Utilizing algal oxygen production for advanced wastewater treatment in a Moving Bed Biofilm Reactor (MBBR) – the Biologically Aerated Reactor (BAR®)

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ABSTRACT
A novel wastewater treatment system has been developed, utilizing an oxygen-rich algal liquid to supply oxygen to an aerobic biofilm reactor. Aerobic treatment of wastewater takes place in a Moving Bed Biofilm Reactor, where the aerobic biomass which breaks down organic and nitrogenous pollutants grows as a biofilm on floating carriers. Algae grown in an open raceway pond produce oxygen through photosynthesis, and are recirculated through the MBBR in order to supply oxygen to the aerobic process taking place on the biofilm. The system has been piloted for 18 months within a municipal WWTP, producing a high quality effluent with no aeration costs, and a fraction of the total energy consumption of conventional processes. The sizing of the required algal raceways and recirculation rate to the MBBR were determined, and the relative functions of the algal raceway and the MBBR were determined by oxygen uptake rate testing of the different components of the system.

Keywords: algae, oxygen production, energy efficiency, MBBR, municipal wastewater, photosynthetic aeration, nutrient recovery

INTRODUCTION
In most intensive wastewater treatment operations, organic material and nitrogenous compounds are degraded by aerobic microorganisms, which require oxygen for their biochemical activity. Conventionally, in order to supply oxygen to these aerobic microorganisms mechanical devices, which introduce atmospheric air into the reactors (surface aerators, air blowers, etc.) are used. These are large consumers of electrical power. In the United States alone, wastewater treatment consumes a staggering 25 billion kWh/yr (1). In fact, aeration power costs can represent 15%–35% of the variable operational costs associated with wastewater treatment, imposing a significant financial burden on communities, as well as adding to fossil fuel consumption and CO₂ emissions.

Production of oxygen by micro-algae has been well documented and utilized extensively in treatment of wastewater, either in conventional waste stabilization ponds (WSPs) or the more engineered high-rate algal ponds (HRAPs). However, these algal-based wastewater treatment systems require large areas of land (due to the photic limitation of algal pond depth) and are usually not highly-controllable systems, resulting in inconsistent effluent quality. These limitations stem, at least partially, from the mixture, in a single environment, of both the photoautotrophic oxygen producers (algae) and heterotrophic oxygen consumers (bacteria), thereby creating conditions which are sub-optimal for both types of organisms (3). Furthermore, in such systems, bacterial residence time (SRT or MCRT) are identical to hydraulic residence time (HRT), meaning that in order to maintain the required bacterial population, long HRTs are required, again requiring large areas of land.
A (patent pending) process has been developed which utilizes the oxygen production capabilities of microalgae, while separating it from the bacterial oxidation of both organic and nitrogenous compounds which occur on an attached-growth aerobic system. In this process, biological oxidation is achieved on an attached biomass, by recycling an oxygen-rich algal stream through a moving bed biofilm reactor (MBBR), resulting in a high quality effluent and a controllable process, requiring a fraction of the energy required for aeration with conventional means (mechanical aeration or blowers), and considerably less space than traditional extensive algal-based systems – 24 hours HRT, compared to 2-6 days in HRAPs and tens of days in facultative and polishing ponds (4).

In addition, algal sequestering of N and P can be utilized for production of fertilizers, and, with additional treatment, algal biomass can be used for the production of animal feed and additional high value algacederived products.

The process has been piloted successfully for 18 months on municipal wastewater, producing the required effluent qualities with negligible energy consumption. The pilot plant was located in the Ra’anana Municipal Wastewater Treatment Plant (WWTP) in Israel. Screened and degritted wastewater is pumped from the plant influent channel to the pilot plant at a rate of 1-3 m$^3$/d. Currently, a full scale demonstration plant, treating 30-50 m$^3$/d, is in the process of being commissioned at the Dan Region WWTP in Israel.

**DESCRIPTION OF THE PROCESS**

Wastewater is screened and degritted before being introduced into an anaerobic stage. Depending on the application, this may be anything from a simple lined earthen anaerobic lagoon to a fully engineered Upflow Anaerobic Sludge Blanket (UASB) reactor. This stage is meant to reduce organic loading, as well as serve as a sink for excess algal and bacterial biomass and potentially produce biogas.

Following the anaerobic stage, the wastewater is introduced into a Moving Bed Biofilm Reactor (MBBR) where aerobic COD removal and nitrification take place. MBBR technology (aerated by conventional aeration systems) is a fully mature wastewater treatment process used in hundreds of WWTPs (industrial and domestic) around the world, and design and operational methodologies are well documented (2). In the process, the active biomass is grown as a biofilm on small, cylindrical HDPE elements (see Figure 4 below) of about 10 mm X 10 mm, designed to maximize protected surface area and mass transfer of substrates and oxygen from the bulk liquid into the biofilm. Unlike activated sludge, the biomass carriers (with the active biomass) are retained within the reactor by sieves, and only excess biomass, shorn off the biomass carriers, is carried over to the final solids-separation system (clarifier, dissolved air flotation unit, or filter) with the effluent. The use of an attached growth system, where the biomass is confined physically to one unit and does not flow through the system, allows the oxygen-rich algal liquid to flow through the system with minimal mixing of algae and bacterial mass; this in turn minimizes contamination of the algal raceway with bacterial biomass, flocs, etc, thereby improving environmental conditions for the algae, in particular with respect to increased turbidity and shading of the algae by bacterial biomass and flocs.
The MBBR stage may be operated with a single reactor, a few reactors in series, or parallel reactors – depending on the degree of BOD removal or nitrification desired. The MBBRs are equipped with mechanical mixers in order to ensure carrier mixing and optimal mass transfer of substrates.

Oxygen to the MBBR is supplied by algae-rich water residing in open raceway reactors. The area, number and staging of the raceway reactors will depend on the process characteristics and amount of oxygen required. The oxygen-rich liquid is recirculated to the MBBR utilizing high-flow, low head pumps; from the MBBR the now oxygen-depleted liquid is returned to the raceway to resume photosynthetic oxygen production.

Final effluent is conveyed either from the MBBR or from the raceway to a final solids-separation unit; depending on the type of application and required effluent quality, this could be anything from a simple clarifier or lagoon to a Dissolved Air Flotation unit. Excess biomass (algal and bacterial) is removed from this stage for further processing, either in the digester, or for production of fertilizer, animal feed, or, in the future, biofuel.

The anaerobic and aerobic segments are sized according to standard design procedures for UASB (or anaerobic lagoons) and MBBR systems, respectively. Experimentation was conducted with the algal raceway sizing and staging, as this is considered to be the component which will require the largest footprint. Raceway ponds with hydraulic retention times of 24 hours were found to be sufficient for full BOD removal.

![Figure 1: Schematic description of the system](image)

The pilot plant operated in the Raanana WWTP consisted of the following process units:

- A vertical cylindrical anaerobic tank which may be operated either as a recirculated UASB or as a simple anaerobic reactor, total volume 2 m³.
- Aerobic treatment in 2 Moving Bed Biofilm Reactors, containing commercial biomass carriers (with an effective surface area of 650 m²/m³ of carriers). The MBBRs are operated either separately or in series, depending on the desired effluent quality. The reactors have an effective volume of 700 liters each.
- Production of photosynthetic oxygen in 2 algal open raceway ponds, again operated in a variety of modes (single, parallel or series). Each raceway has a volume of 1,400 liters, and a surface area of approximately 8 m².
- Recirculation capabilities of oxygen-rich algal liquid to either or both MBBR reactors
- Final separation of biomass and excess algae in a simple gravitational clarifier.
PILOTING METHODOLOGY

Commissioning and basic operation
A micro-algal culture consisting predominantly of *Scenedesmus sp.* was raised in the open algal raceway ponds, until Total Suspended Solids content of the raceway ponds reached 200-250 mg/l, and raceway ponds showed dissolved oxygen concentrations of 12-20 mg/l. Once the supply of algal oxygen was assured, wastewater was gradually introduced into the system. Oxygen rich algal liquid was recirculated to the MBBR and returned to the raceway pond continuously.

Wastewater was introduced into the MBBR in October 2011, and after approximately 8 weeks the aerobic biofilm on the biomass carriers was fully developed (see Figure 4 below). In November, an anaerobic upflow reactor was put on-line before the MBBR, removing about 40% of the influent solids and 30% of the organic load as COD, thereby allowing an increase of the flow to the aerobic system.
The system was then operated at varying flow-rates (45 to 90 liters/h), and operational parameters such as Dissolved Oxygen and pH in the raceway ponds and the MBBR reactors were monitored daily. Recirculation of the oxygen-rich liquid from the raceway ponds was proportional to the influent flow, and was varied between 200% to 600% of the influent flow. The influent flow-rates corresponded to an HRT of 16-24 hours in the raceway, i.e., the daily volume put through the raceway ponds was equal to, or more than, the volume of the active raceway(s).

Effluent was removed from the raceway to a simple clarifier, where clarified effluent was sampled and discharged. Excess biofilm and settled algae were periodically removed from the clarifier for disposal.

Capability of the system to remove carbonaceous pollutants (measured as Chemical Oxygen Demand, COD) were measured by the soluble (filtered) COD levels in the effluents; this parameter, once a correlation to Biochemical Oxygen Demand (BOD) is established, is more rapidly and accurately tested than BOD and the soluble fraction accurately represents the degree of biological treatment (as opposed to the particulate fraction which is a function of solids separation). The plant consistently showed very good removal of soluble organic matter from the wastewater. Results are presented in the next section.

**Oxygen production**

A key question arising from the use of the algal raceway ponds as a “photosynthetic blower” supplying oxygen to the aerobic process is how much dissolved oxygen (DO) can be produced by a given amount of algae, exposed surface area, etc. Oxygenation capacity reported in literature varies according to reactor type, algae type and environmental parameters, ranging 1.5-1.95 g O<sub>2</sub>/g algae produced, or between 0.48-1.85 kg O<sub>2</sub>/m<sup>3</sup>/d (4). However, from an engineering point of view, in order to determine the size of the algal raceway required to treat a certain amount of wastewater a simple empirical mass balance approach was used, recording the DO levels in the raceway pond and the MBBR, as well as algal recycle flow-rate, in order to ascertain that enough oxygen was being supplied, or conversely, determine what
amount of wastewater can be treated with a given size of “photosynthetic blower” with a given recycle rate.

In order to determine these variables, DO logging was conducted in both the MBBR reactors and in the algal raceways, both during the day and during the night. Recycle rates were varied according to the DO in the MBBR, in order to maintain the required residual DO level for proper biological activity. Results are presented in the following section.

**Oxygen consumption**

As discussed above, DO levels drop considerably within the MBBR, indicating consumption of oxygen. However, since HRAPs are used in themselves as wastewater treatment systems, supporting bacterial populations concurrently with the algal biomass, and since algae also go into a respirative stage when under dark conditions (the MBBR tanks were purposely covered in order to prevent algae from developing in them), an important question was how much of the DO consumption can be attributed to bacterial activity on the biofilm, breaking down organic pollutants, and how much of it due to algal respiratory activity.

In order to determine this, respiration tests were conducted under various conditions. The procedure used for the respiration testing consisted of introducing different combinations of algae (both algae grown on a clean medium, i.e., tap water and nutrients, and algae that was grown in wastewater for 9 months), wastewater and acclimated biomass carriers, into a 5 liter Erlenmeyer flask equipped with a magnetic stirrer. Algae were taken from well lit raceway ponds, with DO levels above saturation (12-15 mg/l), and biomass carriers were taken from the active MBBR reactor. Wastewater was taken from the plant influent line. Dissolved oxygen in the liquid was then measured with a hand held Hach Lange LDO oxygen meter, and DO levels were logged every 5-15 seconds for a period of a 5 to 10 minutes. The drop in DO level indicated the rate of oxygen depletion from the liquid, which in turn makes it possible to determine which of the components (algae or biofilm) is responsible for most of the oxygen consumption and therefore most of the degradation of organic pollutants in the wastewater. In addition, the effect of acclimation of the algae to the wastewater and biofilm, or rather, the change in population in the algal mixture growing in the raceway ponds fed with sewage (due to increased bacterial activity in the raceway ponds) was tested by comparing oxygen uptake rates between a clean algal broth (with wastewater alone, and with wastewater and biomass carriers) and acclimated algae under the same conditions.

The combinations tested for oxygen uptake were:

1. Clean, unacclimated algae which had not been exposed to wastewater
2. Unacclimated algae together with wastewater
3. Unacclimated algae with wastewater and biomass carriers
4. Acclimated algae with wastewater
5. Acclimated algae with wastewater and biomass carriers

The results of the tests are reported below.

**RESULTS AND DISCUSSION**
**Basic Operation**

COD removal in the system was consistent throughout the testing period, despite some variations in influent COD and seasonal changes (temperature, sunlight) occurring throughout the testing period. The final effluent soluble COD was consistently in the vicinity of 50 mg/l, which is equivalent, in this wastewater to a soluble BOD level between 5-10 mg/l. Results are shown in Figure 5 below. Note that both parameters measured are filtered (i.e., soluble) COD.

![Figure 5: Influent and effluent soluble COD results, municipal wastewater](image1)

**Oxygen production and consumption**

As depicted in Figure 6, during the daylight hours, DO in the raceway pond varied from 10 to over 20 mg/l (due to limitations of the measuring device maximal measurements are 20 mg/l). It should be noted that throughout the measurement period, wastewater was being introduced into the MBBR and algal liquid recirculated through it as well.

![Figure 6: Dissolved Oxygen levels in the raceway pond during the day](image2)
Naturally, as depicted in Figure 7, at night DO production stopped, and the lack of a source of oxygen for the treatment process requires an engineering or operational solution. This challenge can be addressed in a number of ways, such as night-time storage of wastewater, addition of mechanical aeration for nighttime operation, or artificial lighting.

Within the MBBR, the algal liquid being recirculated through the MBBR was transferring oxygen to the aerobic bacterial biomass, and therefore DO measured inside the MBBR was considerably lower than in the raceway ponds. DO levels in the MBBR were maintained, as is standard in aerobic processes, between 0.5-2.0 mg/l. Figure 8 shows the variations in DO within the aerobic reactor throughout a 24-hour period: While the algal liquid was entering the reactor at super-saturation levels, the liquid exiting the MBBR was depleted of oxygen. At night, of course, no photosynthetic oxygen was being introduced into the MBBR and therefore very low levels of DO were measured there.
Oxygen uptake tests

The results for the different respiration tests conducted are presented in Figure 9 below.

As can be seen by the different slopes, different combinations produced distinctly different oxygen uptake profiles. It can clearly be seen that clean algae, and clean algae with wastewater, show very low oxygen uptake rates (0.02-0.04 mg/l/sec). When biomass carriers are added to the algae and wastewater combination, a higher respiration rate is measured – 0.13 mg/l/sec (green line). In other words, the aerobic biofilm on the biomass carriers was breaking down organic material, and consuming more oxygen in the process.
When acclimated algae and wastewater (no biomass carriers) are tested, a higher oxygen uptake rate is measured than with the equivalent solution of clean algae – the rate measured is 0.06 mg/l/sec. This would appear to indicate that the algal mixture used in an active wastewater treatment system probably contain aerobic organisms (sloughed off the biomass carriers) which continue aerobic activity when in the algal raceway.

The highest oxygen uptake rate was measured on the mixture of acclimated algae, biomass carriers, and wastewater. Under these conditions, an oxygen uptake rate of 0.24 mg/l/sec (blue line) was measured. This rate, 4 times higher than the acclimated algal mixture alone, was twice as high as the combination of clean algae, wastewater and biomass carriers under the same conditions.

These tests indicate that most of the oxygen uptake (and aerobic degradation of pollutants) takes place on the biomass carriers (50% to 75% of the activity), and a mature, acclimated algal mixture also enhances aerobic activity, though to a lesser degree than the biofilm system.

CONCLUSIONS

The concept of using oxygen produced photosynthetically by algae as an oxygen source for aerobic processes taking place in a biofilm system treating wastewater has been shown to be a viable alternative for high quality wastewater treatment. The system has been piloted for 18 months at flow rates of 1-3 m$^3$/d and is currently being upscaled. Conclusions drawn from the piloting effort include the following:

1. The system has shown it is possible to treat municipal wastewater aerobically without mechanical aeration, while supplying oxygen to the aerobic process through an oxygen-rich stream of algae.
2. With sufficient DO maintained within the system, it consistently produced soluble pollutant removal rates equivalent to those found in conventional systems with mechanical aeration.
3. A 24-hour HRT algal raceway pond was found to be sufficient in size to produce the required amount of oxygen required for breakdown of the organic pollutants in the wastewater.
4. Required recycle rates between the algal pond and the MBBR were 200%-600% of the influent flow.
5. Since oxygen production ceases at night time, engineering solutions are required in order to deal with wastewater treatment at night. 4 possible alternatives can be implemented:
   a. Installing aeration blowers and diffusers to be operated at night only
   b. If an anaerobic lagoon is planned upstream, it can serve as an influent buffer were wastewater is stored at night and pumped to aerobic treatment during the day.
   c. Artificial lighting can be examined for continued photosynthetic activity at night; as loads tend to drop off at night, it is possible that oxygen requirements, and so lighting requirements, will be considerably lower than during the daytime.
   d. For applications where more than a 24 hour retention time is desired, i.e., high load applications or applications focused on maximizing nutrient harvesting and algae growth, the averaging effect of day and night operation may be sufficient to produce the desired effluent quality.
6. Oxygen uptake rate testing has shown that most of the respiration takes place on the biomass carriers, and the remaining oxygen uptake can be attributed to
suspended bacterial activity of biomass suspended in the liquid and algal dark respiration.

7. Future directions for study include designing for biological nutrient removal (N and P), improving solids separation, and reuse of the separated biomass for anaerobic digestion or production of reusable end products such as fertilizers and plant growth enhancers. In the future, production of biofuel may also be considered.

REFERENCES
2. Biofilm Reactors, WEF Manual of Practice no. 35, Chapter 5, Water Environment Federation, 2010