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Integrating Algaculture into Small Wastewater Treatment Plants: Process Flow Options and Life Cycle Impacts

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Abstract

Algaculture has the potential to be a sustainable option for nutrient removal at wastewater treatment plants. The purpose of this study was to compare the environmental impacts of three likely algaculture integration strategies to a conventional nutrient removal strategy. Process modeling was used to determine life cycle inventory data and a comparative life cycle assessment was used to determine environmental impacts. Treatment scenarios included a base case treatment plant without nutrient removal, a plant with conventional nutrient removal, and three other cases with algal unit processes placed at the head of the plant, in a side stream, and at the end of the plant, respectively. Impact categories included eutrophication, global warming, ecotoxicity, and primary energy demand. Integrating algaculture prior to activated sludge proved to be most beneficial of the scenarios considered for all impact categories; however, this scenario would also require primary sedimentation and impacts of that unit process should be considered for implementation of such a system.

1. Introduction

Research and practice in the wastewater treatment field has shifted from strictly environmental protection to energy and resource recovery. Biogas and land-applied biosolids from anaerobic digestion are the most common methods of energy and resource recovery, but application of anaerobic digestion is often limited to large facilities. For small systems there remains a need to identify technologies that can accomplish net energy savings and resource recovery. Decreasing nutrient loadings in receiving waters has also become an important goal of wastewater treatment, especially "leading edge" methods employing biological nutrient removal (BNR). While improving local water quality by limiting nutrient emissions, BNR requires high energy demands for aeration, which increases greenhouse gas emissions.[1,2] Alternate processes with low energy requirements are desirable.

Algaculture is one promising means of capturing and utilizing wastewater resources such as water, nitrogen, phosphorus, and carbon dioxide. Wastewater-fed algaculture is receiving a great deal of attention.[3] Much of the recent literature is devoted to creating biofuels, since it has been emphasized that fertilizer consumption in stand-alone algal biofuel production facilities is a serious impediment.[4] The use of wastewater to provide nutrients is one potential path forward toward making algal biofuels sustainable,[5,6] thus the focus has been on whether the wastewater can support algal production. In that scenario the algae simply use the wastewater stream with no consideration of feedback to the wastewater treatment plant (WWTP). It is interesting to consider a different question: whether the use of algaculture can in some way enhance wastewater treatment. Clearly the algae could remove nutrients to improve effluent water quality, but could they also change the behavior of other unit processes to realize some synergistic benefits? This would be a true *integration* of algaculture and wastewater treatment.

One angle for accomplishing WWTP/algaculture integration is to mix algae with bacterial processes in the same tank for combined organic carbon and nutrient removal,[7–9] sometimes called "activated algae".[10] This follows from decades-old work showing that photosynthetic algae can potentially provide enough oxygen for heterotrophic bacteria to perform their function.[11] That approach has some promise, but may require an entirely new WWTP—or a complete overhaul—to create the algal/bacterial reactors, with very different hydraulic and solids retention times than existing plants.

Another angle for integrating algae with wastewater treatment is to keep the algaculture as a separate unit process, but place it at some location in the treatment train (or perhaps a side stream). This would be advantageous if an existing plant were being upgraded, as opposed to greenfield construction. Now that WWTPs are ubiquitous (at least in the developed world) most current construction projects are devoted to upgrades. Having an algal process that can be integrated during such an upgrade is the most likely way in which algaculture will be feasible for small systems in the near future.

There are three main locations in a conventional WWTP where an algaculture unit process could be added. The most commonly discussed location is at the end of the plant, where treated effluent is fed to algae as a polishing step to remove nutrients while growing algae for biofuel. This can be called “tertiary algaculture.” Another likely location for algaculture implementation is at the head of the plant, treating raw or settled wastewater. In this “primary algal treatment” approach the algae not only utilize wastewater nutrients, but can also use organic carbon to increase algal biomass production (given an appropriate species). The remaining likely location for an algaculture unit process can be called “side-stream algaculture.” This refers to the water produced in solids thickening operations, which can impart up to 30% of the plant’s total nitrogen load, depending on the biosolids digestion operation. References for studies using each of the three wastewater types can be found in Table 1.

Table 1: References used to model nitrogen and phosphorus removal efficiencies for various wastewater streams and algal culture types. Asterisks indicate references as cited elsewhere.[12]

WW Type	Culture Type	Removal reported in terms of…	Reference
Treated	Mixed, Biofilm	NO_3^-, TP	13
	Mixed, Biofilm	TN, TP	14
	Muriellopsis sp.	NH_3, TP	15
	Chlorella vulgaris	NH_3, NO_3^-, PO_4^{3-}	16
	Chlorella sorokiniana	NH_3	17
	Scenedesmus sp.	NH_3, PO_4^{3-}	18*
	Mixed, *Scenedesmus sp.*	NH_3, TP	19
	Mixed, Algae/Sludge	NH_3, PO_4^{3-}	20
	Chlorella sp.	TN, TP	21
	Neochloris oleoabundans	NO_3^- , TN, TP	22
Untreated	*Euglena sp.*	NH_3, TN, TP, PO_4^{3-}	23
	Mixed, *Chlorella vulgaris*/Sludge	TN	8
	Scenedesmus sp.	NH_3, TP	18*
	Chlorella sp.	NH_3, TP	24*
	Scenedesmus obliquus, Biofilm	NH_3, PO_4^{3-}	25*
	Mixed, *Chlorella sp.*	NH3, NO3-, and TP	26*
	Botryococcus braunii	NO_3^-, TP	27*
	Scenedesmus sp.	NO_3^-, TP	28*
	Haematococcus pluvialis	NO_3^-, TP	29*
	Mixed	NH_3, NO_3^-	30
	Mixed, *Desmodesmus communis*	TN, PO_4^{3-}	31
	Chlorella sp.	NH_3, TP	32
	Chlorella sp.	TN, TP	21
Sidestream	*Chlorella sp.*	NH_3, TN, TP	24
	Chlorella sp.	NH_3, TP	33
	Chlorella sp.	NH_3, TP	32
	Auxenochlorella protothecoides	TN, TP	34

The potential benefits of algaculture integration are many, beginning with nutrient removal. All three of the above-mentioned options provide nitrogen and phosphorus removal, which is advantageous over the current practice in many WWTPs (especially in small plants) of focusing only on phosphorus removal. Regulations have stressed phosphorus removal, but ecological research is showing that both phosphorus and nitrogen need to be addressed to prevent eutrophication, especially in downstream estuaries and coastal marine environments.[35] Adding to the benefits, algaculture captures nutrients through cell synthesis instead of through the commonly employed phosphorus removal method of chemical precipitation. Nutrients in algal cell biomass may be more bioavailable than in chemically precipitated sludge solids. However, the degree of nutrient removal benefit will likely vary with the location of the unit process. Side-stream algaculture would likely remove fewer nutrients than primary or tertiary algaculture, simply because it does not deal with the entire wastewater load. It is less predictable whether primary or tertiary algaculture would be advantageous; direct comparisons among the options are needed.

A possible advantage of primary and side-stream algaculture over tertiary is the ability to improve the activated sludge operations. Primary and side-stream processes could remove organic carbon and ammonia, decreasing their levels in the activated sludge influent. Some have reported that the nutrient-rich side-stream centrate is the best stream in a municipal treatment plant for removing nutrients to a high degree while achieving high algal biomass yields.[24,32] Combined heterotrophic-photoautotrophic growth has been studied, resulting in greater nutrient removal efficiency, improved lipid yields, and lower algae harvesting costs.[36] This would also decrease oxygen requirements for biological oxygen demand (BOD) removal and nitrification in activated sludge. Additionally, if energy is derived from the algal biomass itself, the decrease in aeration demand could help convert WWTPs from net energy users into net energy producers.[37] Further, in the primary and side-stream algaculture scenarios the activated sludge lies downstream of the algal processes where it can deal with any algal biomass that is not separated. These benefits are not available in tertiary algal treatment where there is no feedback stream to the conventional WWTP processes.

Along with nutrient removal algae may impart an improved capability for the removal of hazardous organic contaminants,[38] and metals[39] though the effects are species and process dependent. It has been shown in some cases that nickel and cobalt have a significant effect on the performance of activated sludge, altering the microbial populations.[40] Algaculture that removes these metals may benefit the overall plant performance. Tertiary treatment would not have an effect here, but primary and/or side-stream algaculture could be advantageous.

With all of the potential benefits, there are certainly hurdles to overcome in integrating algaculture into a WWTP. One main drawback is footprint; because algae utilize sunlight for energy, algaculture reactors are much shallower than other bioreactors (<1 m versus >4 m) and thus much more land area is necessary to achieve the required retention times. This is one of the main reasons to explore algaculture in small treatment systems; small systems are common in rural areas where land is more readily available than in urban areas. Still, minimizing land use is always desirable. This may be one way in which side-stream treatment will be advantageous, with its smaller flow rate and thus smaller reactor size than primary or tertiary treatment.

The cost of new unit processes is always a problem, and certainly for algaculture. In one study of the life cycle costs and environmental impacts for an algal turf scrubber (ATS) treating dairy wastewater, the eutrophication impacts were significantly reduced, but at a cost roughly seven times that of the non-ATS treatment.[41] Reducing that cost—perhaps through a synergistic algaculture/WWTP integration—will be necessary to make the ideas feasible.

Other, subtler issues could occur that would be detrimental to an integrated system. For one, activated sludge requires nitrogen and phosphorus to efficiently remove organic carbon from wastewaters. Low nutrient levels can lead to process upsets such as an overabundance of filamentous bacteria or even the production of exocellular slime that severely increases the sludge volume index (SVI), indicating poor settling.[42] Thus integration of nutrient removal by algae would need to be tailored so as to maintain sufficient nutrient levels in the activated sludge tank. And even if the triacylglycerides (TAG) from algae can be used for biofuel production, it has been reported that harvesting and recycling the nitrogen contained in the non-TAG portion of the cells will be critical to closing the energy balance.[43] Advances in biotechnology will likely be needed along with advances in process engineering.

Because the benefits and challenges for algal implementation are complex, the full life cycle of the system should be explored to make predictions about the net outcome. Life cycle assessment (LCA) is a systems analysis tool that can be used to identify stages or processes that contribute to a system's overall environmental impacts. LCA is finding increased use for evaluating the sustainability of wastewater treatment plants[44] and can be used to identify potential benefits and impacts of integrating algaculture in wastewater treatment. A 2012 study by Godin et al.[45] recommended the net environmental benefit (NEB) approach to analyzing wastewater systems. NEB was developed for remediation technologies dealing with hazardous wastes; it considers the no action scenario impacts (PI_{NT}) and subtracts from those the impacts from treated wastewater (PI_{TW}) and plant operation (PI_{OP}) to determine the NEB of the processes considered (Equation 1). In comparison, a standard LCA would only include the sum of treated wastewater and plant operation impacts (PI_{TW} and PI_{OP}). The NEB approach is especially useful for wastewater systems because it identifies cross-media effects of treatment, such as the tradeoff between reduced impacts to aquatic ecosystems resulting in impacts to terrestrial ecosystems through land application of biosolids.

$$NEB = PI_{NT} - PI_{TW} - PI_{OP} \tag{1}$$

This study seeks a fuller understanding of how algaculture can be integrated into small WWTPs. Both process modeling and life cycle modeling are used to explore how this integration may affect treatment operation and the resulting environmental effects, as well as how much algal biomass production may be expected if these technologies are adopted.

2. Methods

2.1 Goal and Scope Definition

The goals of this study are to assess the environmental benefits of using wastewater streams within an existing plant to cultivate algal biomass and to identify potential energy and resource recovery opportunities that algaculture can provide. The focus is on small (less than about 5 million gallon per day [MGD]) WWTPs in the United States.

To ground the study in a realistic scenario, an existing WWTP was chosen as a model: the Cochran Road Wastewater Treatment Plant in Clemson, South Carolina with a service area population of approximately 6,680. It is currently rated at 1.15 MGD with an average flow of 0.6 MGD but there are plans for expansion to 2 MGD in the near future. The existing plant is typical for small systems in rural areas; it is an extended aeration design with an equalization basin, an anoxic selector for control of filamentous bacteria, three aeration basins, two secondary clarifiers, and aerobic sludge digestion. Aerobic digestion is typical at plants this size because it is simpler to operate, whereas anaerobic digestion often requires more advanced training to maintain successful operation. Solids produced from primary sedimentation (primary solids) are problematic for plants without anaerobic digestion, so Cochran Road (like many small plants) does not have primary clarifiers; through extended aeration, the biodegradable portion of what would be primary solids is treated in the activated sludge aeration basins. Sodium aluminate is added prior to sedimentation for phosphorus removal. Although alum is more common and less expensive than aluminate, the low alkalinity regional water necessitates aluminate over alum.

Expansion of the existing system is being considered in the upgrade. This would include addition of a fourth aeration basin and a third secondary clarifier as well as expansion of the anoxic basin to achieve denitrification through mixed liquor recirculation. In this proposed expansion, efforts to achieve nutrient removal impart large costs to the treatment plant; nitrogen removal will require high energy consumption for aeration (to achieve nitrification) and recirculation pumping (to achieve denitrification), and phosphorus removal will require continued addition of aluminate.

This work models the proposed expanded system (four aeration basins and three clarifiers), but compares the proposed nutrient removal strategy to three types of algaculture integration to achieve nutrient removal. A life cycle approach is used to compare the four nutrient removal strategies with wastewater and algaculture models used to generate inventory data. The functional unit is 2 MGD (7,570 m^3) of raw wastewater treated. There is some debate about use of raw wastewater as a functional unit for LCAs of such systems due to differences in effluent quality, but through a modified NEB approach these differences will be accounted for in the results of the LCA. The study's system boundaries are drawn at the untreated wastewater leaving the plant headworks (bar screens) and include all emissions to the environment, including effluent discharge, air emissions, and trucking and land application of biosolids. No consideration was given to the impacts from aluminate production, transportation, or disposal. Construction and end-of-life impacts are also outside of the scope.

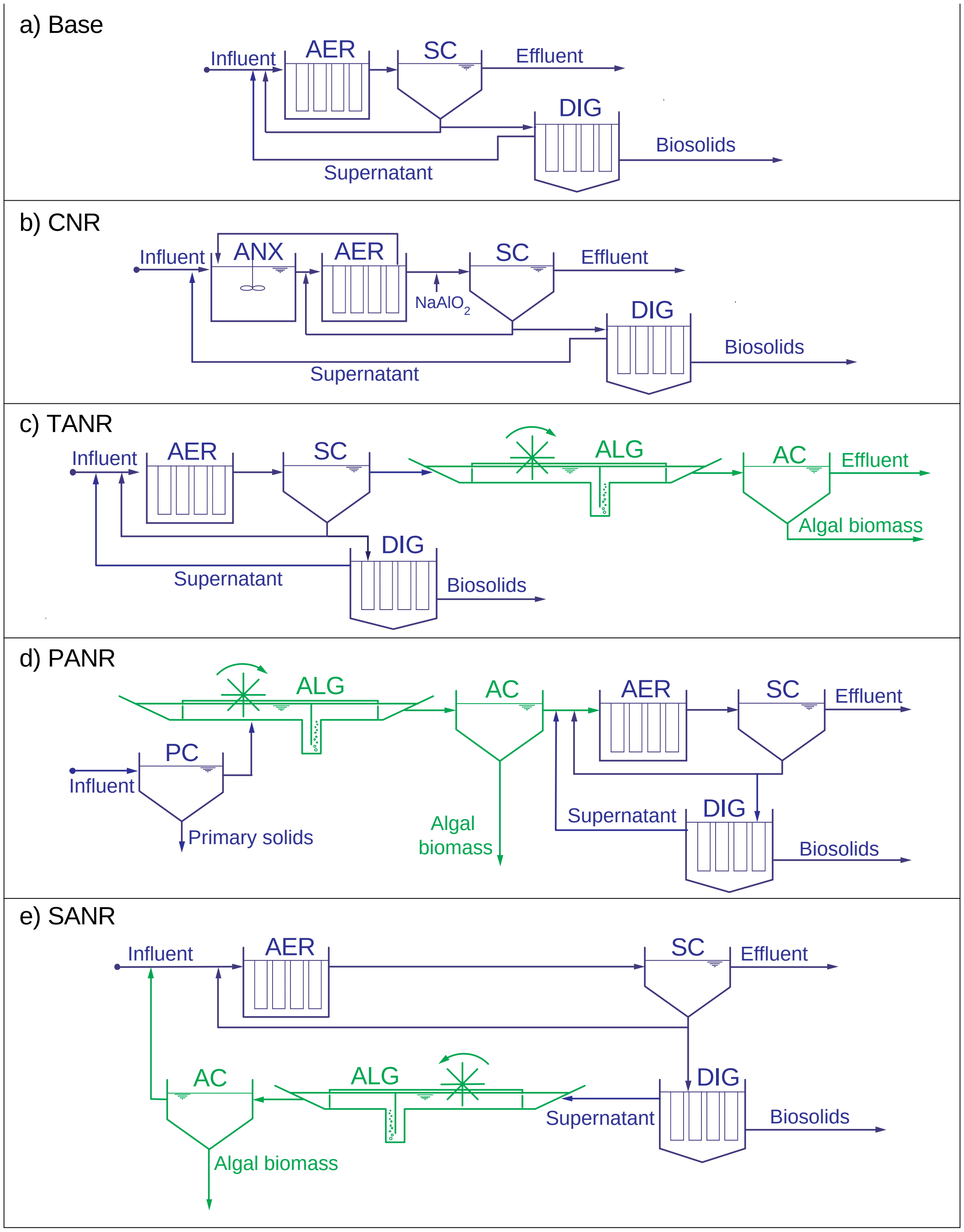

Figure 1: Processes and flows for treatment scenarios showing the location of the aeration basins (AER), secondary clarifiers (SC), aerobic digestion (DIG), algaculture ponds (ALG), anoxic basin (ANX), and primary clarifier (PC). Processes are: (a) the conventional activated sludge system that serves as a baseline for this analysis, (b) the conventional nutrient removal (CNR), (c) tertiary algal nutrient removal (TANR), (d) primary algal nutrient removal (PANR), and (e) side-stream algal nutrient removal (SANR).

2.2 Treatment scenarios

The goal of this study was to quantitatively model and evaluate treatment performance and life cycle impacts of several wastewater treatment scenarios, including options with integrated algaculture. The five scenarios considered (Figure 1) share the same basic activated sludge and secondary sedimentation systems which serves as a baseline for the rest of the analysis. The four other cases represent modifications to the baseline that are intended to achieve some degree of nutrient removal. The function of all scenarios is to treat two million gallons per day raw wastewater. Each system was modeled using three wastewaters, low, medium, and high strength, as described in Metcalf & Eddy,[46] to determine the variability in performance.

The baseline system (Base) is the proposed expansion of the extended aeration activated sludge system at the Cochran Road WWTP. This plant is designed to remove BOD and to minimize biosolids production. Nitrification is achieved in this system, converting ammonia nitrogen to nitrate, due to the long solids retention time (SRT, 18 days), but it is not designed to achieve total nitrogen removal by denitrification. Waste sludge is stabilized by aerobic digestion, decanted, and supernatant is returned to the head of the plant.

The second case represents the upgrade proposed to achieve nutrient removal which is commonly used in small systems and is referred to as the conventional nutrient removal (CNR) case. In addition to the baseline system described above, CNR also includes an anoxic tank prior to the aeration tanks, with mixed liquor recirculation, to achieve partial denitrification. Aluminate is added to the mixed liquor prior to clarification to achieve precipitation and thus reduction of phosphorus in the effluent.

The three other systems have integrated algaculture unit processes, each being placed at a different point in the treatment train. The most commonly cited use of algaculture in wastewater treatment is as a tertiary treatment step to remove residual nutrients after activated sludge. This scenario is referred to as tertiary algal nutrient removal (TANR). In another scenario (primary algal nutrient removal, PANR), primary treated effluent is fed to the algaculture system, which serves to remove nutrients prior to activated sludge. This scenario will also require addition of primary sedimentation, which is not common at small treatment plants, to allow light penetration. Finally, side-stream algal nutrient removal (SANR) uses the algaculture unit process to treat concentrated wastewater produced during sludge thickening. This strategy takes advantage of the high nutrient content of the concentrated side stream.

2.3 Modeling approach

For each case, the activated sludge process was modeled using BioWin 4.0 (Envirosim) to determine effluent quality, direct greenhouse gas emissions and biosolids properties for land application. Additionally, algaculture processes were modelled in tandem with Excel (Microsoft) to quantify the changes in aquatic, terrestrial, and atmospheric emissions; the potential algal biomass production; and the land area required for raceways ponds.

The baseline activated sludge model in BioWin consisted of four aerated tanks in parallel, with a total volume of 5.6 ML, a hydraulic residence time of 10.8 hours, and a solids residence time of 18 days followed by three clarifiers in parallel with a combined surface area of 476 m^2. Influent conditions were set *a priori*, except for PANR, for which primary sedimentation and algaculture treatment were modeled and the effluent from these processes served as the influent to the activated sludge system. Side-stream characteristics were determined by the output of the sludge thickening process model in BioWin and from the algaculture treatment model in SANR. BioWin default values were used where not specified. It is recognized that numerical modeling with packages like BioWin has its limitations; models typically require significant parameter verification and comparison with plant data to ensure accuracy. However, for this study the goal is a comparison among process options and by keeping the parameters consistent it is felt that valid comparisons can be made. Further, there is precedent in the literature for using BioWin models to generate life cycle inventories;[2] similar methods were used here.

The algaculture process was modeled using nitrogen and phosphorus removals reported in the literature (Table 1) and the Redfield ratio[47] ($C_{106}H_{263}O_{110}N_{16}P$). Because these values vary in published reports, and there is inherent uncertainty in how the algae will behave in practice, the modeling input parameters were set as distributions, instead of single values. For each of the three algal-integration scenarios, seven parameter distributions were created: TN and TP removals were the first two, and the stoichiometric coefficients of C, H, O, N, and P were the remaining five. TN and TP removal literature data roughly followed a gamma distribution, so that distribution shape was chosen for modeling. Alpha and beta (shape and rate parameters, respectively) for the gamma distributions were set to best fit the literature data (see supplementary information for more details). Stoichiometric coefficient values for C, H, O, N, and P were generated using normal distributions with the mean of each set to its Redfield ratio value. The standard deviation of these normal distributions was set to 25% of the mean. Each model was run using random numbers within the seven distributions, in a stochastic Monte Carlo approach. Results are reported as the average of 1000 such runs.

A sensitivity analysis was performed to determine which of the seven algae model parameters most affected the results. Each parameter was tested individually, using its distribution in 1000 model runs, but keeping the other parameters set at their mean values. The resulting model outputs for algal biomass production, N uptake into algal biomass, and P uptake into algal biomass were collected as final distributions. The model was considered to be most sensitive to the individual parameters that led to the highest standard deviations in model outputs.

The potential nutrient uptake (removal efficiency multiplied by nutrient loading) for both nitrogen and phosphorus was used to determine the limiting nutrient (N or P) based on the elemental composition of algal biomass. Nutrient uptake was calculated assuming uptake for the limiting nutrient was equal to the potential uptake. Nutrient removal for the non-limiting nutrient was determined by the elemental composition and production of algal biomass. The quality of the effluent was determined based on limiting- and non-limiting nutrient uptake. Nitrogen and phosphorus variables from BioWin that were modeled as available to algae were ammonia, nitrate, readily biodegradable Kjeldahl nitrogen, and orthophosphate. Changes in total organic carbon (TOC) in algaculture were also determined by the elemental composition of the algal biomass, assuming carbon dioxide and TOC were both able to be used as carbon sources for algal growth. Carbon available from wastewater was calculated in BioWin from total dissolved CO_2 and readily and slowly biodegradable COD in the influent to the algaculture process. COD was converted to TOC, as described in Metcalf & Eddy.[46] It was assumed that additional CO_2 would be supplied when CO_2 and TOC in the wastewater were not sufficient to satisfy the demand determined by the elemental composition (i.e. when carbon was the limiting nutrient).

Land area required for algaculture was calculated assuming raceway style ponds as described by others[48] with a hydraulic residence time of 4 days and a depth of 0.3 m. Dilution of side-stream wastewater is reported in literature and is accounted for in land area calculations. Harvesting efficiency of algal biomass was generously assumed to be 100%, but implications of lower efficiencies are discussed. It is important to note that the purpose of this study is not to design algae ponds for use at treatment plants. Instead it looks at how algaculture could potentially relieve the operational burdens associated with treating oxygen demand and nutrients.

2.4 Impact Assessment

A comparative impact assessment was performed and results for the following impact categories are presented: eutrophication, global warming potential, ecotoxicity, and primary energy demand. These categories were chosen to represent the most relevant impacts to treatment operations and emissions. The modified NEB approach was used, where impacts from direct release of untreated wastewater to freshwater were subtracted from operational impacts to determine the net (rather than gross) impacts. The impact assessment results are not comprehensive of the entire life cycle of the treatment plant, but are a comparison of operational stage of the different treatment scenarios as previously described.

This LCA was conducted using Gabi 6.2 (PE International) platform and based on inventory data from process models and the Gabi database for electricity and transportation. Biosolids transportation to agricultural land was modeled assuming 2% solids content and a distance of 100 km from plant to application site in a 22 ton truck. Primary solids generated in the PANR were assumed to be treated off-site and transportation was modeled like biosolids transportation, except 6% solids were assumed because of the better settlability of primary solids.[46] TRACI 2.1[49,50] was the impact assessment method used for eutrophication and global warming. Greenhouse gas emissions were calculated as described in Foley et al., 2010.[2] USEtox[51–53] was used for ecotoxicity, which is primarily a result of metals concentrations in biosolids; biosolids metals concentrations were used as reported in Foley et al. 2010.[2] Although considered in biosolids, metals are not reflected in effluent, algal biomass, or avoided emissions which is recognized as a limitation to the calculation of ecotoxicity impacts. Primary energy demand was calculated from United States (East) electricity grid mix and truck transport using GaBi database processes and characterization factors (Professional 2013 and Energy extension databases).

3. Inventory results

Analyzing life cycle impacts of a process involves first gathering data on relevant mass and energy flows to build a life cycle inventory. To understand the impacts from an LCA, it is necessary to first interpret the life cycle inventory data to give a better understanding of what is driving the impacts. This interpretation step also allows a better understanding of the drawbacks and potential improvements to the processes analyzed.

3.1 Treatment

The primary function of a wastewater treatment plant is to provide a barrier for release of contaminants that will negatively impact the receiving water and thus it is pertinent to understand how new technologies developed for use at wastewater treatment plants will impact effluent quality. Primarily, effluent concentrations of BOD and total suspended solids (TSS) must meet permit limits for discharge (9.5 mg BOD/L and 30 mg TSS/L respectively in the Cochran Road case). For all modeled treatment scenarios, effluent was found to comply with standards for BOD (Table 2). In addition, all systems were shown to comply with TSS standards (data not shown). In the TANR case this was directly influenced by the 100% harvesting efficiency assumed for the algaculture process, which is difficult to achieve with current algae technologies[54]. In real systems, 100% removal of algal cells would require a robust separation, such as membrane filtration,[55] which would likely impart large energy demands to the algaculture system. Harvesting efficiency and energy consumption of proposed algaculture systems should be addressed prior to implementation of tertiary algal nutrient removal. Implications of harvesting efficiency issues provide motivation for developing an alternative to tertiary treatment for algaculture integration at WWTPs.

Beyond the standard treatment targets of BOD and TSS, effluent nitrogen and phosphorus concentrations are important for controlling eutrophication in receiving waters. Total nitrogen (TN) and total phosphorus (TP) effluent concentrations for each scenario are shown in Table 2. All nutrient removal strategies had improved effluent quality in terms of TN over the Base scenario, with TANR and PANR showing the best performance. Again, consideration should be given to assumption of 100% removal of algal biomass before discharge for the TANR case. For both low and medium strength wastewaters, PANR is also competitive with CNR in terms of phosphorus removal, and has the benefit of non-harvested algal biomass being captured in activated sludge and secondary sedimentation processes.

Table 2: Influent and effluent wastewater characteristics for low, medium, and high strength wastewaters.[46] Units are mg/L.

	Strength	COD	BOD	TN	TP
Influent	Low	250	122.9	20	4
	Medium	430	211.4	40	7
	High	800	393.3	70	12
Effluent					
Base	Low	20.8	2.6	15.5	2.9
	Medium	30.1	2.6	32.0	5.1
	High	63.5	5.5	54.1	8.5
CNR	Low	19.4	2.2	6.3	0.3
	Medium	28.4	2.2	12.1	0.3
	High	57.8	4.3	20.2	0.8
TANR	Low	16.7	2.6	1.9	1.0
	Medium	24.3	2.6	4.5	1.2
	High	56.9	5.5	9.5	2.2
PANR	Low	17.5	3.2	2.9	0.3
	Medium	19.3	3.2	8.2	0.4
	High	44.4	3.8	16.9	2.6
SANR	Low	20.8	2.6	14.7	3.0
	Medium	30.0	2.6	30.6	5.3
	High	84.6	5.8	52.7	9.2

The effluent quality from SANR is essentially the same as Base; the small flow (approximately 1% of the influent flow) receiving nutrient removal in the SANR scenario does not result in large changes to effluent nutrient concentrations. It should be noted, however, that these results represent a steady-state simulation and side-stream flows are rarely constant, especially for plants that decant digesters as is common for aerobic digesters, such as in the model plant used here. Therefore, the pulse input from the decanting operation could cause a larger perturbation than is captured in this steady-state simulation and thus side-stream algaculture may serve as a type of equalization for small concentrated streams.

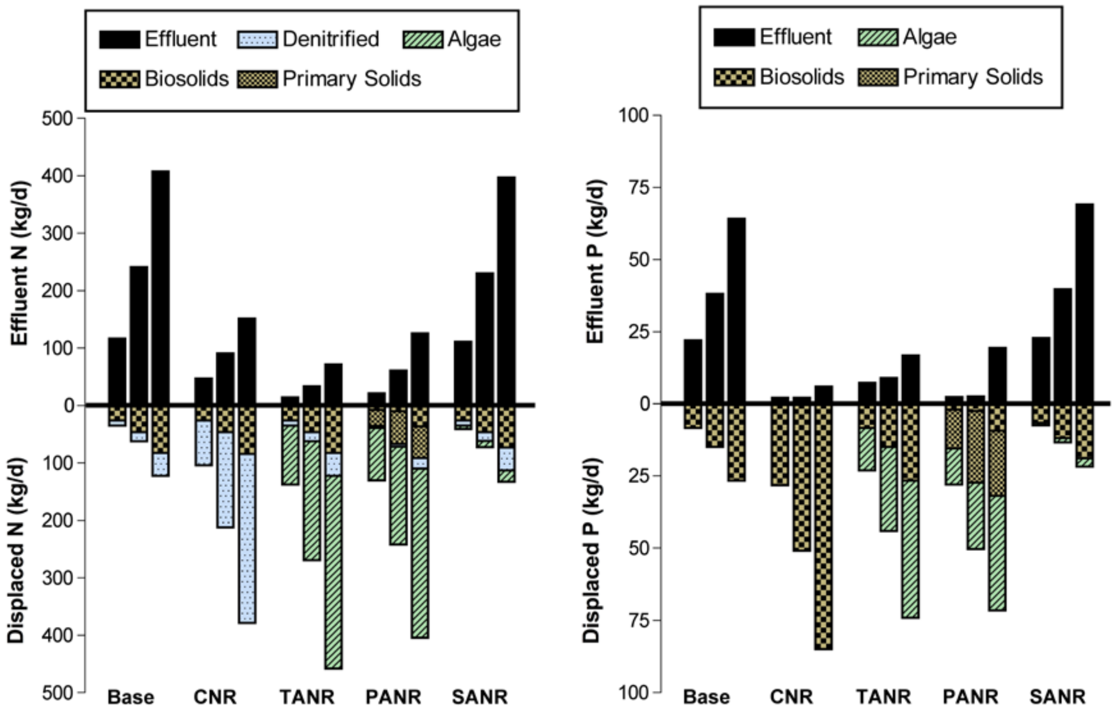

Figure 2: Effluent loading and fate of displaced total nitrogen (TN) and total phosphorus (TP) for each scenario. The three bars for each scenario represent low, medium, and high strength wastewater respectively.

Reduction of nitrogen and phosphorus from effluent is the result of changing the state of these compounds from the dissolved form to solids or gases. Understanding the fate of nutrients helps elucidate where other impacts occur as a result of nutrient removal. Figure 2 tracks the fate of both nitrogen and phosphorus in each case. N and P leaving in biosolids represent the potential benefit of improved soil quality and fertility when biosolids are land applied. However, in CNR much of the phosphorus is bound in stable metal complexes and is not available for plant growth. Additionally, if the end-use of the algal biomass is as a replacement of a terrestrial crop, N and P that leave the plant in algal biomass can also be considered a benefit due to the offsets of fertilizer that would be required to grow the terrestrial crops the algae is replacing.

Nitrogen removal through denitrification (to N_2 gas) is the main approach to nitrogen removal in the wastewater treatment industry, as represented by CNR, but this process is also the main source of nitrous oxide at WWTPs.[56] This approach to nitrogen removal reduces impacts to receiving waters but because N_2O is such a potent greenhouse gas, may increase overall environmental impacts due to global warming effects, which are discussed in detail later. Implications of primary solids in PANR are also discussed later.

3.2 Biosolids production

Land application of stabilized biosolids is a common method of disposal for small treatment plants and can be viewed as a benefit or an impact to the environmental performance of the plant. On the one hand, nutrients and organic carbon in the biosolids serve to replace industrial fertilizers and sequester carbon by increasing soil organic matter. On the other hand, biosolids have been shown to contain pollutants including heavy metals and other toxic compounds, and land application of these contaminants poses an exposure risk to humans. Additionally, transportation and disposal costs provide incentive to minimize biosolids production. These factors must be weighed in design of plant modifications.

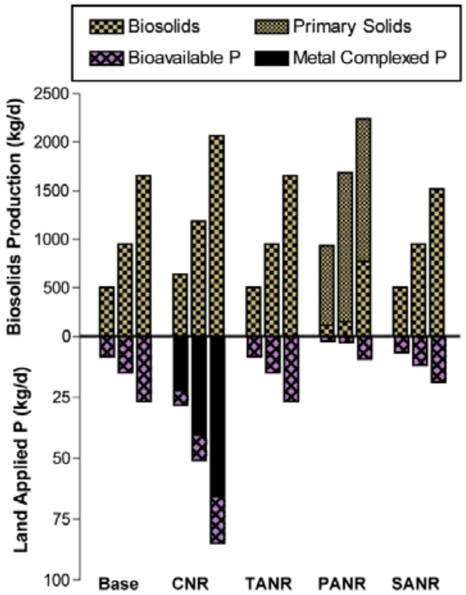

Figure 3: Biosolids production rates and phosphorus loading rates to agricultural land resulting from land application.

Figure 3 shows the results of digested biosolids production from all studied scenarios, including the phosphorus application rate which is the target for nutrient recovery because it is a non-renewable resource. Base, TANR, and SANR cases show similar performance in terms of biosolids production and phosphorus content. CNR resulted in higher biosolids and phosphorus loading rates, but again this can be attributed to the use of chemical precipitation whose metal-bound phosphorus may not contribute well to fertilization of the receiving soil. In addition, the increase in aluminum from aluminate may increase risks associated with land application.

The diminished rate of biosolids production seen for the PANR case is counteracted by primary solids production. Aerobic digestion of primary solids is uncommon, therefore this scenario would only be applicable if an alternative treatment or use of the primary solids is available. Transportation and disposal of the primary solids would be a major consideration for implementation of such a system. One potential end use for the algal biomass could be anaerobic digestion, and if that strategy were employed these additional solids could also be anaerobically digested; this is discussed in more detail later.

3.3 Direct greenhouse gas emissions

International standards for life cycle assessment state that CO_2 emissions from wastewater treatment are not included in calculations of global warming potential because all the influent carbon is assumed biogenic.[57] However, to capture the overall benefits of using algaculture in wastewater treatment, it is pertinent to consider the utilization of carbon dioxide by algae. In the algaculture model, carbon necessary to sustain growth was calculated from the stoichiometric coefficient. Both dissolved CO_2 and readily biodegradable organic carbon in the wastewater were available for algae growth and additional CO_2 necessary was calculated. In both TANR and SANR, it was seen that additional carbon is necessary to achieve the intended nutrient removal due to the lower C:N ratio as compared to untreated wastewater in PANR. This additional carbon requirement could be provided from CO_2 emissions from the activated sludge or digestion processes which produce far more than is required in algaculture (Figure 4).

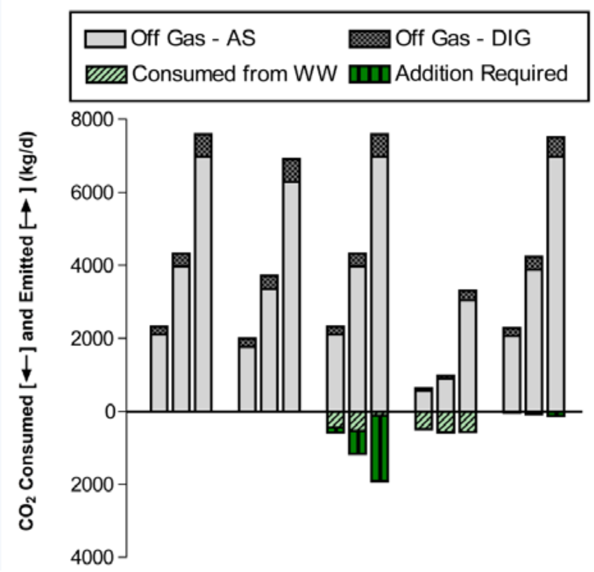

Figure 4: Carbon dioxide emissions from activated sludge (AS) and digestion (DIG) and consumption in algaculture, showing both CO_2 consumed from the wastewater and required addition.

In addition to carbon dioxide, methane and nitrous oxide are potent greenhouse gases that may be produced at wastewater treatment plants. The scenarios considered should not be significant contributors to CH_4 emissions because they do not include anaerobic digestion; this was verified by BioWin models. Nitrogen removal processes (nitrification and denitrification) are often cited as the source of N_2O, but any reactor with low dissolved oxygen can emit this gas. Figure 5 shows the calculated N_2O emissions for the activated sludge systems and the digester in each scenario. Though nitrification and denitrification are considered the major source of N_2O, these emissions (in CNR) are minimal when compared to the overloaded systems, except for PANR which was comparable with CNR.

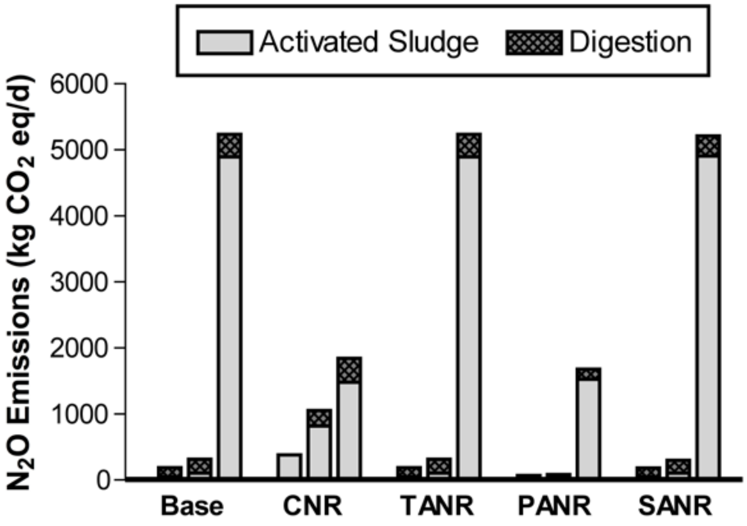

Figure 5: Nitrous oxide (N_2O) emissions for each wastewater strength (low, medium, and high) showing the influence of high loading rates on global warming potential.

3.4 Energy use

Electricity use is a prominent cause of impacts in wastewater treatment life cycle assessment studies. Electricity is primarily used to run blowers to provide aeration to activated sludge systems and for running pumps within the system. Reported aeration rates and recycle pumping rates from BioWin show CNR and PANR reduced the required aeration from the Base scenario (Figure 6). For CNR, this is a result of the treatment of BOD occurring in the anoxic selector, which is not aerated. The savings in aeration seen in CNR, however, are the result of recycle pumping required to achieve denitrification in the anoxic selector, thus increasing pumping energy requirements. On the other hand, when algaculture is used prior to activated sludge (PANR), COD loading to activated sludge is reduced, decreasing the aeration requirements for activated sludge. The right panel of Figure 6 highlights the influence of primary sedimentation and algaculture on COD removal. In addition to the reduced aeration and recycle pumping rates seen in PANR, it also has the benefit of not requiring additional aeration to algaculture to provide necessary carbon (Figure 4) unlike the other algaculture scenarios.

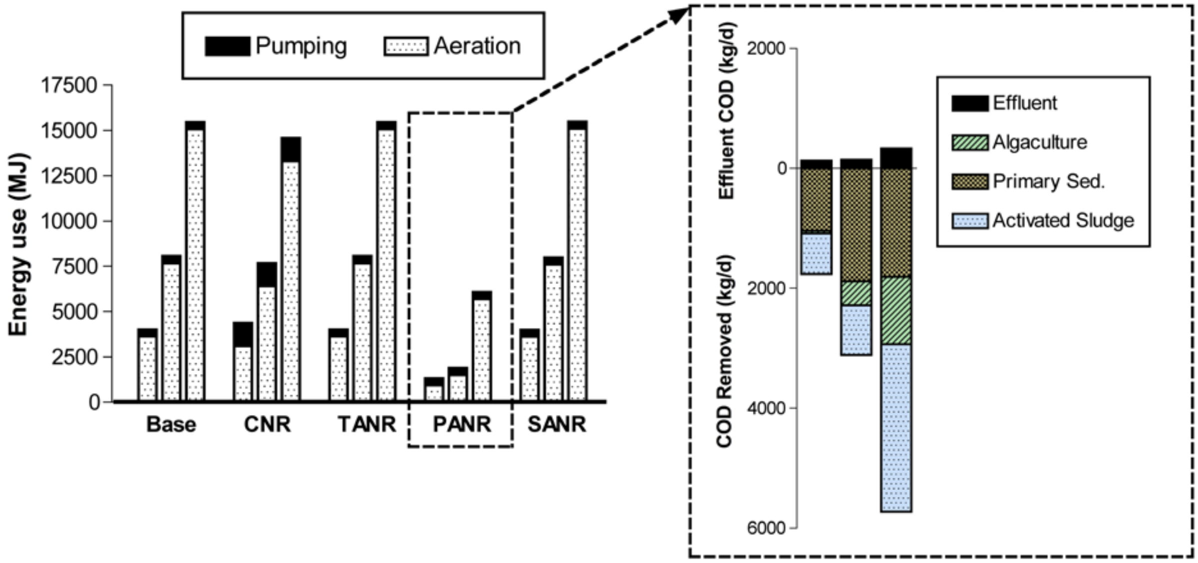

Figure 6: Energy use for activated sludge and digestion, showing aeration and pumping contributions (left) and COD removal in each unit operation in PANR (right).

3.5 Land use

The land required for algaculture exceeds that necessary for traditional activated sludge systems due to shallow tank depths necessary to sustain sunlight penetration in algaculture. Results show that for TANR and PANR, approximately 10 hectares are required to support raceway ponds; PANR would also require land for primary sedimentation (approximately 150 m^2 or 0.015 hectares). For SANR, only 0.2 hectares were required, including 50% dilution of side-stream wastewater cited in literature for this type of wastewater.

3.6 Sensitivity analysis

The life cycle inventory for this study relies on predictions about performance for both wastewater treatment unit processes and algal cultivation unit processes. The wastewater treatment aspect is based on BioWin models and, while not perfect, they have been vetted through common use. The algal cultivation modeling is not based on such standard methods and its parameters are less certain. It is therefore interesting to evaluate how sensitive the algae models are to the input parameters.

Sensitivity results for algal biomass production, N uptake into algal biomass, and P uptake into algal biomass are plotted for each algal treatment scenario (TANR, PANR, and SANR) in the supplementary information. The first observation is that algal biomass was more sensitive, in general, to the stoichiometric coefficients for C, H, O, N, and P than it was to the TN and TP uptake parameters. This simply reflects the fact that wider distributions were used for the stoichiometric coefficients than for the uptake parameters. For predicting algal biomass it will be important to understand the stoichiometric coefficients for the species of interest, under the conditions of interest, in order to limit the prediction error.

The sensitivity results give insight into the behavior of algal unit processes in terms of limiting nutrients. Both nitrogen uptake and phosphorous uptake for the TANR scenario (Figure S7) were sensitive to the N and P coefficients. A closer look at the data (not shown) reveal that during the stochastic TANR modeling N was the limiting nutrient about ¾ of the time while P was limiting for ¼ of the runs. When either nutrient was limiting, it affected both N and P uptake by affecting the total biomass; thus both parameters had an impact on the sensitivity, though N had the greater effect. In the PANR model (Figure S8) P was limiting in 2/3 of the runs, while N was limiting in 1/3 of the runs. This explains why algal biomass and P uptake are most sensitive to the P coefficient, and even N uptake (though most sensitive to the N coefficient) is affected by the P coefficient. In the SANR model (Figure S9) greater than 99% of the runs had N as the limiting nutrient. Thus nitrogen uptake was only sensitive to the TN-uptake parameter, and P uptake was also highly affected by the N coefficient. These results lend motivation for future laboratory and field work to determine which nutrients are limiting in practice, as those will significantly affect the algaculture behavior. Because the wastewater unit processes can dramatically affect the limiting nutrients, and because algaculture can in some cases feed back to the wastewater processes, a clear understanding is needed of how the processes integrate.

4. Impact assessment

Life cycle impact assessment is an important tool for engineers, policy makers, and water systems managers for direct comparison of the sustainability of wastewater treatment processes by addressing the tradeoffs between local and global impacts (e.g. eutrophication and global warming, respectively). The impact categories presented in this study were chosen to reflect both primary (at the treatment plant) and secondary (from upstream and downstream processes) impacts of wastewater treatment operation.

The LCA modeling in this study shows both impacts and benefits from treatment operation (Figure 7). Most relevant are eutrophication impacts and benefits. Although there are impacts associated with release of untreated BOD, TN, and TP to receiving waters, use of net impacts shows the huge reductions in eutrophication potential at WWTPs; the magnitude of the benefit directly reflects the effluent quality in each case.

In addition to benefits from reduction of aquatic pollution, there is also a possible benefit in terms of global warming associated with algal nutrient removal. While implementation of TANR may have potential to be a carbon neutral option, the models indicate that PANR is a carbon consuming process within the scope of this study. Treatment and disposal of the primary solids generated in this scenario, which is outside the scope, should also be considered if implementation of this technology is to be sustainable.

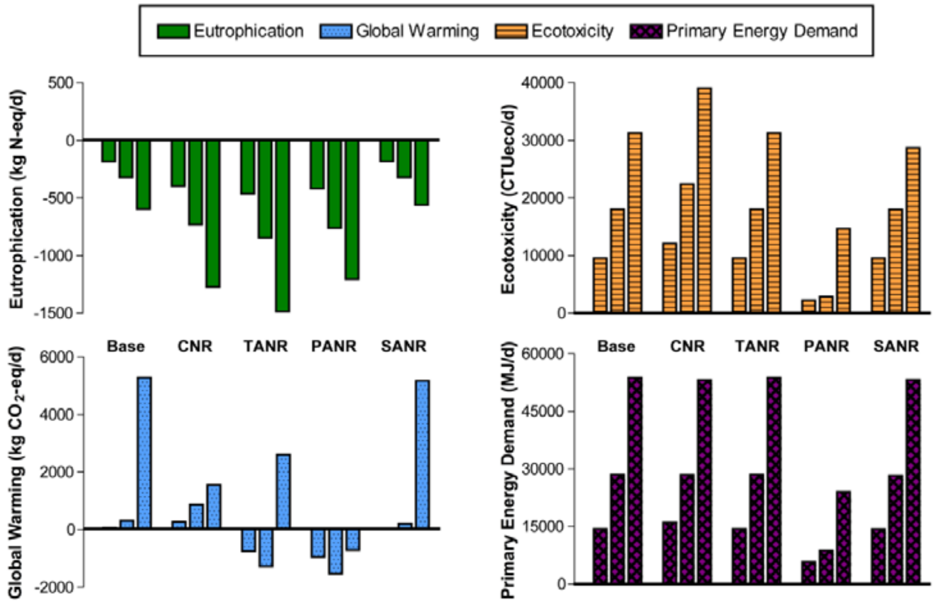

Figure 7: LCA results showing eutrophication (top left), global warming (bottom left), ecotoxicity (top right), and primary energy demand (bottom right). Negative values reflect a net negative impact, i.e. a benefit. All values are reported for one functional unit (2 MGD of raw wastewater treated).

Results for both ecotoxicity and primary energy demand assessment show impacts for all scenarios, the lowest in the PANR case. The ecotoxicity and energy demand impacts are consequences of land application of biosolids and electricity consumption at the treatment plant. Ecotoxicity arises from heavy metals which are common, though regulated, in land applied biosolids. The large reduction in biosolids production that results from PANR explains reductions in ecotoxicity for this scenario. Primary energy demand is also greatly affected in the PANR case as a result of several factors. First, aeration required in activated sludge following PANR is far lower due to the removal of COD by algal growth and primary sedimentation. Additionally, this reduced BOD and nutrient loading to activated sludge is the cause of reduction in biosolids production, which in turn requires less energy for both digestion and transportation to agricultural sites for land application. For a side-by-side comparison of all categories and treatment scenarios, Figure 8 shows the impacts on a scale from zero to one, representing the lowest and highest impact respectively in each category; therefore, the smaller a scenario's area, the more beneficial it is. The small size of the PANR petal demonstrates its advantages over the other scenarios. The large relative impact for land use in the PANR scenario identifies one of the drawbacks to this technique, but highlights the motivation for employing the process at small WWTPs, likely in rural areas where land may be more readily available than in urban areas.

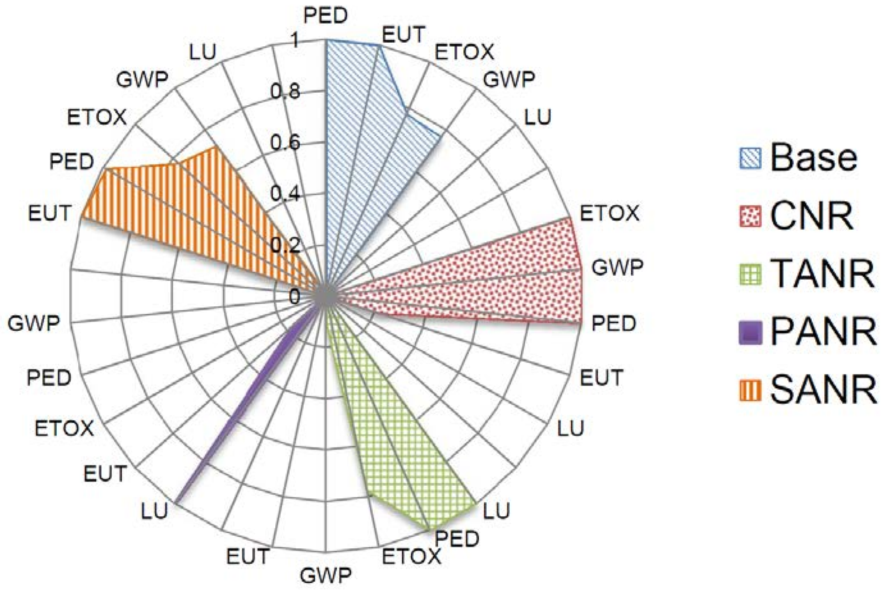

Figure 8: Life cycle impacts for the five treatment scenarios in five categories: primary energy demand (PED), eutrophication (EUT), ecotoxicity (ETOX), global warming potential (GWP), and land use (LU). The scale from zero to one represents the lowest and highest impact respectively in each category. Categories for each petal (each scenario) are ordered from highest to lowest impact.

4.1 Algal biomass production

In all ANR scenarios, algal biomass produced (Table 3) could conceivably be used beneficially, either in conjunction with existing treatment operation, or by an outside entity. A great deal of recent research has focused on the use of algae as a feedstock for biofuel production, but there are other options as well.

Table 3: Predicted algal biomass production for three algaculture-integrated scenarios for each wastewater strength. Values represent the mean and 95% confidence intervals expressed in kg/d.

	Algal Biomass Production		
	Low	**Medium**	**High**
TANR	1676 ± 29	3347 ± 54	5436 ± 88
PANR	1456 ± 24	2705 ± 46	4667 ± 79
SANR	94 ± 2	176 ± 4	327 ± 8

In the context of the wastewater treatment operation, there are three promising uses. First, land application of algal biomass can provide beneficial nutrients and organic matter to soil. Algal biomass has higher nutrient content than typical biosolids so may be more beneficial as a fertilizer. In addition, algal treatment processes are less energy-intensive than activated sludge processes resulting in reduced operational impacts and costs for a treatment plant to produce this organic fertilizer. If land application is chosen, however, it will be pertinent to include the impacts associated with land application, including heavy metals and transportation.

Another option for re-use is as a substrate for anaerobic digestion (AD). Although AD is not common for small plants, it has been proposed that a centrally located site for anaerobic digestion may serve to digest neighboring systems' biosolids.[58] It is also recommended that accepting other organic wastes can improve payback periods for digesters. If ANR can serve as a substrate for biogas production and as a means to decrease costs associated with wastewater treatment, this may further improve payback periods.

In addition to land application and biogas production, algal biomass from nutrient removal processes could serve another wastewater treatment purpose as a biosorbant. Algae have been shown to be effective in removal of metals and other contaminants present in wastewaters at low concentrations, and could potentially be used on site at municipal WWTPs or distributed for use at contamination point-sources. These point sources would likely be factories or other industrial wastewater producers.

4.2 Recommendations

Treatment, algaculture, and life cycle assessment models in this study have shown the benefits of using algal nutrient removal at small wastewater treatment plants, but further laboratory and pilot scale research is necessary to move this technology into the real world.

Wastewater specific algal growth rates, nutrient uptake rates, and areal productivity values will be necessary to design functional ANR systems. Improved algaculture models should also be pursued allowing for optimization of integrated processes.

5. Conclusions

This study supports the hypothesis that integrating algaculture at wastewater treatment plants can improve the sustainability of wastewater systems. Primary algal nutrient removal proved most promising due to huge reductions in operational energy and biosolids production. However, this scenario would require primary sedimentation, which is an important consideration. Improvements in effluent quality and efficiency over conventional treatment strategies through algal nutrient removal can provide an innovative way for small communities to contribute to a growing interest in energy and resource recovery in the wastewater industry.

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