encapsulation of medicinal plant seeds with it were studied. As the object of research, the species *Ferula tadshikorum* (kovrak), growing in the Surkhandarya region, was selected. *Ferula tadshikorum* seeds are characterized by low natural germination rates, while their biological properties and germination conditions in soil have not been sufficiently studied. In particular, in the territories of Boysun and Qiziriq State Forestry of the Surkhandarya region, the natural germination rate of this species proceeds extremely poorly. Therefore, the use of biologically active biogels to enhance their germination potential is considered both scientifically and practically relevant. The seeds of *F. tadshikorum* are morphologically elliptical with a smooth surface, having an average length of 1.5–2.0 cm and a width of about 0.8–1.0 cm. The absolute seed mass reaches up to 35–40 g. In natural germination, cold resistance and the dormancy phase play an important role. In the study, these seeds were divided into two groups: the first group consisted of untreated (control) seeds, while the second group included seeds encapsulated with a biogel based on CMC enriched with TERIA-S bacteria. The experiment was conducted under field conditions during 2022–2024. In December 2022, the seeds were sown in rainfed land at a depth of 0.5–1.0 cm. Before sowing, the seeds had been stored at a temperature of +4 ℃. The plots were monitored under natural conditions without any agro-technical treatment. Seeds treated with the biogel demonstrated distinct features, such as water retention in the soil, supply of microelements, stimulation of root system development, and protection of plants against stress factors.

Field observations showed that seeds treated with the biogel demonstrated significantly higher germination rates compared to the control group. Plant water demand decreased by up to 50–55%, the root system developed more actively, and soil salinity and gypsum content were reduced. Moreover, due to the biological activity of TERIA-S bacteria in the biogel composition, the plants were supplied with essential elements such as phosphorus, potassium, calcium, nitrogen, and sulfur. As a result, the plants showed increased resistance to diseases and pests, while yield quality and quantity increased by up to 30–35% compared to the control group.

Due to the low natural germination rate of *Ferula tadshikorum* seeds, field experiments were carried out to improve germination efficiency through encapsulation with the biogel. Seeds were sown at a depth of 0.5–1.0 cm in natural rainfed fields. Within the experiment, one group of seeds was treated with the biogel (experimental group), while the other was sown with plain water (control group). Germination rates were monitored every 5 days.

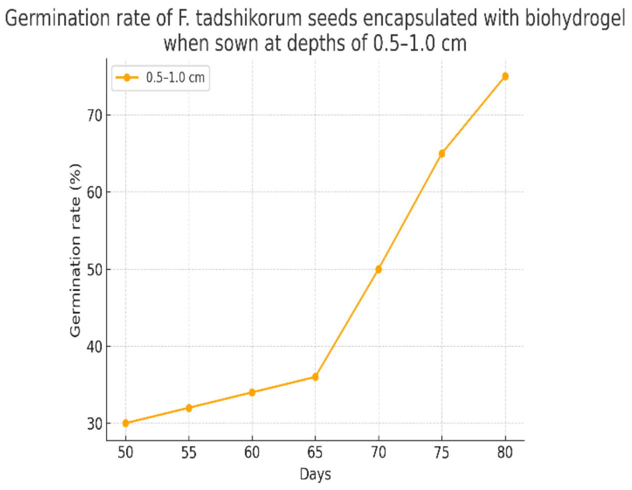


Table 3. *Germination rate of F. tadshikorum seeds encapsulated with biohydrogel when sown at depths of 0.5–1 cm*

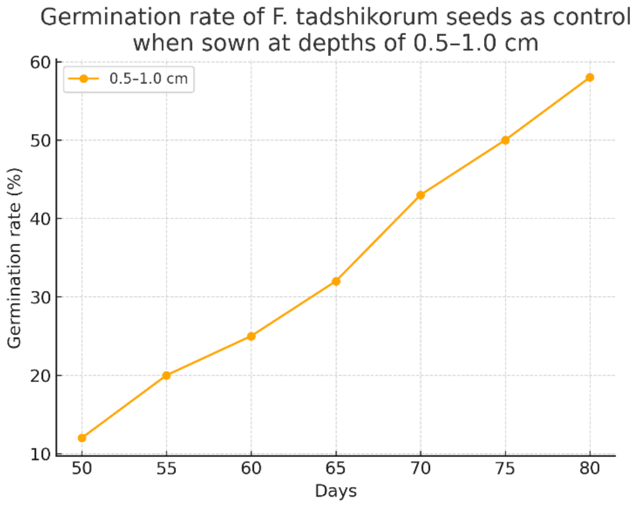


Table 4. *Germination rate of F. tadshikorum seeds as control when sown at depths of 0.5–1 cm*

According to the analysis results, the germination rate of seeds encapsulated with the biogel reached 28% on day 50 and increased up to 75% by day 80 (Table 3). In contrast, in the control group, germination was recorded at 13% on day 50 and reached a maximum of 58% on day 80 (Table 4).

This difference can be explained as follows:

- The biogel ensures an optimal microclimate around the seeds by retaining moisture for a long period.
- The hydrogel enriched with TERIA-S bacteria mobilizes microelements in the soil and creates a favorable environment for growth.
- The biogel stimulates root development and reduces stress in the rhizosphere.

The morphological parameters of *F. tadshikorum* leaves—length, width, and petiole length—were analyzed over a 3-year period in groups grown under encapsulation with the biogel and in control conditions. Measurements were conducted on 100 samples in each group. In plants treated with the biogel, stable and higher growth rates were observed across all parameters during the three years. In particular, leaf length reached up to 22 cm, width up to 12 cm, and petiole length up to 22 cm (Table 5). These values were higher compared to the control group, where the respective parameters reached only 15 cm, 9 cm, and 18 cm (Table 6).

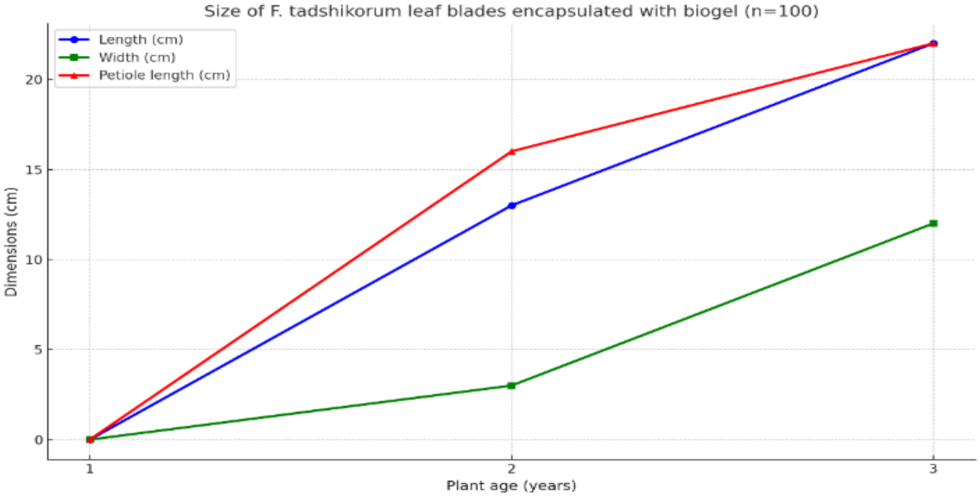


Table 5. *Leaf size of F. tadshikorum when seeds were sown encapsulated with the biogel (n=100)*

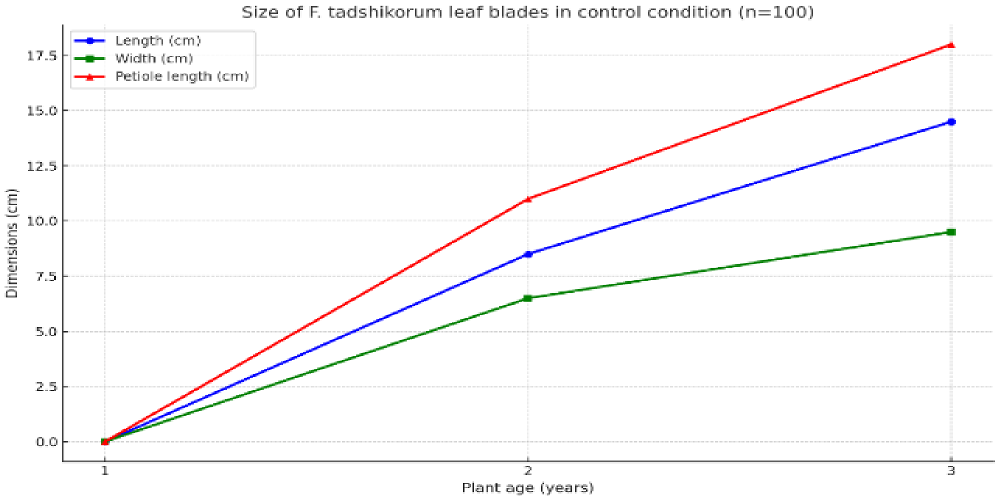


Table 6. *Leaf size of F. tadshikorum when seeds were sown as control (n=100)*

Such a difference is primarily associated with the hydrophilic properties of the biogel. By creating an optimal microclimate around the roots, the hydrogel maintains stable soil moisture. In addition, the biogel with immobilized TERIA-S bacterial cells supplies the plant with micro- and macroelements that stimulate plant physiology. The above results demonstrate that the biogel has a positive effect on the leaf morphology of *F. tadshikorum*. This not only accelerates the vegetative development of the plant but also enhances its overall ecological stability and adaptive capacity. Such an approach can be recognized as a highly effective agro-biotechnological method for the establishment of medicinal plant plantations.

During the study, eight key morphobiological indicators of the root system of *F. tadshikorum*—total root length, tuber length, root diameter, root collar diameter, lateral root length, fresh weight, dry weight, and dry matter content—were monitored and analyzed over a two-year period in samples grown under biogel treatment and in control conditions. Considering that the main medicinal compounds of *F. tadshikorum* accumulate in the root parts, special attention was paid to root system morphology in the research. For each experimental variant, 100 root samples were selected, and measurements were carried out based on standard morphobiological criteria.

The experimental results showed that in plants encapsulated with the biogel, all indicators demonstrated higher values compared to the control group. In particular, by the end of the third year, the total root length in the biogel group reached 54.6 cm (Table 7), whereas in the control it was 31.5 cm (Table 8). The tuber length was 20.5 cm and 14.25 cm, the root diameter was 6.0 cm and 2.25 cm, and the root collar diameter was 5.9 cm and 1.6 cm, respectively. The length of lateral roots, as well as fresh and dry weights, were also higher in the biogel group: the fresh weight amounted to 180.5 g, while the dry weight was 24 g.

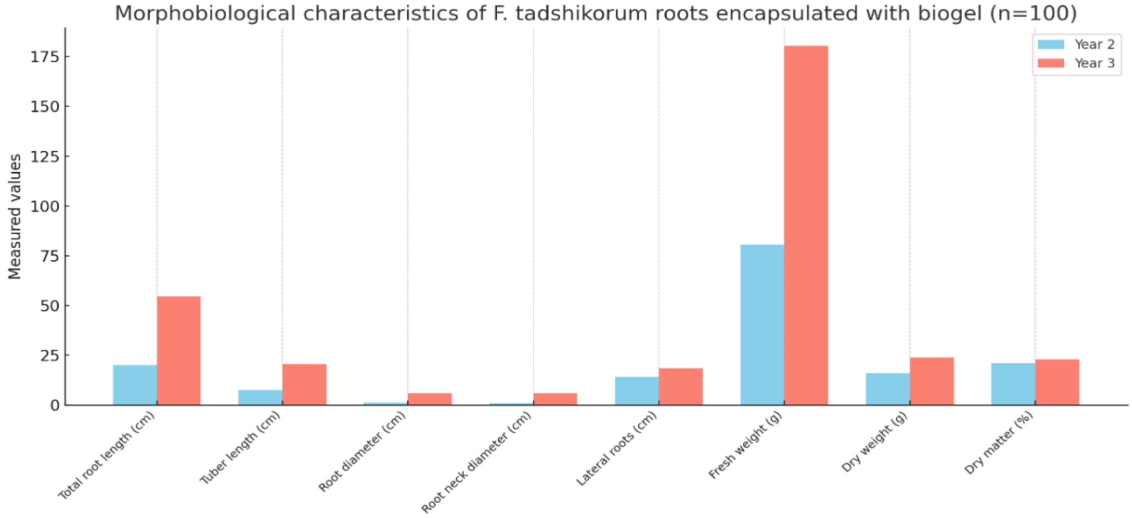


Table 7. *Morphobiological classification of F. tadshikorum roots when seeds were sown encapsulated with the biogel (n=100)*

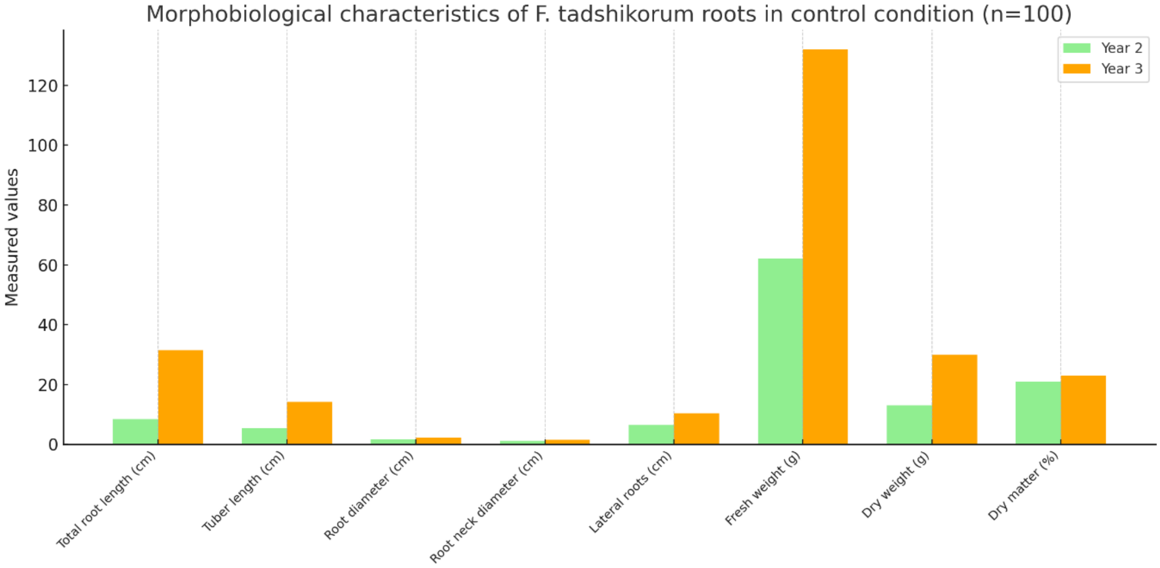


Table 8. *Morphobiological classification of F. tadshikorum roots when seeds were sown as control (n=100)*

These differences are primarily explained by the ability of the biogel to retain soil moisture and by the influence of TERIA-S bacteria in synthesizing macro- and microelements, which stimulate the development of the plant root system. By creating optimal climatic conditions for the plant, the biogel ensured deep and strong root development, which contributed to a stable supply of water and nutrients. In contrast, in control plants, the root system was poorly developed, the tuber parts grew weakly, and the root collar diameter was considerably smaller. This indicates that *F. tadshikorum* plants sown under ordinary conditions exhibit low resistance to nutrient deficiency and drought. In conclusion, the biogel provided significant morphobiological advantages in the development of the *F. tadshikorum* root system, and this approach can be recommended as a technology with high agrobiotechnological and ecological efficiency for the establishment of medicinal plant plantations.

4. Conclusions

Within the framework of this study, a hydrogel was synthesized on the basis of natural polymers such as carboxymethyl starch (CMS), and TERIA-S bacterial cells were immobilized into its structure, resulting in the creation of an environmentally safe and biologically active biogel. The main advantages of the synthesized hydrogel are related to its biodegradability in soil, hydrophilic properties, the ability to preserve bacterial viability, and its capacity to retain essential macro- and microelements required for plants. Due to these properties, it demonstrated high agrobiotechnological efficiency not only under laboratory but also under field conditions. The immobilization of TERIA-S bacteria within the biogel further enhanced its biological activity, ensuring the long-term viability of microorganisms within the hydrogel and guaranteeing their beneficial activity in the rhizosphere. Such a system stimulates plant nutrition, increases resistance to stress conditions, and accelerates overall growth.

Field experiments revealed that when *Ferula tadshikorum* seeds were sown at a depth of 0.5–1.0 cm in an encapsulated biogel form, their germination rate increased by 30–40% compared to the control group. The biogel not only created an optimal microclimate around the plants and retained water for an extended period but also supplied essential elements. Particularly under conditions of water scarcity, salinity, and sandy soils, the water retention and nutrient carrier functions of the biogel proved to be crucial. Indicators of the root system of *F. tadshikorum* (root length, diameter, tuber formation, weight, and dry matter content) were significantly higher in the biogel-treated samples compared to the control group. Furthermore, leaf size and vegetative development stages were accelerated under the influence of the biogel. These results indicate that this approach is effective not only under experimental conditions but also in real agro-technical environments.

The practical significance of this experiment lies in the fact that medicinal plants such as *F. tadshikorum* can be successfully cultivated even in water-deficient and resource-limited environments. Field trials conducted in rainfed lands of the Surkhandarya region confirmed that the use of biologically active biogel significantly increases seed germination, agrobiological stability, and productivity of medicinal plants. As a result, large-scale plantations can be established, the raw material base can be stabilized, and the quality of bioactive compounds can be improved.

In conclusion, the synthesized CMS-based biogel represents an innovative approach in agricultural technology, playing an important role in developing ecologically safe, economically efficient, and scientifically substantiated methods for plant cultivation. This, in turn, is a promising outcome that can be widely applied in the fields of pharmaceuticals, agrochemistry, and environmental protection.

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