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AlgalTextile - a new biohybrid material for wastewater treatment

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ABSTRACT

Efficient nutrient extraction from wastewater and reuse as bio-fertilizer is an important task for reducing anthropogenic load toward circular economy. Inspired by microbial mats and biofilms, we developed a new material AlgalTextile (AT) that effectively absorbs nutrients from a medium. AT consists of three fully organic components: microalgae, alginate and textile. AT sequestered up to 99% of phosphorus ($P\text{-}PO_4$) and 76% of total bound nitrogen from a medium. The uptake rate of phosphorus and nitrogen by AT was highest among all methods using photosynthetic microorganisms, but lower than EBPR and physicochemical methods for phosphorus removal, and anammox and denitrifying bacteria for nitrogen removal. Advantages of AT are its easy production, possibility of seasonal use and utilization as fertilizer. AT as biofertilizer for cress resulted in 35% greater length compared to the control. This outlines a promising technique for seasonal wastewater treatment, improving soil fertility and treatment of polluted surface runoff.

1. Introduction

Nowadays it is necessary to develop methods to reuse nitrogen and phosphorus from wastewater, as these elements cause eutrophication of water bodies [1], and phosphorus is an exhaustible resource. The demand of phosphorus as an essential element in agriculture is steadily growing because of a constant increase in food production for the world's growing population [2]. When phosphorous fertilizers are applied to the fields, up to 66% is washed off into ground waters [3] leading to the release into water bodies and the initiation of eutrophication. Given that phosphorus is a non-renewable resource [4], the economic need to recycle it increases as the cost of its mining continues to rise [5]. Cost-effective use of harvested biomass is crucial for the development of a circular economy in wastewater treatment [6].

The cultivation of photosynthetic micro-organisms using wastewater as a nutrient medium is a promising alternative to traditional treatment methods for municipal, industrial or agricultural wastewater [7–9]. Microalgae are able to efficiently accumulate nutrients from water. Their biomass can be a valuable product and used for various purposes [10]: fertilizer, additives in animal feed, biofuel, etc. [11,12].

One of the main problems for the reuse of microalgal biomass as a bio-fertilizer is the low microalgae harvesting efficiency. Various methods are used for harvesting of microalgae (centrifugation, sedimentation with ballast agents, flocculation, flotation, etc. [13,14]). The most cost-effective method up to date is passive cell sedimentation [10]. Nevertheless, microalgal biomass harvesting is still a quite expensive and time-consuming process [15]. There is need for a method that would enable efficient absorption of nutrients, but at the same time allow for convenient collection of biomass and further use in the form of biofertilizer.

Inspiration by a natural process could help to achieve these goals. Microbial mats and biofilms develop on the surface of the littoral part of lakes and in the water flows of hydrothermal springs. They are highly productive, actively participate in the cycling of nutrients and can reach a thickness of several centimeters [16,17]. Microbial mats are thought to have dominated the Earth's surface during the Precambrian and served as a basis of ancient ecosystems [18]. Modern technologies make it possible to exploit the high microbial activity of microbial mats and

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biofilms and enhance their mechanical properties through the use of modern materials.

In order to increase the efficiency of wastewater treatment using microalgal biomass and its further utilization, we have developed a new nature-inspired biomaterial called AlgalTextile (AT). AT is made from natural materials: microalgae immobilized in alginate gel are attached to organic textile. This approach achieves a high rate of nutrient uptake by microalgae combined with the convenience of simplified biomass collection after use. We also tested the possibility of using the resulting material as a bio-fertilizer for plant growth.

2. Methods

2.1. Preparation of the inoculum for the experiments

A culture of the microalgae *Chlorella sorokiniana* IPPAS C-1 kindly provided by IPPAS collection of microalgae and cyanobacteria of Timiryazev Institute of Plant Physiology of the Russian Academy of Sciences was used. Microalgae were grown in 500 ml Erlenmeyer flasks on medium adapted from [19], in the following called "Trebon" medium (g/L): KNO_3 3.68, $MgSO_4{\times}7H_2O$ 0.2, KH_2PO_4 0.23, $CaCl_2$ 0.086, H_3BO_3 0.000833, $MnCl_2{\times}4H_2O$ 0.003294, $ZnSO_4{\times}7H_2O$ 0.002678, $(NH_4)_6Mo_7O_{24}{\times}4H_2O$ 0.000171, NH_4VO_3 0.000014, $CoSO_4{\times}7H_2O$ 0.000617, $CuSO_4{\times}5H_2O$ 0.000945) on ELMI orbital shaker DOS-20 L at 120 rpm at 25 °C and 3200 lux illumination (40μmol*m^2*s^{-1}; KingLED plant lamps located at the height of 1 m above the working surface). Biomass of *C. sorokiniana* C-1 was collected for experiments at the end of exponential growth phase. Besides, 15 ml of *C. sorokiniana* C-1 suspension with $\Delta OD_{(680–720)}$=0,045 ($2.25{\times}10^{-5}$ g of cells/ml of alginate) was centrifuged and the pellet was used to make 1 stripe of AT.

2.2. Experimental cultivation conditions

The illumination in all experiments was 3200 lux. No additional aeration of the nutrient medium during the experiments was carried out. The temperature was 25 °C. For all experiments the medium described above was used. For the comparison of nitrogen and phosphorus uptake by AT at different medium concentrations, the same modified medium concentrated by a factor of 2, 3 and 5 was used. For all experiments, 300 ml of nutrient medium was used.

2.3. AlgalTextile production

To make one AT stripe, 45 ml of a 2% alginate solution in water was used. An inoculum of *C. sorokiniana* C-1 (for concentration see 2.1) was added to the solution and mixed to reach the even distribution. The resulting gel was then applied to a 93 × 450 mm stripe of cotton textile and sprayed with a 2% anhydrous $CaCl_2$ solution to polymerize. The AT was then placed in a mini-photobioreactor (mini-PBR) and fixed on top with magnets (Fig. 1b, 1d). At the end of each experiment with AT, the nutrient medium was microscopically examined for free microalgae cells.

2.4. AlgalTextile drying

The stripes of AT were prepared in the same way as in 1.3 and then left on the laboratory table under ambient conditions for 28 days to dry. At the beginning of the experiment with dried AT, the dried stripes were placed in the mini-PBR without any further modification.

2.5. Preparation of alginate beads

Alginate beads were used as control to immobilize the cells of *C. sorokiniana* C-1. To prepare alginate beads, 45 ml of a 2% solution of alginate in water was used [20]. A pellet of inoculum was added to the alginate and the microorganisms were mixed into the gel. The gel with microorganisms was then placed in a syringe with a silicone tube. The gel droplets were released into a container with a 2% $CaCl_2$ water solution where the droplets were polymerized to form beads about 4 mm in diameter. The beads were collected and placed in 9 cm Petri dishes with 3 mm holes melted on the side of the dishes to allow the nutrient medium to pass freely. The dishes were then placed in a mini-PBR and fixed with a synthetic rubber Terostat IX (Fig. 1a, 1c).

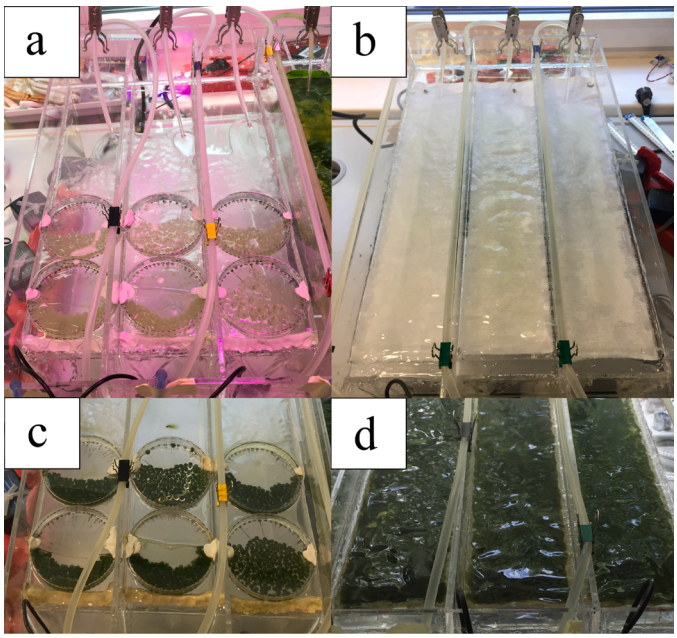

Fig. 1. – AT and alginate beads at the start and in the end of the experiment. 1a - alginate beads at day 0; 1b - AT at day 0; 1c - alginate beads at day 10; 1d - AT at day 10.

2.6. Preparation of suspension

To prepare an experiment with a *C. sorokiniana* C-1 suspension, an inoculum pellet was distributed in 350 ml of modified "Trebon" medium and added to the mini-PBR for free circulation at a speed of 200 L/h.

2.7. Mini-photobioreactor for model wastewater treatment

For experiments under conditions simulating wastewater treatment we developed an open-type horizontal photobioreactor. Sheets of 5 mm thick clear polymethyl methacrylate (PMMA) were laser-cut and glued together with plastic adhesive. The flat working surface was inclined at an angle of 15° The nutrient medium flowed from the top to the bottom of the working surface into the medium collecting tank, from where it was pumped through silicon tubes to the top of the working surface at a speed of 200 L/h. Worktop length was 50 cm and width 9.5 cm. The volume of the collection tank was 500 ml, and 350 ml of nutrient medium was used for convenience. All experiments were performed in triplicate. One photobioreactor comprises three lines of working surfaces for easy experimentation in three replicates.

2.8. Nitrogen and phosphorus measurement in the nutrient medium

Samples were taken daily from each replicate to determine the amount of total nitrogen bound (TN_b) and phosphate phosphorus ($P\text{-}PO_4$) in the nutrient medium. The measurements were made using LCK349 and LCK138 cuvette tests (Hach Lange GmbH, Germany) in accordance with the manufacturer's instructions [21].

2.9. Measuring the chlorophyll content of AlgalTextile

To measure the amount of chlorophyll *a* contained in AT, the samples of the gel part of AT of 2×10^{-8} m^3 were frozen at −80 °C for 15 min. 200 µl acetone with 0.004 g $4MgCO_3 \bullet Mg(OH)_2 \times 5H_2O$ was added to each sample. Then samples were placed in a homogenizer TissueLyser II from QIAGEN with 5 mm metal ball for 1.5 min at 30/s frequency. The total volume of each sample was added to 6 ml acetone and centrifuged for 5 min at 4500 rpm at 4 °C, the OD of the supernatant was measured at 645, 662 and 710 nm. The calculation of the amount of chlorophyll *a* in the samples was performed according to [22].

2.10. Cress growing with biomass-loaded AlgalTextile fertilizer

The seeds of cress *Lepidium sativum* were obtained from "Frankonia Samen" (Philipp Klein GmbH, Miltenberg, Germany). The experiment was repeated thrice, using 10 seeds for each variant. Each experiment was carried out in a separate tray lined with paper towels as an additional water storage underlay. All variants were placed on a 93 × 115 mm underlay area. In the experiment with biomass-loaded AT as a fertilizer (AT), a piece of AlgalTextile was placed on paper, a piece of cotton wool was placed on top and the seeds were placed on top of the cotton wool. As control #1 (C1), polymerized algae-free alginate gel on a substrate of cotton fabric was placed under the cotton wool instead of AT. For control #2 (C2), a piece of cotton fabric was placed under the cotton wool. In control #3 (C3) there was only cotton wool between the seeds and the paper (Fig. 2). After placing the seeds, the paper and cotton wool were moistened with 20 ml of distilled water. In the experiment with distilled water only, it was added to the plants once a day until the end of the experiment. In the experiment with tap water, starting from 5th day, 0.25 ml of tap water was poured over each seed once a day. The chemical composition of the tap water is presented in the Table 1. The growth of cress in each variant was evaluated by measuring the sprout length in mm at day 14 [23]. Accuracy of measurements was calculated with a confidence interval of 0.95. Averaged values were used for comparisons.

Table 1
- Composition of tap water in Juelich, Germany (according to Eurofins Hygiene Institut Berg GmbH, test period 02.06.2020 - 17.06.2020).

Parameter	mg/L
Calcium (Ca)	57
Potassium (K)	2,7
Magnesium (Mg)	15.4
Sodium (Na)	14.2
Sulfate (SO_4)	63
Nitrate (NO_3)	36

3. Results

3.1. Nitrogen and phosphorus uptake by phototrophic microorganisms in a horizontal flow-through photobioreactor

AT sequestered nitrogen and phosphorus faster than two control cultivation methods. After the first day of incubation, AT sequestered 0.267 mM P-PO_4; that is 20 times more than the amount sequestered by alginate beads and 7 times more than by the suspension of *C. sorokiniana* (Fig. 3a). By the end of the experiment, AT and the alginate beads had sequestered phosphorus almost completely (up to 99%), while the suspension sequestered only 20% of the P-PO_4 during the same time. Uptake of nitrogen by AT rapidly increased during the experiment and was significantly higher than that in other conditions (Fig. 3b). At the end of the experiment, AT had sequestered up to 76% of the TNb contained in the medium, 4 times the amount of nitrogen sequestered by the alginate beads and 5.5 times the amount of nitrogen sequestered by the microalgae suspension.

In order to test the ability of AT to absorb nitrogen and phosphorus at different concentrations, we cultivated AT on standard “Trebon” medium (“Trebon x1”) and medium concentrated by 2 (“Trebon x2”), 3 (“Trebon x3”), and 5 times (“Trebon x5”). The highest phosphorus uptake was observed "Trebon x5″ medium. On this type of medium AT sequestered 82% of P-PO_4 by day 10 of the experiment. AT showed the best TNb uptake rates on “Trebon x3” medium: by the end of the experiment 53.36 mM TNb was sequestered (29% of total content), which is 1.7–2.4 times the TNb sequestered by AT from other media

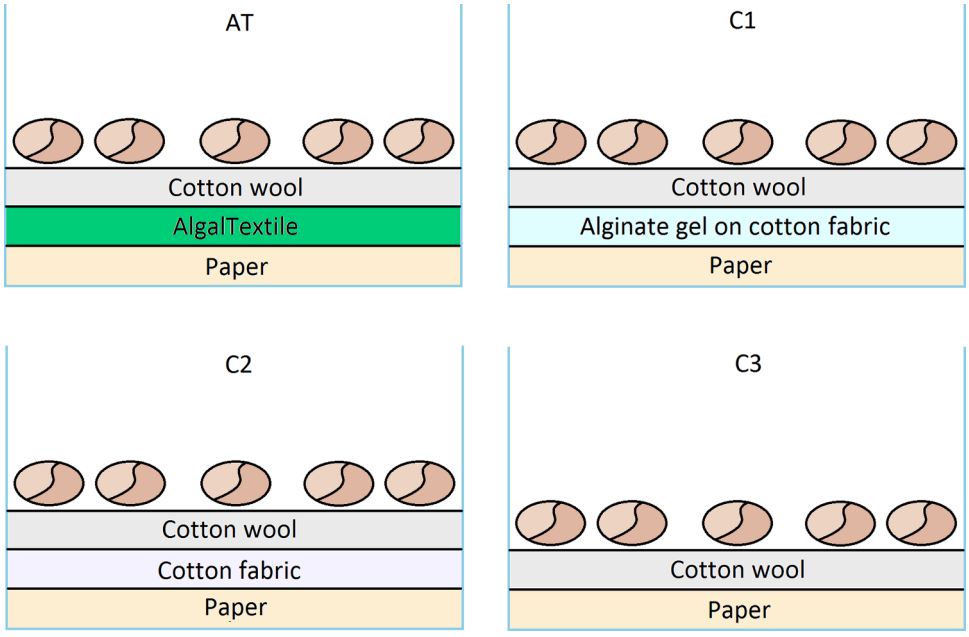

Fig. 2. – Scheme of cress cultivation experiment using textiles treated in different ways. “AT” - AlgalTextile as a fertilizer; “C1” – alginate gel on cotton fabric as a fertilizer; “C2” – cotton fabric as fertilizer; “C3” – no use of fertilizer. Paper and cotton wool were moistened with 20 ml of distilled water.

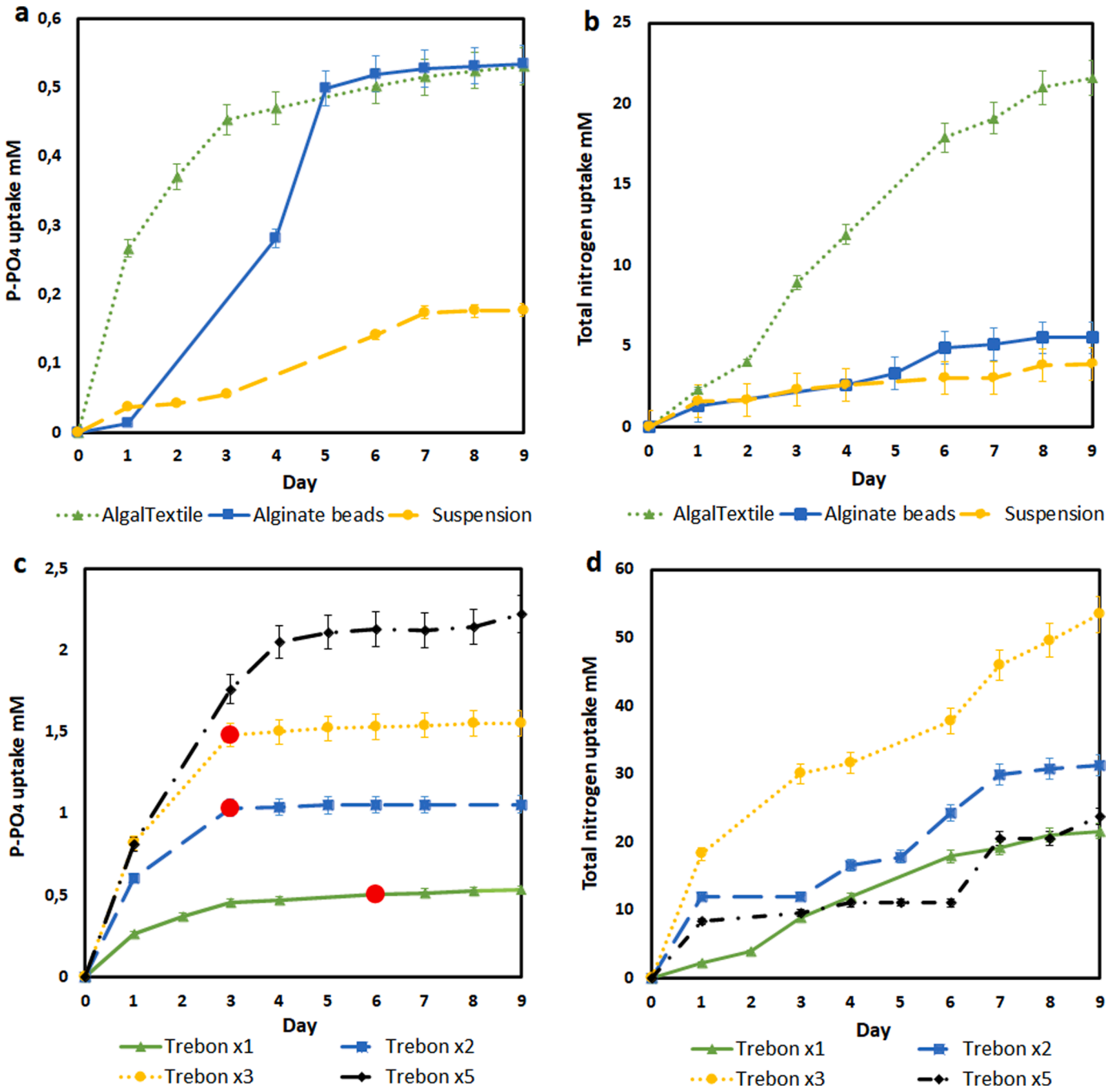

Fig. 3. – Phosphorus and total nitrogen uptake. 3a – Phosphorus uptake by microalgae in different cultivation methods. 3b – Nitrogen uptake by microalgae in different cultivation methods. 3c – Phosphorus uptake by AT at different concentrations of "Trebon" medium (red dots show the day when the P-PO_4 uptake reached 90% of the initial concentration in the medium). 3d - Nitrogen uptake by AT at different concentrations of "Trebon" medium.

concentrations (Fig. 3d). In the case of "Trebon x5", the growth decrease probably was the result of exceeding the optimum amount of nutrients in the medium for *C. sorokiniana* C-1 culture. Besides, with increase of the amount of nutrients in the medium, the content of chlorophyll *a* in gel fraction of AT drastically increased: 377 μg/ml^{-1} with "Trebon x1"; 395 μg/ml^{-1} with "Trebon x2"; 457 μg/ml^{-1} with "Trebon x3" and 497 μg/ml^{-1} with "Trebon x5", while the initial concentration was 0.0075 μg/ml^{-1}.

3.2. *The usability of dried AlgalTextile*

We tested the viability of long-term storage and transportation of the new material in the form of fully prepared dried AT stripes. Its efficiency after 28 days of storage compared to freshly prepared AT was tested. The amount and rate of uptake of P-PO_4 and TNb by dried AT were at the same level as that of freshly prepared AT (Fig. 4a, 4b). Thus, the method of AT stripes drying on the table at room temperature is appropriate for storing fully prepared lines without loss of their efficiency.

3.3. *Use of biomass-loaded AlgalTextile as a fertilizer for cultivated plants*

Use of AT as a fertilizer has a stimulating effect on the growth of plants. When tap water was used, all plants survived up to day 14 of the experiment. Cress with AT as fertilizer grew faster (Fig. 5, 6). By day 14,

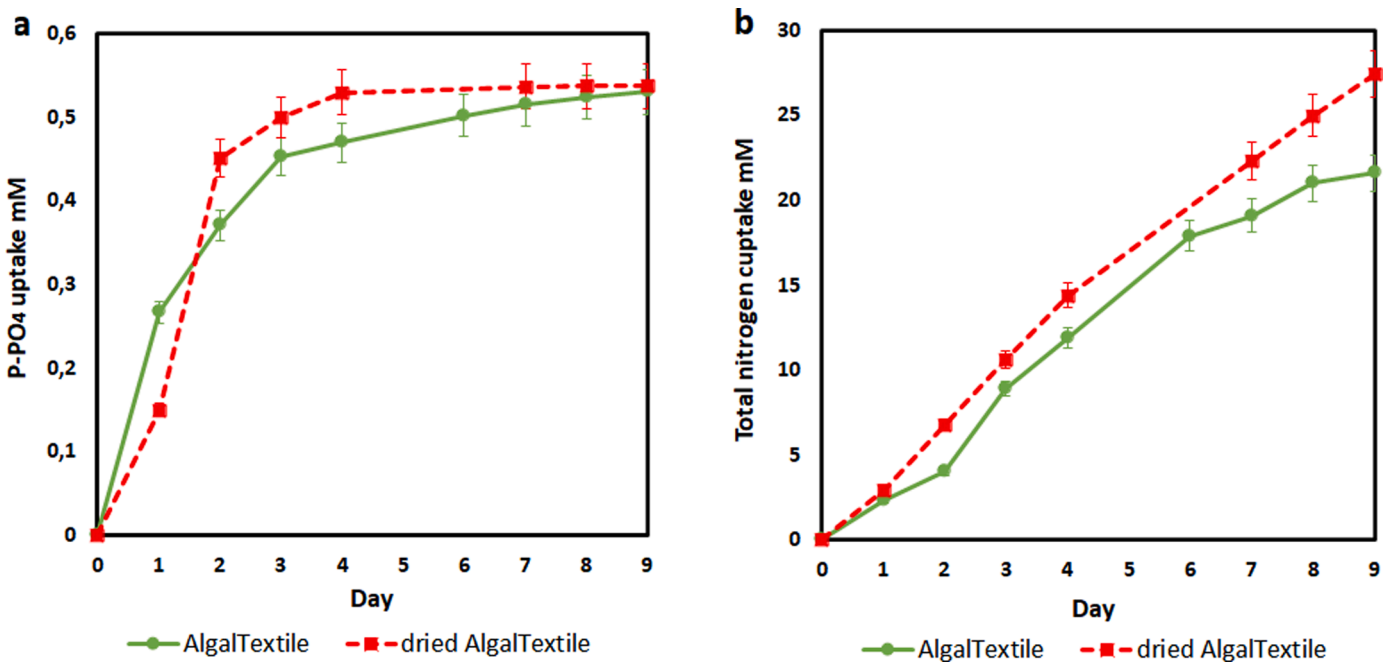

Fig. 4. Phosphorus (4a) and nitrogen (4b) uptake by fresh and dried AlgalTextile.

Fig. 5. – A control cress plant grown with an Alginate-on-cotton fertilizer (left) and a cress plant grown with a biomass-loaded AT fertilizer (right) on day 14 (scale value - 1 cm).

their height was 50 mm, an average of 35% higher than the height of all three controls. In the variant with distilled water only, by the 11th day, growth continued only in the AT variant, while all the plants in the controls died. The experiment with the cress growth on AT ended on day 14 of cultivation with the final plant height of 40 mm.

4. Discussion

Microbial mats that form in extreme ecosystems, such as salt lakes and hot springs, are among the most productive ecosystems [7]. This is achieved by the dense organization of photosynthetic microorganisms in the form of biofilms developing on the bottom surface [24]. We used a nature-inspired approach based on the principles of microbial mat and biofilm organization to create an artificial system that could efficiently absorb nitrogen and phosphorus from wastewater. The AlgalTextile material contains a high number of photosynthetic microorganism cells embedded in a biodegradable polymer matrix that gives a high initial density of microorganisms, while the textile backing gives the material physical strength and the ability to quickly unfold it on the desired surface. AT can be modified in order to achieve the necessary properties: size, type of textile, type of microorganisms, type of gel and its density, etc. At the end of wastewater treatment, AT is easy to roll up for further processing. To determine the potential range of applications of AT, we have carried out a comparative assessment of the developed method with other methods of nutrient removal from wastewater.

AT absorbs phosphorus from the medium much faster than other types of photosynthetic bioreactors, including microalgae in suspension and in alginate beads, biofilm membrane photobioreactor with microalgae, twin-layer wastewater treatment system with microalgae, tube photobioreactor with purple non-sulfur bacteria and sequencing batch membrane-aerated biofilm reactor with activated sludge (Table 2). Nevertheless, AT is about one order of magnitude less effective than enhanced biological phosphorus removal (EBPR) systems and 1–3 orders of magnitude less effective than physicochemical methods of phosphorus removal. To remove the amount of phosphorus AlgalTextile consumes in 4 days, it is enough to use 0.5 g of "Ligand based composite" adsorbent in water for 1,5 h [25]. Due to high porosity and ion-exchange properties, some adsorbents have a high ability to fix phosphorus from solutions.

However, the physicochemical methods have certain drawbacks [26]. Chemically induced precipitation of phosphorus and nitrogen from wastewater is cost-effective, but produces a significant amount of sediment leading to secondary pollution. The phosphorus removal after adsorption can thus be hampered. Alkalis are used to elute the adsorbed phosphorus, and acids prepare the adsorbent for further use. To reclaim the phosphorus eluted from the iron-containing sludge as a fertilizer, biochar is pyrolyzed at 400 °C in an N_2 atmosphere for 2 h [27]. Membrane separation also shows high efficiency in wastewater treatment, but it is an energy consuming method [26]. Compared with these methods, the phosphorus in AT and EBPR systems is bioavailable and can be used as a biofertilizer. Currently, the EBPR method is the most efficient microbiological method of phosphorus removal from the

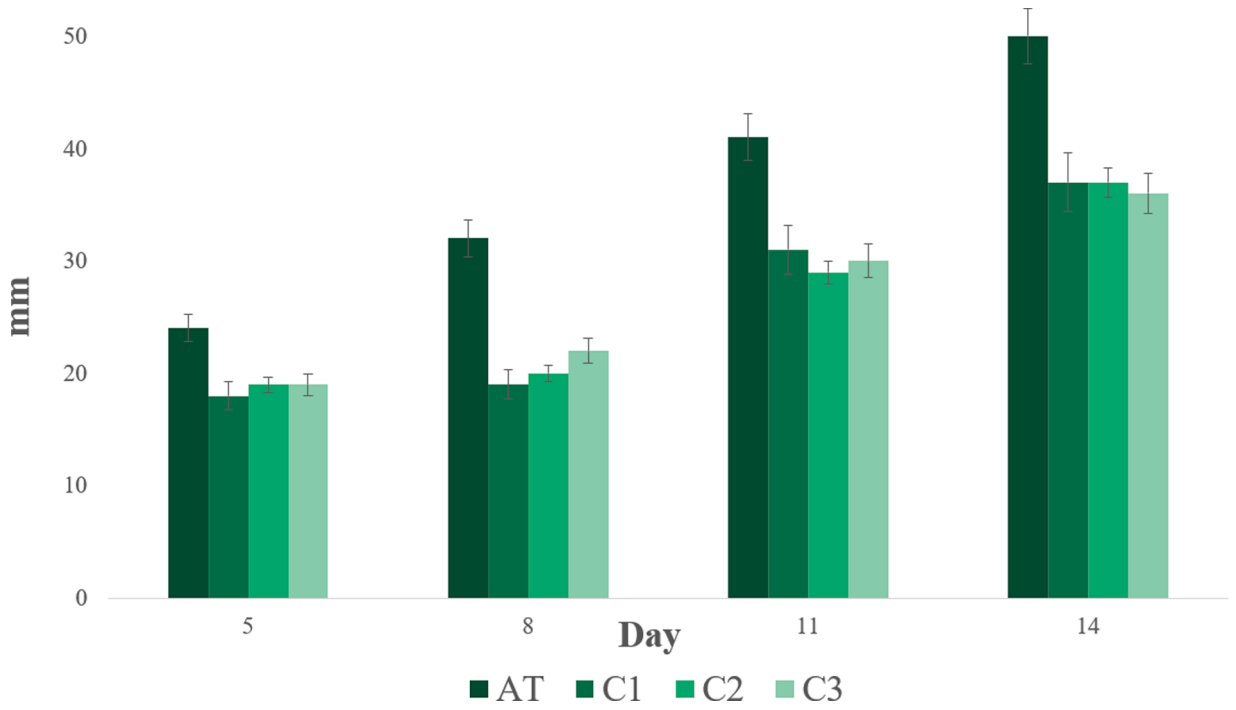

Fig. 6. – Cress growth with biomass-loaded AlgalTextile as a fertilizer and tap water. "AT" - AlgalTextile as a fertilizer; "C1" – alginate gel on cotton fabric; "C2" – cotton fabric; "C3" – no fertilizer.

Table 2
- Nitrogen removal methods.

Treatment design	Removing agent	TN content at the beginning (mg/L)	Removal (mg/L)	Removal (%)	Treatment period (day)	Removal (average mg/L per day)	Reference
Microorganisms							
Inclined biofilm photobioreactor with cells immobilized in alginate gel (AlgalTextile)	Microalgae (*Chlorella* sp.)	1480	519.5	35.1	7	74.2	This article
Biofilm membrane photobioreactor	Microalgae (*Chlorella* sp.)	15	12.4	82.5	6	2.1	[32]
	Microalgae (*Scenedesmus dimorphus, Scenedesmus quadricauda*)	64.3	51.3	75.1–79.8	9	5.7	[33]
Suspension in a flask with barbotage	Microalgae (*Dunaliella* sp., *Nannochloropsis*, and *Tetraselmis* sp.)	65–90	88.2	94.1–98.1	13–18	5.9	[34]
	Microalgae (*Chlorella vulgaris*)	93	46.5	50	10	4.7	[35]
Cylindrical photobioreactors with pine bark as a substrate for immobilization	Groups of different cyanobacteria and microalgae	80	64.8	81	42	1.5	[36]
Tube photobioreactor containing cellulose beads with immobilized bacteria	Purple non-sulfur bacterium (*Rhodobacter capsulatus*)	19.8	14.4	72.6	0.86	16.4	[37]
Enhanced biological phosphorus removal and recovery	Community of the polyphosphate accumulating organisms (PAOs) and denitrifying PAOs	10		64	6-hour cycles (4 h aerobic/2 h anoxic)	18.72	[28]
Sequencing batch membrane-aerated biofilm reactor	Activated sludge (aerobic and anaerobic bacteria)	65–75	67.5	90	long-term running	50	[38]
Flat-panel air-cathode microbial fuel cells	Microbial community	28	26.3	94	0.1	263	[39]
Sequencing batch reactor	Anammox and denitrifying bacteria	80 (ammonium) 160 (nitrite)	77.6 149.9	97 93.7	0.125	620.8 1280	[29]
Chemical methods							
Chemical removal	Catalytic reactions of hydroxyl and chlorine radicals	50	50	100	0.06	833	[40]

wastewater, but it requires stable flow of wastewater, long time to achieve maximum productivity, the organization of alternating aerobic and anaerobic cycles, as well as complex technical equipment [28].

AT method allows to remove 1.5–49 times more nitrogen than previously described photosynthetic methods and sequencing batch membrane-aerated biofilm reactor with activated sludge (Table 3), but it is significantly less efficient than batch reactor with anammox and denitrifying bacteria. Anammox and denitrifying bacteria consume dozens of times more nitrogen [29] but this technological process requires stable inflow of contaminated water and complex technical

Table 3
- Phosphorus removal methods.

Treatment design	Removing agent	P-PO4 content at the beginning (mg/L)	Removal (mg/L)	Removal (%)	Treatment period (day)	Removal (average mg/L per day)	Reference
Microorganisms							
Inclined biofilm photobioreactor with cells immobilized in alginate gel (AlgalTextile)	Microalgae (*Chlorella* sp.)	91.8 mg L-1	83.9	91.4	4	21	This article
Suspension in a flask on shaker	Effective Microorganism (EM-1)	2.3 mg L-1	2.1	86.1–91.3	8–10	0.2	[41]
	Microalgae (*Chlorella* sp.)		1.1	27.3–49.7	6	0.2	
	Effective microorganism (EM-1) and microalgae (*Chlorella* sp.)		2.3	85.9–99.9	6–10	0.3	
Immobilization in alginate beads	Microalgae (*Chlorella* sp.)	10 mg L-1	5	50	2	2.5	[42]
	Microalgae (*Chlorella* sp.) and non-immobilized activated sludge		10	100	2	5	
Biofilm membrane photobioreactor	Microalgae (*Chlorella* sp.)	0.8	0.7	85.9	6	0.1	[43]
Twin-layer wastewater treatment system	Microalgae (*Chlorella vulgaris*)	3	2.7	90	2	1.35	[44]
Tube photobioreactor containing cellulose beads with immobilized bacteria	Purple non-sulfur bacterium (*Rhodobacter capsulatus*)	10.1	1.3	12.4	0.86	1.5	[37]
Sequencing batch membrane-aerated biofilm reactor	Activated sludge (aerobic and anaerobic bacteria)	9–13 (total phosphorus)	11.1	85	long-term running	8	[45]
Enhanced biological phosphorus removal	Community of the polyphosphate accumulating organisms (PAOs) and denitrifying PAOs	8		83	6-hour cycles (4 h aerobic/ 2 h anoxic)	29.4	[28]
Enhanced biological phosphorus removal	Community of the polyphosphate accumulating organisms	88.2	86.2	97.8	8-hour cycle on the 44th day of operation (2 h anaerobic/4 h aerobic/1 h settling/1 h idle)	344.8	[28]
Physico-chemical methods							
Filtration systems	Mineral-based filter material Polonite	1.5–6	1.29–6	86–100	long-term running	0.7	[46]
Adsorbents	Red mud, a waste residue of alumina refinery	0.8 mg P-PO4 / g adsorbent			0.25	Depending on the amount of adsorbent	[47]
	Ligand based composite	159.13 mg P / g adsorbent			0.06		[26]
Chemical removal	Electric arc furnace steel slags	0.13 - 0.28 mg P / g slag			7	Depending on the amount of adsorbent	[48]
	Basic oxygen furnace steel slags	1.14–2.49 mg P / g slag			7		
	Bittern for crystallization of struvite (MgNH4PO4 • 6H2O)	100 (TP)	100	100	0.35	285	[49]

equipment. Moreover, as a result of the activity of denitrifying bacteria, gaseous nitrogen forms and escapes into the atmosphere. Thus, nitrogen cannot be recycled as fertilizer, in contrast to AT.

Given the comparative advantages and disadvantages of AT in comparison with other methods of nutrient removal, the area of its potential application can be determined. The most relevant method of AT application is the treatment of wastewater with an uneven inflow of pollutants during the year; for example, at recreational areas with a small amount of pollution during the year, but an increase during the summer tourist season. A stable supply of a large amount of polluted water throughout the year is required for the effective functioning of sewage treatment systems with anammox and denitrifying bacteria or EBPR whereas in the case of seasonal wastewater treatment the use of AT would be more feasible.

Another possible application of AT is the treatment of polluted surface runoff. This method will not only reduce the content of nutrients in runoff, but could also help prevent local erosion of soil; although the AT's potential for erosion control needs further validation, e.g. plantings on the material on a test slope to evaluate facilitation of substrate stabilization during plant growth and subsequent material degradation. We have shown that AT keeps its activity after a long drying period, allowing it to be conveniently stored and transported to the place of use.

Cotton textile was chosen for use in AT because of its low cost and biodegradability. Under natural conditions, in direct contact with soil, cotton textiles decompose in 3 weeks to 6 months [30]. Other types of natural fibers (flax, jute, hemp, coconut etc.) and biodegradable polymers (polylactide, polyhydroxyalkanoates et c.) can also be potentially used to create AT.

We have shown that the used AT have a stimulating effect when growing plants. Adding AT allowed plants to develop significantly faster in comparison with control plants grown only on the substrate and various AT constituents without microalgae. On the 14th day of cultivation, the height of cress grown with AT was 35% higher than the control plants. Due to the various controls used, we show that the stimulating effect of AT is obtained because of the concentrated biomass inside the material. Control #1 included an alginate gel on the fabric with no added microalgae. Since this material had no stimulating effect on the plant growth, we demonstrate that AT did not stimulate cress growth only due to water retention.

The separation of biomass from the gel is problematic, so AT further use is reasonable for applications where the final production of pure biomass is not necessary. Used AT can potentially be used as biofertilizer, anti-errosion and anti-desertification agent, and biofuel feedstock (Fig. 7) [31]. Further research is needed on biofuel production, AT

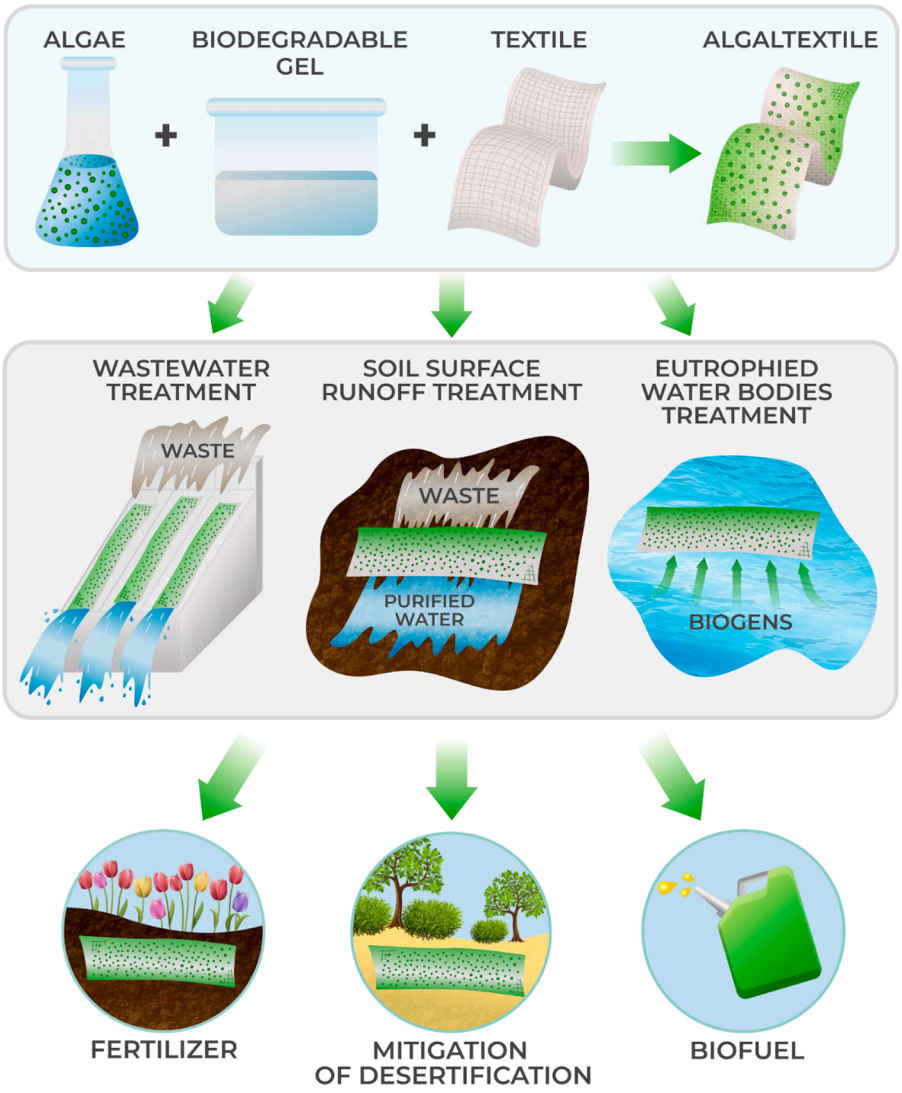

Fig. 7. – Potential application and utilization of AlgalTextile.

biodegradation, and use in growing crops.

5. Conclusion

A new material AlgalTextile based on microalgae immobilized in alginate gel with cotton textile was developed. Due to high density of the microalgae and high permeability it consumed large amounts of nutrients from the medium. During one day AT piece of 0.043 m^2 area sequestered 18.21 mM TNb and 0.82 mM P-PO_4 from 1 liter of "Trebon 3x" nutrient medium. After three days the amount of sequestered nutrients reached 30 mM TNb and 1.48 mM P-PO_4. The uptake rate of phosphorus and nitrogen by AT was the highest among all methods using photosynthetic microorganisms but lower than EBPR and physicochemical methods for phosphorus removal, and anammox and denitrifying bacteria for nitrogen removal. Using AlgalTextile for the cultivation of cress showed a 35% higher growth in length than in the control.

6. Author contributions

A. Melnikova: Conceptualization, Methodology, Investigation, Data curation, Writing - Original draft preparation; **A. Komova:** Writing - Original draft preparation, **Z. Namsaraev**: Conceptualization, Writing - Original draft preparation, Supervision, Reviewing and Editing; **I. Meuser**: Methodology, Analytics, Investigation; **M. Roeb**: Methodology, Analytics, Investigation; **B. Ackermann:** Methodology, Analytics, Investigation; **H. Klose:** Resources, Writing - Reviewing and Editing; **C. Kuchendorf**: Conceptualization, Methodology, Investigation, Resources, Supervision, Writing- Reviewing and Editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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