Decoupling a novel *Trichormus variabilis*-Synechocystis *sp.* interaction to boost phycoremediation

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To conserve freshwater resources, domestic and industrial wastewater is recycled. Algal systems have emerged as an efficient, low-cost option for treatment (phycoremediation) of nutrient-rich wastewater and environmental protection. However, industrial wastewater may contain growth inhibitory compounds precluding algal use in phycoremediation. Therefore, extremophyte strains, which thrive in hostile environments, are sought-after. Here, we isolated such an alga - a strain of *Synechocystis sp.*

We found to be capable of switching from commensal exploitation of the nitrogen-fixing *Trichormus variabilis*, for survival in nitrogen-deficient environments, to free-living growth in nitrate abundance. In nitrogen depletion, the cells are tethered to polysaccharide capsules of *T. variabilis* using nanotubular structures, presumably for nitrate acquisition. The composite culture failed to establish in industrial/domestic waste effluent. However, gradual exposure to increasing wastewater strength over time untethered *Synechocystis* cells and killed off *T. variabilis*. This switched the culture to a stress-acclimated monoculture of *Synechocystis sp.* which rapidly grew and flourished in wastewater, with ammonium and phosphate removal efficiencies of 99.4% and 97.5%, respectively. Therefore, this strain of *Synechocystis sp.* shows great promise for use in phycoremediation, with potential to rapidly generate biomass that can find use as a green feedstock for valuable bio-products in industrial applications.

Fresh water is a vital domestic and industrial resource, which also supports global food production systems and economic growth. Current trends in population growth, together with increased climate volatility and change, are putting pressure on fresh water supplies, making water a scarce resource. Withdrawals of freshwater in the last 50 years have tripled, with year-on-year demand increasing by 64 billion cubic meters1. Agriculture accounts for 70% of global water consumption2, with industrial and domestic sectors in close pursuit. However, considerable amounts (~2.2 million m³ globally) of wastewater are generated annually from domestic, industrial, and agricultural processes3. To conserve water, recycling of wastewater is integral to water management systems and policies of many countries4.

Wastewater is rich in nutrients (C, N, P) and heavy metal ions (Ph, Zn, Cd, Cr, Cu and Ni)5 that could cause environmental degradation if released without removal. Microalgae thrive on such nutrients6,7 and so are appropriate biological systems for wastewater treatment. Algae are particularly desirable because they are phototrophs, with the capability to fix carbon, thereby mitigating the negative effects of greenhouse gas emissions8 and also rapidly generate biomass using nutrient-rich wastewater. Biomass can be used as a valuable source of energy, providing an opportunity to link wastewater treatment with microalgae cultivation and bio-energy production9–16.

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Several studies demonstrated the utility of microalgae in wastewater treatment, for example, (i) several genera of green algae; *Chlorella*17, *Scenedesmus*18,19, *Haematococcus*, *Chlorococcum*20, *Chlamydomonas*, *Microactinum*, *Oocystis* and *Tetraselmis*, and (ii) the blue-green algae *Oscillatoria* and *Phormidium*21. Combinations of microalgae with other organisms, such as diatoms22 or a mixture of bacterial species23 have also shown effective nutrient removal from wastewater. In addition to utilising nitrate and phosphate9,24 for growth, the microalgal systems are also effective at removal of metals, such as Cd, Cu, Zn, Ni, Hg and C25–28, and metalloids, such as As, Sb, and Bi29. For example, *Chlorella vulgaris* efficiently removes both N and P25, and heavy metals30 from wastewater. Therefore, microalgal systems have emerged as a preferred wastewater treatment option due to their rapid growth and efficient nutrient and metal removal.

We have interest in screening for and developing dual-purpose algal strains, which can be used for wastewater treatment and generation of valuable products for industrial applications. In this study, we focused on *Trichormus variabilis* (syn. *Anabaena variabilis*)31, a freshwater filamentous Nostocoidae subfamily32,33 blue-green alga capable of fixing nitrogen. It can grow phototrophically, heterotrophically, or mixotrophically34–36 across a wide range of temperature35,37 and light38 conditions, making it a favorable microorganism to grow in variable conditions. In a nitrate-rich growth medium, filaments predominantly consist of vegetative photosynthetic cells, akinetes appearing at the end of the exponential growth phase in response to nutrient limitation or stress cues39,40. However, in nitrate-depleted environments, 5–10% of the vegetative cells differentiate to form akinetes39,40, whose main function is nitrogen fixation. Nitrogen fixation is catalysed by nitrogenase enzymes and generates molecular hydrogen as a by-product. Given the remarkable potential for bio-hydrogen generation39,42, incorporation of *T. variabilis* in microalgal wastewater treatment systems43,44 is commercially attractive.

A key incentive proposed for the use of microalgal systems in wastewater treatment is the potential for conversion of the biomass generated during treatment into different forms of bio-energy, including biogas45, biodiesel46,47 and bio-hydrogen48. This energy could be used to defray operational costs at waste treatment plants, or sold on local energy markets. The ability of *T. variabilis* to fix atmospheric nitrogen is of immense interest as one of the recognised shortfalls in using microalgae for biofuel production is the relative high cost of nitrogen versus the energy generated40. In this study, we wanted to explore the potential use of *T. variabilis* as a microalgal system suitable for coupling wastewater treatment to energy production. Although the study initially aimed to optimise cultivation of *T. variabilis* in wastewater, our results revealed an unexpected commensal relationship between *T. variabilis* and a strain of *Synechocystis* sp., which has remarkable stress resilience and an ability to grow and thrive in wastewater. The physical interaction of *T. variabilis* and *Synechocystis* sp. provides a new model system for studying cell-cell communications in biological systems.

**Results**

**Acclimation for growth in wastewater.** Initial attempts to grow algal cells in the mixed domestic + industrial wastewater were futile. Algal cells failed to multiply and colonise the wastewater (Fig. 1). There was still no growth even after adjusting the wastewater pH from the pH 8–9 range down to the BG-11 growth medium pH 7.1. *T. variabilis* grows optimally in BG-11 medium. It was not clear whether failure to support algal growth was a result of lack of some essential nutrient(s) or the presence of growth inhibitory substances. We then made a 50% dilution of the wastewater with BG-11 growth medium as a way to supplement essential nutrients, which could be absent from the wastewater. Again there was no growth in this diluted wastewater (Fig. 1), suggesting that growth inhibition from components within the wastewater was the likely explanation of these results. Thus, we concluded that the wastewater contained growth inhibitory compounds affecting algal cell multiplication.

In order to survive in adverse environmental conditions, many prokaryotes and eukaryotes require an acclimation period during which the organism is first exposed to intermediate levels of the stress factor(s) to gradually change gene expression for growth under the extreme conditions43,45. We reasoned that exposure of *T. variabilis* cells to increasing concentrations of the wastewater could enable them to gradually acclimate and survive the “stress factors” present in the wastewater. Thus, BG-11 medium supplemented with 1% wastewater was inoculated...
with algal cells. The cells multiplied successfully and 7 days later, 1% wastewater culture was used to inoculate BG-11 medium spiked with 3% wastewater. Again there was successful growth of the cells in 3% wastewater. The sequential inoculation of progressively higher wastewater strength was repeated at 3 percentage point increases until we attained a stably growing algal culture in 50% wastewater over a 5 months period. Interestingly, attempts to increase wastewater strength by ≥5% at any point resulted in failure to grow, a strong indication that acclimation was vital for growth in increasing wastewater strength. Figure 1 shows acclimated algal cultures growing in wastewater.

But we noticed that algal cultures that had acclimated for growth in wastewater had a different appearance to original _T. variabilis_ cultures growing in BG-11, or BG-11 media. BG-11, and BG-11 differ in that the latter contains the full complement of nutrients required for algal growth, while the former does not have nitrates. While control BG-11 cultures had thaloid or spherical clumps growth forms, acclimated cultures were homogenous cell suspensions (Fig. 1). When aeration is switched off from BG-11, and BG-11 cultures, the algal sheets immediately settle to the bottom of the flask, while acclimated cells remain in suspension for several hours before finally sedimenting to the bottom of the flask. When the acclimated cells were inoculated back into BG-11 medium, they maintained the same culture properties, suggesting that acclimation had triggered long-lasting changes.

**Synechocystis sp. constitutes the acclimated cultures.** To understand the basis for the change in appearance and physical properties of the acclimated cultures, we used microscopy to visualise the cells and make comparisons with the original _T. variabilis_ cultures. Low power light microscopy of BG-11-grown cultures not exposed to wastewater revealed _T. variabilis_ filaments with the typical vegetative cells, heterocysts and akinetes (Fig. 2a). In contrast, only single cells with no filaments were present in samples from acclimated cultures (Fig. 2b). This explains why the acclimated cultures were homogenous cell suspensions as opposed to the thaloid sheets in the non-acclimated cultures. The average vegetative cell diameter in filaments was 4.18 ± 0.54 μm (n = 10), while the diameter of acclimated single cells was 1.43 ± 0.53 μm (n = 10). Transmission electron microscopy (TEM) revealed detailed ultrastructural differences between vegetative cells of filaments from BG-11 cultures (Fig. 2b,c) and single cells of the acclimated cultures (Fig. 2d). Cells from acclimated cultures had pronounced folds of thylakoid membranes and many darkly-stained bodies. It is these single cells in the acclimated cultures that have resilience to as yet unidentified growth inhibitory compound(s) in wastewater, being able to rapidly multiply and attain very high biomass in a short space of time (~2.7 ± 0.1 mg.mL⁻¹.day⁻¹) through cell division, (Fig. 2f), instead of germination known to occur in akinete cells.

Transition of the filamentous _T. variabilis_ culture to a rapidly growing, stress-resilient (SR) unicellular culture after acclimation raised questions. Was the original algal culture obtained from CCAP not axenic? Did it contain 2 distinct algal species – one filamentous and one unicellular? We decided to work on the hypothesis that, in addition to having _T. variabilis_ filaments, a second unicellular alga might have constituted a very minor component of the original culture. This can easily be resolved via sequencing of genes used in bacterial taxonomy and identification.

Therefore, we isolated algal DNA and sequenced the 16S ribosomal RNA (rRNA) from filamentous non-acclimated samples and from acclimated unicellular samples. The sequence obtained from the filamentous culture was used as a query in BLAST searches against the entire NCBI nucleotide database and the top 5 hits, all with sequence identities above 99%, are displayed in Table 1. The top hit is _T. variabilis_ and the others are either _T. variabilis_ or _Anabaena_ sp. This confirms that the filamentous alga is indeed _T. variabilis_. However, the sequence obtained from the unicellular algal cells had high identity with several _Synechocystis_ sp. The top 5 candidates, with sequence identity at 100%, are various strains of _Synechocystis_ sp. (Table 2). More importantly, aligning the _T. variabilis_ and _Synechocystis_ sp. 16S rRNA sequences led to a low sequence identity of 88.5%, confirming that the multicellular filaments and the single cell cultures are from two distinct algae. Taken together, these results show that the acclimated cell culture is a strain of _Synechocystis_ sp., whose precise identity will require future whole genome RNA sequencing.

**Synechocystis sp. procures nitrogen via commensal interaction with _T. variabilis_.** Our initial microscopic examination of the original cultures obtained from CCAP (Edinburgh, UK) and subsequent sub-cultures derived from these had revealed the presence of only filamentous _T. variabilis_ cells with no unicellular _Synechocystis_ sp. (Fig. 2). Thus, we reasoned that _Synechocystis_ sp. must have been present as a very minor component, which acclimates and starts to increase in abundance when _T. variabilis_ is killed off by toxic compounds in the wastewater. This could explain how a stress-resilient pure culture of _Synechocystis_ sp. constitutes the acclimated cultures.

The cells had developed nanotubular outgrowths from the cell periphery, which tethered the cells to the polysaccharide capsule of neighbouring _T. variabilis_ filaments (Fig. 3). This was very clear in instances where both the _Synechocystis_ sp. and _T. variabilis_ cells were in the same focal plane of the section.

_Trichormus variabilis_ can switch between 2 modes of nitrate acquisition – uptake from the growth medium or fixing atmospheric nitrogen when growing in a medium bereft of nitrate. Acquisition of nitrogen is one likely reason why cells of _Synechocystis_ sp. may attach to _T. variabilis_ filaments in a commensal relationship, which does not harm the host. Therefore, we conducted experiments to investigate if _Synechocystis_ sp. can grow in the absence of nitrate in the medium. _Synechocystis_ sp. grew well in BG-11 medium (Fig. 4a), which has nitrates, but attempts to get growth in the nitrate-deficient BG-11 medium were unsuccessful (Fig. 4a). When biomass grown in the optimal BG-11 medium (with nitrate) was transferred to the nitrogen-deficient BG-11 medium,
Synechocystis sp. cultures died after several days (Fig. 4b). T. variabilis cultures similarly grown in BG-11 and then transferred to BG-11 0 not only survived, but continued to grow under the nitrogen deficiency conditions (Fig. 4c). Taken together, this demonstrates that Synechocystis sp. does not have the ability to fix atmospheric nitrogen and so has to assimilate nitrate from an external source. We speculate that the nanotubular physical connections seen between cells of Synechocystis sp. and T. variabilis filaments may effect material exchange (particularly nitrate) between the two organisms. In support of such a hypothesis are the observations that (i) in pure culture, Synechocystis sp. fails to grow when inoculated into N-deficient BG-11 0 medium and (ii) Synechocystis sp. originally grown to high density in the N-containing BG-11 medium undergoes chlorosis and then dies if transferred to N-deficient BG-11 0 medium (Fig. 4). Thus, Synechocystis sp. survives in N-deficient BG-11 0 medium only when in association with T. variabilis filaments. However, its growth under such conditions is infinitesimally low, presumably as to be almost imperceptible.

Figure 2. Microscopic images of cells from acclimated and non-acclimated algal cultures. (a) Filamentous cells not exposed to wastewater. Heterocysts and akinetes are indicated by red and blue arrows, respectively. (b) Vegetative cells in a filament from BG-11 cultures. (c) Higher magnification of vegetative cells in a filament. (d) Single cells in algal cultures acclimated for growth in wastewater. (e) Higher magnification of a single cell from the wastewater-acclimated culture. (f) Wastewater-acclimated single cell captured in the process of cell division.
The effluent’s oxygen demand (COD) was also dramatically decreased by more than 40% (Table 3).

Table 3. BLAST search results of 16S rRNA gene sequence of filamentous algal cells.

| Description | Query cover | E-value | Identity |
|-------------|-------------|---------|----------|
| Trichormus variabilis ES09-6 16S rRNA gene, partial sequence | 100% | 0.0 | 99% |
| Trichormus variabilis MACC-57 16S rRNA gene, partial sequence | 99% | 0.0 | 99% |
| Anabaena sp. SAG 28.79 16S rRNA gene and 16S-23S rRNA intergenic spacer, partial sequence | 99% | 0.0 | 99% |
| Trichormus variabilis NQAF309 16S rRNA gene, partial sequence | 99% | 0.0 | 99% |
| Trichormus variabilis CCAP 1403/12 16S rRNA gene, partial sequence | 99% | 0.0 | 99% |

Table 1. BLAST search results of 16S rRNA gene sequence of filamentous algal cells.

| Description | Query cover | E-value | Identity |
|-------------|-------------|---------|----------|
| Synechocystis sp. MA01 16S rRNA gene, partial sequence | 99% | 0.0 | 100% |
| Synechocystis sp. IPPAS B-1465 chromosome, complete genome | 99% | 0.0 | 100% |
| Synechocystis sp. CCAP 6803 sub-strain GT-G, complete genome | 99% | 0.0 | 100% |
| Synechocystis sp. KSU-WH-2 16S rRNA gene, partial sequence | 99% | 0.0 | 100% |
| Synechocystis sp. CCAP 6714, complete genome | 99% | 0.0 | 100% |

Table 2. BLAST search results of 16S rRNA gene sequence of acclimated unicellular algal cells.

Potential for application in phycoremediation. We investigated the effectiveness of the stress-resilient Synechocystis sp. strain in nutrient removal from wastewater. Mixed domestic and industrial wastewater was inoculated with 1 g/500 mL (FW/V ratio) of culture. The cells grew very rapidly, giving dark green algal cultures. A week after inoculation, samples were withdrawn for analysis of ammonium, phosphates, and chemical oxygen demand. Comparison of the background ammonium and phosphate content of untreated effluent with post-treatment levels revealed 99.4 and 97.5% removal of these nutrients by acclimated cultures, respectively (Table 3). The effluent’s oxygen demand (COD) was also dramatically decreased by more than 40% (Table 3). Reduction of COD together with ammonium and phosphate are key targets for effluent treatment. Taken together, the increased growth of acclimated Synechocystis sp. (Fig. 4a) and its efficient nutrient removal (Table 3) demonstrate how this alga could be a very effective tool for effluent treatment.

Discussion
An impediment to use of algal systems for wastewater treatment is the presence of phytotoxic or growth-inhibiting compounds within certain streams of industrial and/or domestic waste. We found that our starting algal material was a composite culture of T. variabilis and a strain of Synechocystis sp., with the latter being a minor component. Neither of these algae survived when directly inoculated into a mixed domestic and industrial effluent. Our objective was to acclimate the culture for growth in the wastewater. Gradual exposure of the culture to minute quantities of the wastewater and increasing the quantities over time appeared to recapitulate the process of acclimation seen in nature. This phenomenon is wide-spread, having been reported in many organisms, including plants49 cyanobacteria50 and insects51,52. In all of these instances, the acclimation process is driven by changes in gene expression enabling the organism to survive under what previously was a threat to the organism.

Microscopy revealed that our starting composite algal culture switched from T. variabilis dominance to a culture exclusively consisting of Synechocystis sp. It is clear that T. variabilis was eliminated from the culture by toxic compounds within the wastewater. However, the nature of these phytotoxic and growth-inhibitory compound(s) in the mixed effluent remains unknown. From examination of the cultures, we noticed that T. variabilis cells were purged early during acclimation, at ≤3% wastewater strength. However, Synechocystis sp. remaining as a monoculture still continued to require step-wise small increments in wastewater strength, with large increases ≥5% not being tolerated. This indicates that Synechocystis sp. required gradual acclimation to grow in the wastewater. At this point, the biochemical basis for Synechocystis sp. acclimation is unclear and the subject of ongoing research. We found this organism to already have a fascinating innovation for survival in natural environments. This phenomenon is wide-spread, having been reported in many organisms, including plants49 cyanobacteria50 and insects51,52. In all of these instances, the acclimation process is driven by changes in gene expression enabling the organism to survive under what previously was a threat to the organism.

The vegetative cells of filamentous T. variabilis can differentiate into 2 cell types (akinetes and heterocysts) under specific environmental conditions83. Akinetes are survival cells usually appearing when there is stress, such as nutrient limitation, low light, or low temperature90,94. Heterocysts differentiate in response to depletion of external sources of nitrogen. Differentiation of heterocysts is accompanied by changes in cell morphology and expression of genes for the oxygen-sensitive nitrogenase enzymes responsible for nitrogen fixation. Only a few cells along each filament differentiate into heterocysts, which exchange nitrate for sugar with neighbouring photosynthetic vegetative cells along the chain. In the composite culture grown in nitrogen-depleted BG-110 medium, we found cells of Synechocystis sp. nesting to T. variabilis vegetative cells. Since Synechocystis cells die when incubated in BG-111 medium, their perpetual presence in the composite culture means they somehow derive their nitrate requirements from the nitrogen-fixing T. variabilis. Development of nanotubular structures on Synechocystis cells, hooking them to the polysaccharide capsule of T. variabilis filaments is a possible route for nitrate acquisition in what appears to us a commensal relationship. We speculate that the very low cell number of
Synechocystis sp. in the composite culture ensures that nutrient withdrawals are not too high to prevent debilitat-
ing T. variabilis growth.

The nanotubular structures were not present in Synechocystis cells growing in the nitrogen-rich BG-11
medium or wastewater. Therefore, their development could be cued by the environmental nitrogen limitation. Morphological change entailing development of extracellular appendages hitching together neighbouring cells is not unprecedented in the Synechocystis genus. For example, Synechocystis sp. PCC 6803 was reported to develop such appendages in response to limited oxygen gas55. In fact this phenomenon was observed in other algae, such as the appendages connecting co-cultured cells of Pelotomaculum thermopropionicum and Methanothermobacter thermoautotrophicus, which are thought to effect cross-species material transfer55,56.

Changes in cell morphology in response to environmental cues are also prevalent in microorganisms beyond algae. For example, the wheat pathogen Zymoseptoria tritici can grow as filamentous hyphae or a yeast-like culture of unicellular micropycnidiospores50 as driven by external light cues. The micropycnidiospores are not dormant spores, but rather vegetative cells, which divide and grow in a yeast-like fashion. Darkness stimulates filamentous growth and light stimulates yeast-like growth58. While the change in morphotype of this fungus is cued by light, stress has previously been reported to serve as a stimulus triggering a change in bacterial morphology. For exam-
ple, the loosely packed coccobacillus cells of the heterotrophic bacterium Acidocella sp. (strain GS19h) can switch to chains of coccidal lenticular cells or filaments when exposed to heavy metal stress59. In T. variabilis nitrogen depletion is a powerful cue for vegetative cell differentiation into heterocysts53.

The strain of Synechocystis sp. isolated here could be employed for commercial development of an algal waste-
water treatment system. Rapid growth of acclimated Synechocystis sp. in wastewater led to efficient reduction of nutrients, such as ammonium and phosphate. The biomass can be used for fractionation of products for use in industrial applications. However, many aspects of algal growth and large-scale production require optimisation before developing this strain for industrial exploitation. Therefore, our study provides an avenue by which algae could be optimized for both wastewater treatment and as a resource for industrial feedstocks.
**Materials and Methods**

**Cultivation of algae.** The original culture of *Trichormus variabilis* CCAP 1403/4B was obtained from the CCAP collection (Edinburgh, UK) and cultivated in BG-11 (Blue-Green) culture medium according to Stainer *et al.*\(^6\) A litre of BG-11 growth medium contains: 1.5 g NaNO\(_3\), 40 mg K\(_2\)HPO\(_4\), 75 mg MgSO\(_4\).\(_7\)H\(_2\)O, 36 mg CaCl\(_2\).2H\(_2\)O, 6 mg citric acid, 6 mg ammonium ferric citrate green, 1 mg EDTA\(_{2}\)Na\(_2\), 20 mg Na\(_2\)CO\(_3\), 2.86 mg H\(_3\)BO\(_3\), 1.81 mg MnCl\(_2\).4H\(_2\)O, 220 µg ZnSO\(_4\).7H\(_2\)O, 390 µg Na\(_2\)MoO\(_4\).2H\(_2\)O, 80 µg CuSO\(_4\).5H\(_2\)O, and 50 µg Co(NO\(_3\))\(_2\).6H\(_2\)O. For some experiments, cultures were also cultivated in BG-110 medium,\(^6\) which is N-depleted BG-11 medium with all metal nitrates replaced with CoCl\(_2\). Biomass was grown in sterilised glass tubes or flasks incubated with illumination at 65.5 \(\mu\)E.m\(^{-2}\).s\(^{-1}\) and 25 °C. Stationary cultures were aerated by bubbling filter-sterilised air through a sterile glass tubing releasing air at the bottom of the culture vessels. Cultures in conical flasks were aerated by orbital shaking (LS-X, Adolf Kühner AG, Birsfelden, Switzerland) at 115 rpm.

**Transmission electron microscopy.** For electron microscopy, cells were cryo-fixed by high-pressure freezing with a high pressure freezer EM ICE (Leica Microsystems Inc, Buffalo Grove, US). Super quick-freeze substitution was performed using 1% OsO\(_4\), 0.5% uranyl acetate and 5% H\(_2\)O in acetone followed by embedding into epoxy resin.\(^6\) Ultrathin sections (50 nm) were prepared using ultramicrotome UC6 (Leica Microsystems Inc, Buffalo Grove, US) contrasted for 10 min each in 1% uranyl acetate in ethanol followed by Reynolds lead citrate. Sections were viewed at 100kV with a Hitachi H-7600 transmission electron microscope (Hitachi, Tokyo, Japan).

**Wastewater treatment and nutrient analysis.** Mixed municipal plus industrial wastewater effluent (anaerobic digestate sludge liquor returns) were obtained from Bran Sands Waste Treatment facility of Northumbrian Water Ltd. (Middlesbrough, UK). At the waste processing plant, after anaerobic digestion the effluent is centrifuged, the solids are separated out and the liquor goes back into the plant for further treatment.

**Figure 4.** External source of nitrate is required for viability and growth of *Synechocystis* sp. (a) Growth curves of *Synechocystis* sp. in N-deficient BG-11\(_0\) and N-replete BG-11 growth media. *T. variabilis* growing in N-deficient BG-11\(_0\) medium was included as a positive control. (b) Gradual cell death of *Synechocystis* sp. grown in BG-11 after transfer to BG-11\(_0\). (c) *T. variabilis* culture grown in BG-11 and transferred to BG-11\(_0\) medium continues to grow.

| Parameter | Untreated (mg/L) | Treated (mg/L) | Reduction (%) |
|-----------|------------------|----------------|---------------|
| NH\(_4\)+ | 443              | 2.48 ± 0.01    | 99.44         |
| PO\(_4\)- | 520              | 12.8 ± 0.5     | 97.53         |
| NO\(_3\)- | 410              | 24 ± 0.16      | 94.14         |
| COD      | 1890             | 1115 ± 30.9    | 41.00         |

Table 3. Wastewater parameters before and after treatment with acclimated *Synechocystis* sp.
Samples of this sludge liquor return were obtained and all endogenous organisms killed by autoclaving prior to use in experiments. The wastewater was sterilised by autoclaving prior to inoculation with *T. variabilis*. We acclimated the cultures for growth in wastewater via consecutive passaging through a serial dilution of increasing wastewater strength. Experiments were conducted using glass culture vessels incubated at 25 °C/65.5 μE m⁻² s⁻¹ and bubbling compressed air. Inoculums of 100 mg filamentous culture was added to 70 mL BG-11 containing -1% (v/v) wastewater and allowed to grow for a week. An aliquot from this culture was used to inoculate a 3% wastewater-containing BG-11 medium. This process was repeated successively, with 3% wastewater increments each week until growth was stabilised at 50% wastewater. The acclimated culture was then used for subsequent experiments.

To evaluate the efficacy of algal cultures in wastewater treatment, triplicates of 500 mL wastewater were inoculated with 1 g of the acclimated algal culture. A week later, samples were withdrawn for determination of ammonium and phosphate content, and the chemical oxygen demand (COD) were analysed using LCK test kits according to the manufacturer's instructions (Hach Lange, Manchester, UK).

### Sequencing 16S rRNA gene.

The original algal culture obtained from CCAP was grown in BG-11 medium and the biomass, which was dominated by *T. variabilis* filaments, harvested at the exponential growth stage for DNA extraction. An algal culture acclimated for growth in wastewater (as described above) was grown in BG-11 medium and harvested at the exponential growth phase for DNA extraction. This culture consisted of single cells with no filaments. DNA extraction and PCR analysis were performed as described previously using the primers Cya359F "GGGGAATTTGGCAGATGGG" and "ACGGGGGT ATGTTATC", where Y is any pyrimidine. The DNA samples were submitted to Sequtetch (Mountain View, CA, USA) to perform the sequencing. To identify the species, the NCBI BLASTN 2.8.0+ program was used to search the entire NCBI database (https://blast.ncbi.nlm.nih.gov/Blast.cgi) using the nucleotide sequences as the query. For comparison of the sequence obtained from the filamentous algal culture to the sequence from the unicellular algal culture, we used the William Pearson’s ALIGN program, an online sequence alignment tool found on the EXPASY Bioinformatics Resource Portal (https://embnet.vital-it.ch/software/LALIGN_form.html), which utilizes an algorithm developed by Huang and Miller.

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**Author Contributions**

F.R.A., B.G., O.T. and H.J. conceived the initial research; S.C. and H.C.G. designed the experiments; S.A. and I.C. performed experiments; S.A. and S.C. wrote the manuscript; all authors reviewed the manuscript.

**Additional Information**

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