

Treatment Using Hybrid Algal-Bacterial Bioreactors: A New Dimension in Wastewater Engineering

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India treats barely a third of the urban wastewater it generates every day; the rest flows into waterbodies, largely untreated. Conventional biological treatment processes are energy-intensive primarily because of the mechanical aeration required to sustain aerobic microorganisms. This article describes an engineered hybrid algal-bacterial system we developed in our laboratory at IIT Hyderabad as an alternative to conventional systems to address this issue. It exploits a symbiotic partnership that exists between microalgae and heterotrophic microorganisms in natural systems and promotes the same in the new system to reduce the energy use while also removing organic carbon, nutrients, and a class of compounds called 'emerging pollutants' or micropollutants, which are mostly anthropogenic. One version of this technology has already been commercialized and is in operation at an industrial site. I walk through the genesis of the idea, the development phase the technology is in today, and the real-world issues that we faced in moving it from the laboratory to the market – hurdles that, I believe, offer useful lessons for everyone at the institute trying to commercialize their own research.

Wastewater Treatment in India: The Underlying Problem

Wastewater treatment & reuse remains a major infrastructural gap in India. The existing infrastructure can hardly treat about one-third of the urban wastewater it generates every day; the rest flows into receiving water bodies, largely untreated, thereby putting public health at risk. The discharge guidelines have become much stricter in recent years, and the government emphasizes removing both organic carbon (measured as BOD and COD, which indicate the oxygen demand exerted by pollutants) and nutrients (such as nitrogen and phosphorus) from wastewater so that the treated water can be safely reused for non-potable purposes.

It is difficult to achieve high carbon and nitrogen removal simultaneously using conventional technologies without incurring much expenditure. They require multiple bioreactors working one after another – one for carbon removal (aerobic, and also needed for extended aeration) and another for nutrients (anaerobic or anoxic). The mainstay of conventional treatment, the Activated Sludge Process (ASP), depends on heterotrophic microorganisms that need a continuous supply of air to function. This aeration step, driven by blowers, accounts for 45 to 75 percent of a treatment plant's total power bill. That leaves a clear engineering opportunity –

a technology that can achieve carbon oxidation and nutrient removal in fewer steps, at a lower cost, preferably in a single tank, without sacrificing treatment efficiency.

The Proposed Technology and the Science Behind It
Our R&D on the algal-bacterial treatment process is based on the symbiotic association that exists between heterotrophic microorganisms (mainly bacteria) and predominantly photoautotrophic microalgae in nature (Figure 1). The central idea is straightforward - Microalgae, in the presence of light and carbon dioxide, perform photosynthesis releasing oxygen as a by-product. Heterotrophic bacteria then use this oxygen to break down and mineralize organic matter in the wastewater, releasing carbon dioxide, nutrients (nitrogen and phosphorus), and other minerals that the microalgae take up in turn for maintaining their growth. This back-and-forth exchange sharply reduces the mechanical aeration – and therefore the energy – that treatment would otherwise require.

The algal-bacterial symbiosis has many advantages and goes well beyond energy saving. Reactive oxygen species produced during algal photosynthesis chemically break down micropollutants, the trace organic contaminants that are primarily anthropogenic, which conventional processes tend to handle poorly, as they are not designed to do so in the first place. Another notable advantage of this association is that aqueous-phase nitrogen is assimilated into algal-bacterial biomass rather than being converted to nitrogen gas and lost to the atmosphere, as in conventional nitrification-denitrification process; it remains within the biosphere and can be recovered as a resource. That makes the resulting sludge more valuable too: instead of being disposed of as pure waste, it can be turned into fertilizer, animal feed, or biofuel feedstock. Also, as such hybrid systems produce fewer biological and biochemical emissions, they also leave a smaller carbon footprint than conventional alternatives.

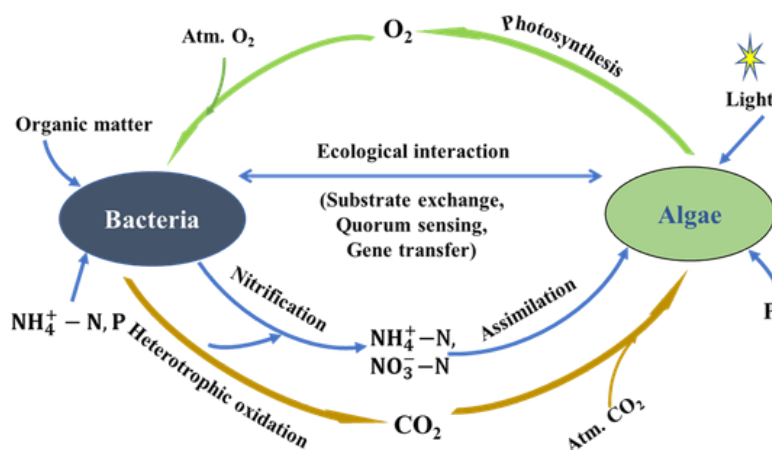


Figure 1. Algal-bacterial symbiosis: microalgae supply oxygen through photosynthesis for use by heterotrophic bacteria, while the bacteria supply carbon dioxide and nutrients that support algal growth.

What Is New in This Approach

Algal treatment is not new in itself; algal ponds have long been used as a tertiary (final polishing) step in wastewater treatment, but they require large areas of land, which limits their practicality. Our work instead positions the algal-bacterial process as a secondary (that is, principal biological) treatment step, using hyper-concentrated algal-bacterial cultures that occupy a much smaller footprint while still achieving substantial removal of carbon, nitrogen and phosphorus within short retention times. The objective is to replace, or supplement, the conventional biological treatment unit itself, achieving simultaneous removal of organic carbon, nutrients, and micropollutants in a single tank at a lower energy cost and a smaller carbon footprint, while producing a biomass by-product that can be potentially reused as fertilizer.



Figure 2. Pilot-scale Algal-Bacterial Attached Growth System, illuminated with blue LEDs to promote diatom-dominated biofilm growth on the textile support medium.

Present Status of the Technology

We have developed two prototypes. The first is an algal-bacterial attached-growth system, in which wastewater is sprayed over a vertically hung, textile-like support medium suspended in a caged framework; algal-bacterial biofilm develops on this medium as water trickles down its surface, and LED lighting (we used blue LEDs, which favour diatom growth, although white light or sunlight works equally well for green microalgae) promotes photosynthesis. This unit is designed to sit upstream in the biological treatment train, substantially reducing the organic-

load — and hence the downstream aeration requirement — before the wastewater reaches the main treatment process (Figure 2).

The second is an anaerobic-aerobic algal-bacterial suspended-growth system, in which a conventional activated sludge reactor is modified by introducing LED lighting into one chamber, allowing algae and bacteria to develop as a suspended culture rather than as an attached biofilm. Minimal external aeration is maintained, principally to keep the biomass in suspension, while the bulk of the oxygen demand is met photosynthetically (Figure 3).



Figure 3. Pilot-scale anaerobic-aerobic algal-bacterial suspended-growth reactor, showing the LED-illuminated chamber where algal photosynthesis supplies the bulk of the oxygen otherwise provided by mechanical aeration.

Technology Readiness Level and Commercialization

Both prototypes have progressed well beyond the laboratory stage. The Algal-Bacterial Attached Growth System has been commercialized and has reached Technology Readiness Level 9 (TRL 9 denotes a technology validated through full-scale, real-world operation). It is currently installed as an intermediate treatment unit in the condenser processing effluent treatment and reuse plant of a sugar-distillery industry (Figure 4).

Although the prototypes were originally conceived with gated residential communities in mind, industry became our first client, since industrial effluent — provided it does not contain chemicals detrimental to algal growth — suits the process well. The Anaerobic-Aerobic Algal-Bacterial Suspended-Growth System has completed pilot-scale development trials (TRL 6–7), and we are actively engaging with industries interested in taking it to field scale.



Figure 4. Field-scale installation of the Algal-Bacterial Attached Growth System, commissioned at a sugar-distillery effluent treatment plant.

Way Forward: Technological and Commercialization Challenges

Every technology carries both strengths and limitations, and ours is no exception. Meeting statutory discharge or reuse standards for BOD and COD has not proved difficult. Consistently meeting nitrogen removal limits through the assimilative (algal uptake) pathway, however, remains challenging, largely because the carbon-to-nutrient ratio of the incoming wastewater is often unfavourable for algal growth. At laboratory scale, we have validated the ideal carbon-to-nutrient ratio reported in the literature, and we are now examining whether blending different wastewater streams — a strategy commonly used in the biological transformation of solid organic waste to supply a favourable co-substrate — can correct this imbalance under field conditions. We are also investigating the engineering control of quorum-sensing molecules, the chemical signals that regulate algal-bacterial interactions, with a view to sustaining high algal populations, and hence high nutrient removal, throughout plant operation.

The commercialization process itself surfaced a different, and in some ways more instructive, set of challenges. Any new technology finds few early adopters, because of the financial risk involved: installing an effluent treatment plant is an investment running into several crores of rupees, and industries — for whom treatment is often a regulatory compulsion rather than a discretionary choice — understandably favour conventional, proven technologies over unproven alternatives. This caution is one reason why, despite successfully commissioning an effluent treatment plant during the COVID-19 period, we had to wait three years before securing a second field opportunity.

A second, less obvious obstacle arises after commissioning. Many industries outsource the operation and maintenance of their treatment plants to third-party contractors once the initial annual maintenance contract ends. These contractors are trained to operate conventional systems, and their unfamiliarity with a new technology and its underlying concepts acts as a further impediment to adoption, independent of the technology's technical merit. These are practical realities that we, as academic researchers, sometimes fail to anticipate. An aggressive and sustained marketing and training strategy is, therefore, as essential to commercialization as the underlying science — a lesson that may prove particularly relevant to small and medium enterprises and startups that partner with IITs and other academic institutions for product and process development under schemes such as UAY and IMPRINT.

My own conclusion, after this experience, is that technical validation is necessary but not sufficient: sustained engagement with the client, and with those who will ultimately operate the technology, is equally indispensable if a research innovation is to succeed once it leaves the laboratory and enters the market.

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