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Landfill leachate – a water and nutrient resource for algae-based biofuels

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There is a pressing need for sustainable renewable fuels that do not negatively impact food and water resources. Algae have great potential for the production of renewable biofuels but require significant water and fertilizer resources for large-scale production. Municipal solid waste (MSW) landfill leachate (LL) was evaluated as a cultivation medium to reduce both water and elemental fertilizer demands of algae cultivation. Daily growth rate and cell yield of two isolated species of algae (*Scenedesmus* cf. *rubescens* and *Chlorella* cf. *ellipsoidea*) were cultivated in MSW LL and compared with Bold's Basal Medium (BBM). Results suggest that LL can be used as a nutrient resource and medium for the cultivation of algae biomass. *S*. cf. *rubescens* grew well in 100% LL, when pH was regulated, with a mean growth rate and cell yield 91.2% and 92.8% of those observed in BBM, respectively. *S*. cf. *rubescens* was more adaptable than *C*. cf. *ellipsoidea* to the LL tested. The LL used in this study supported a maximum volumetric productivity of 0.55 g/L/day of *S*. cf. *rubescens* biomass. The leachate had sufficient nitrogen to supply 17.8 g/L of algae biomass, but was limited by total phosphorus. Cultivation of algae on LL offsets both water and fertilizer consumption, reducing the environmental footprint and increasing the potential sustainability of algae-based biofuels.

Keywords: algae cultivation; landfill leachate; algal biofuels; bioremediation; *Scenedesmus*

Introduction

Algae have the potential to substantially contribute to the production of renewable fuels [1–3]; they can potentially meet 48% of US petroleum imports for transportation.[4] Recent analyses of algae-based biofuels, however, have shown that current production methods face significant challenges before a sustainable algal biofuel industry can develop. Among the most critical factors in the development of photosynthetic algae-based biofuels are satisfying the water and nutrient requirements for cultivation.[4–7] Utilizing waste nutrient and water resources for algae cultivation may alleviate economic constraints on large-scale algae cultivation. Exploiting previously fixed nitrogen within wastes avoids the energy-intensive Haber–Bosch process for nitrogen fixation, thereby increasing the efficiency and sustainability of algal cultivation. Many studies suggest using municipal sewage wastewater for the cultivation of algae.[8–10] However, the nitrogen from sewage wastewater alone, typically 15–20 mg/L, is insufficient to support large-scale algae biomass production for biofuels.[11] We present data that support the use of high ammoniacal-nitrogen leachates generated from municipal solid waste (MSW) landfills as an alternative waste nutrient resource to meet the water and fertilizer needs of algae-based biofuel production.

Landfill leachate (LL), the liquid waste generated by landfill sites, is a societal burden due to its high nutrient content and other constituents but may have intrinsic value as an algal culturing medium. LLs can potentially provide algal cultivation with copious amounts of high-nitrogen aqueous media.[12,13] Landfills continue to produce leachates throughout the lifespan of the landfill, even after closure. In Florida, MSW landfills generate an average of 7200 L/ha/day of leachate.[14] These leachates must be managed to prevent environmental contamination. Algae cultivation on LL fulfils a dual role of leachate remediation and biomass production,[15,16] reducing the societal and environmental burden imposed by these pervasive waste disposal centres.

MSW is inherently variable on a spatio-temporal basis and therefore the leachate generated by the MSW landfill is also variable and is contingent on the type of refuse, local climate, precipitation, management techniques, and age of the landfill.[12] Landfills progress through distinct maturation phases as they age.[17] The concentration of total ammoniacal-nitrogen within LLs increases with landfill age and is identified as a long-term issue for the management of MSW LL.[17] Additionally, the pH of LL increases over time as organic acids from decomposing refuse are microbially converted into methane and carbon dioxide gases.

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In comparison, leachates from younger landfills often have high chemical oxygen demand (COD), acidic pH, and relatively low ammonia content.[12] This study focused on the utilization of mature, high ammoniacal-nitrogen MSW LL.

Current literature on algae growth in LL is sparse and suggests that dilution with water and/or extensive pretreatment (15–30 days of mechanical aeration) of the leachate is necessary for algae to survive.[15,16,18] Even at high dilutions (90%), reported growth is only moderate [15] and the diluted leachate would not replace synthetic fertilizers typically used to cultivate algae as a biomass resource. Furthermore, high concentrations (>30%) of LL were shown to be inhibitory or acutely toxic,[15,16] making the use of LL apparently impractical as an algal culture medium. No literature has demonstrated a cultivation strategy to deal with the toxic LL environment, other than dilution [15] or mechanical aeration.[16] This research study aims to evaluate the potential of MSW LL as a cultivation medium for supplying both water and fertilizer nutrients for algae biomass production by comparing algal growth in MSW LL and in a standard growth medium, Bold's Basal Medium (BBM).

Table 1. Physico-chemical composition of MSW LL.

Component	Average ± std. dev. ($n = 3$)
pH	7.52 ± 0.101
COD (mg/L)	2107.3 ± 39.5
Conductivity (mS/cm)	17.19 ± 0.07
Total solids (g/L)	8.24 ± 0.04

Note: LL, landfill leachate.

Table 2. Elemental composition of LL compared with BBM.

Component	LL	BBM
Macronutrients (mg/L)		
Nitrogen	980	41.2
Ammonia-N	980	–
Nitrate-N	–	41.2
Phosphorus	13.2	53.2
Potassium	980	106.0
Magnesium	88.0	7.4
Calcium	110	6.8
Iron	16	1.0
Sodium	3700	86.3
Chloride	1800	27.5
Micronutrients (mg/L)		
Manganese	0.11	0.5
Copper	0.17	0.4
Zinc	0.06	2.0
Cobalt	0.07	0.1
Toxic metals (mg/L)		
Arsenic	0.13	–
Antimony	<0.06[a]	–
Cadmium	<0.0032[a]	–
Chromium	0.12	–
Lead	<0.013[a]	–
Selenium	<0.068[a]	–

Notes: LL, landfill leachate; BBM, Bold's Basal Medium.
[a]Minimum detection limit.

Materials and methods

Algae media

Leachate from a closed, methanogenic-stage landfill (Alachua County Southwest Landfill (ACSWL), Archer, Florida) was used in all experiments. The ACSWL is a 10.9 ha, lined landfill site, which received MSW from 1988 to 1999. The ACSWL was one of the first landfills in the state of Florida to incorporate a bottom liner to mitigate the environmental impact of MSW leachate.[19] After closure, an impermeable top liner was used to seal the landfill and reduce the amount of leachate generated from rainfall events. When active, leachate generated by this landfill averaged 85,000 L/day.[19] Methods employed in leachate management at this site have included research projects on leachate recirculation, including infiltration ponds and horizontal injection; additionally, a major method of management was leachate transport (via tanker truck) to a publically owned treatment works.[19] Current leachate management at the ACSWL involves recirculation by horizontal injection. This mature, closed landfill was chosen as the test facility since all landfills will eventually reach this stage of maturity.

Leachate was routinely collected directly from mainline recirculation plumbing of the ACSWL and stored in airtight containers at 4°C. Leachate from a representative sample was used in cultivation experiments. Basic physico-chemical characterization of the MSW LL is presented in Table 1. Sample pH was measured using an Orion 520A pH meter with an Orion pH electrode (Orion Research Inc., Boston, MA) in accordance with standard method 4500-H^+.[20] Conductivity was measured with an Accumet Model 30 conductivity metre (Thermo Fisher Scientific, Waltham, MA) in accordance with standard method 2510-B.[20] COD was measured by colorimetry after closed reflux with potassium dichromate, in accordance with standard method 5220-D.[20] Total ammoniacal-nitrogen was measured using an ion-selective electrode (Orion 95–12) with an Orion IonAnalyser 701A meter (Orion Research Inc., Boston, MA) in accordance with standard method 4500-NH_3 D.[20] Total phosphorus was measured by colorimetry in accordance with standard methods 4500-P B/C.[20] Metals (sodium, potassium, calcium, magnesium, iron, manganese, copper, zinc, cobalt, arsenic, antimony, cadmium, chromium, lead, and selenium) were analysed by acid digestion and inductively coupled plasma-atomic emission spectrometry (Model 5300 DV, Perkin Elmer, Waltham, MA) (EPA methods 3010A/6010C [21]). Chloride was measured by ion chromatography (EPA method 300.0 [22]). BBM (pH 6.8) was formulated following Andersen et al. [23] and compared with the composition of ACSWL leachate (Table 2).

Algae isolation and cultivation

Algae collected from the ACSWL site were diluted with sterilized BBM and incubated on agar plates (2% BD Bacto™ Agar in deionized water) under 150 μmol photons/m^2/s illumination. Individual colonies were lifted and cultured in sterilized BBM. Single plating isolations yielded two unialgal isolates, tentatively identified by morphological characteristics as *Chlorella* cf. *ellipsoidea* and *Scenedesmus* cf. *rubescens*, respectively. A modified BBM was formulated by adding 2% LL to a stock solution of BBM and this was used in maintaining mother cultures of the isolates. The photon flux density of photosynthetically active radiation was measured using a Li-Cor LI-189 instrument (Li-Cor Biosciences, Lincoln, NE) equipped with a quantum sensor. Illumination in laboratory experiments was provided by T5 fluorescent lamps to give 150 μmol photons/m^2/s lighting, provided on a 24:0 photoperiod, at 25 ± 1.5°C.

Algal growth experiments were conducted in 125 mL Erlenmeyer flasks (75 mL active volume). LL was inoculated with exponentially growing mother cultures at a volumetric ratio of 20% (v/v). Mixing was provided by aeration (0.45 μm filtered air at a rate of ~0.065 L/min/flask). Deionized water was added to cultures daily to replace volume lost by evaporation. Algal growth was monitored using absorbance at 680 nm (A_{680}) with a spectrophotometer (Genesys 10vis, Thermo-spectronic, Rochester, NY). Mean growth rate (μ) was estimated as follows:

$$\mu = \frac{\ln A_{680n} - \ln A_{680o}}{n}, \qquad (1)$$

where A_{680o} is the initial absorbance, A_{680n} is the final absorbance, and n is the number of days elapsed. Cell population was estimated from A_{680} after standardization with a haemocytometer (American Optical Co., Buffalo, NY). Dry weights were calculated from A_{680} after standardization with algal biomass dried to constant weight at 105°C.

The content of reduced nitrogen within ACSWL leachate indicated that it may be necessary to regulate the pH of the medium to avoid the known inhibitory effects of free ammonia.[24] It was, therefore, presumed and confirmed by preliminary testing (data not shown) that pH regulation of free ammonia toxicity in ACSWL leachate would be necessary. In pH-adjusted cultures, LL was neutralized by titrating with 1M HCl to an initial pH of 7.0 ± 0.1 (<1%v/v). For both algal isolates, growth medium treatments included a negative control of 100% LL without pH neutralization (LL-Control), a positive control (BBM), and an experimental treatment using neutralized 100% LL (HCl-adjusted LL). All treatments were replicated in triplicate.

Statistical analysis

Experiments were conducted in replicates of three. Means, standard deviations, and Student's t-tests (two-tailed, unpaired, unequal variances, at a 95% confidence level) were calculated with Microsoft Excel (Microsoft, Inc., Redmond, WA).

Results

Growth of algal isolates

Time course of growth and pH of *C.* cf. *ellipsoidea* are shown in Figures 1 and 2, respectively. Growth in the positive control (BBM) and in the pH-adjusted treatments was nearly identical over the first 24-h period. From 24 to 72 h, the HCl-adjusted LL treatment plateaued and growth was minimal, whereas the BBM treatment culture continued to grow. LL without pH neutralization (LL-Control) showed little change in algal growth for the duration of the experiment. The BBM treatment showed a gradual increase in pH over the course of the experiment, while the LL-Control treatment had a higher initial pH which rose to 8.9 within the first 24 h and remained alkaline for the duration of the experiment. In contrast, acidification of the culture medium was observed in the HCl-adjusted LL treatments, eventually reaching a pH of 5.2 at 72 h.

Time course of growth and pH of *S.* cf. *rubescens* are shown in Figures 3 and 4, respectively. Growth within the BBM and HCl-adjusted LL treatments was nearly identical over the first 24-h period. Growth within the HCl-adjusted LL medium showed less growth than BBM from 24 to 48 h, but nearly equal growth from 48 to 72 h. The *Scenedesmus* culture continued to grow from 72 to 96 h, whereas the BBM treatment culture plateaued and growth was minimal. Growth within LL without pH neutralization (LL-Control) showed little change over the course of the experiment. General trends observed in pH dynamics during the cultivation of *S.* cf. *rubescens* were: the pH of the BBM treatment increased with growth, the pH of the LL-Control rose rapidly in the first 24 h, and the HCl-adjusted LL treatment had acidified rapidly by 48 h.

S. cf. *rubescens* exhibited significantly ($p = 0.014$) greater growth in the HCl-adjusted LL treatment than *C.* cf. *ellipsoidea* (Table 3). Neutralization of LL by acid addition significantly improved the cultivation of both the *Chlorella* and *Scenedesmus* isolates compared with the growth in LL controls without acid addition ($p < 0.05$ for both isolates). General pH dynamics followed similar trends in both algal cultures and in respective media. Notably, both the rise in pH in BBM and the acidification within HCl-adjusted LL were more pronounced in the *Scenedesmus* culture.

Estimated growth rates of *C.* cf. *ellipsoidea* in BBM and HCl-adjusted LL treatments were only comparable within the first 24 h. Although the HCl-adjusted LL was not toxic to the *Chlorella* isolate, inhibition of growth for this isolate was apparent after 24 h (Figure 1). In contrast, *S.* cf. *rubescens* showed growth in the HCl-adjusted LL (0.83/day) nearly equal to that of growth observed in BBM (0.91/day). Estimated mean growth rate and daily

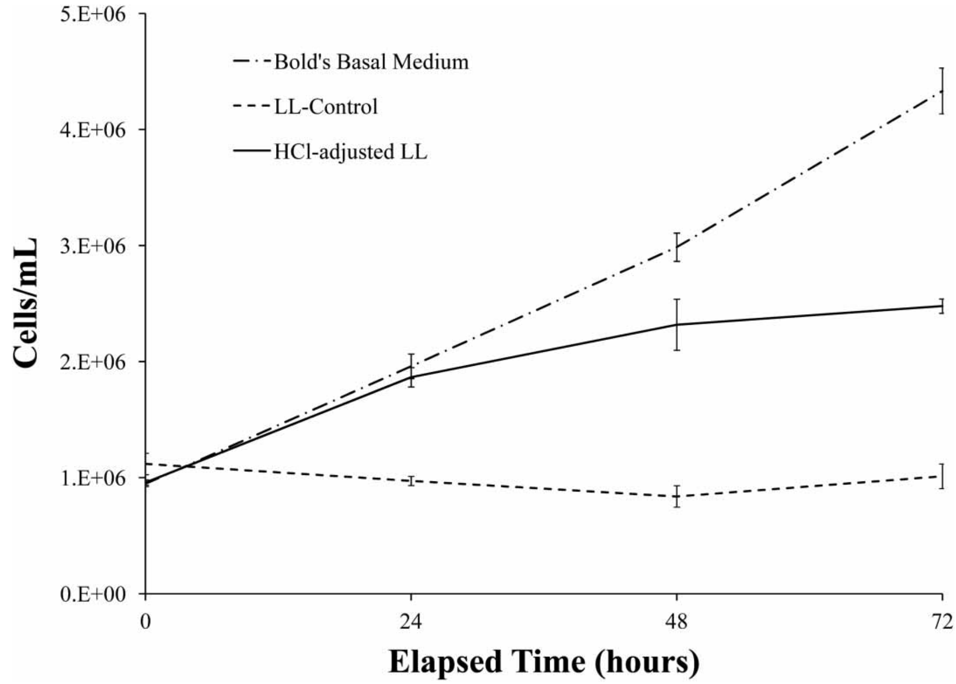

Figure 1. Cultivation of *C*. cf. *ellipsoidea* in BBM (-•-•-), 100% LL with pH adjustment via HCl (solid line) and 100% LL without pH adjustment (control, - - -); data represent means of triplicate cultures with standard deviations as error bars.

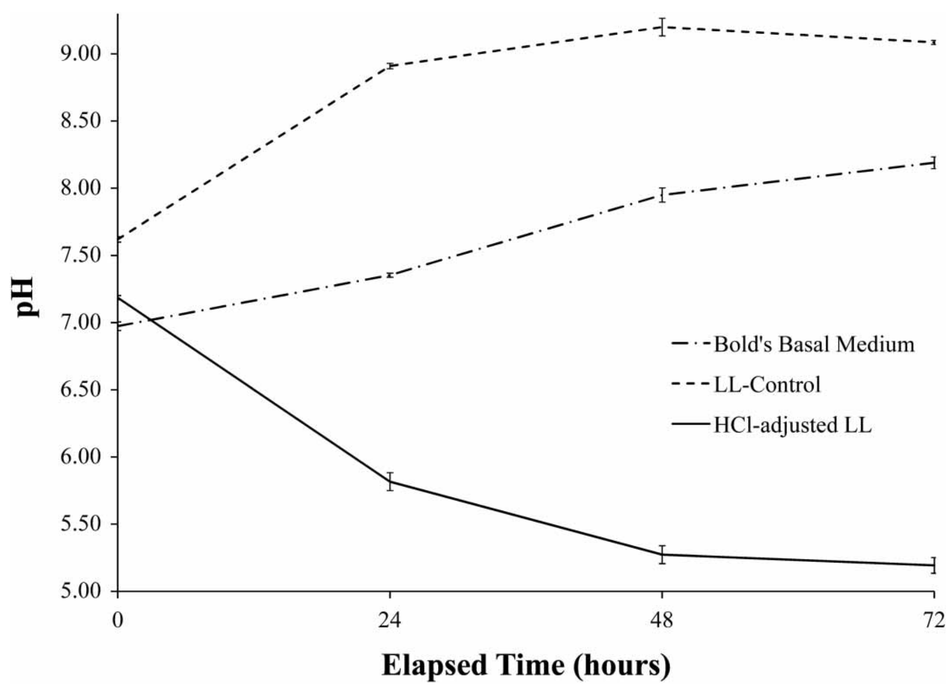

Figure 2. pH values during cultivation of *C*. cf. *ellipsoidea* in BBM (-•-•-), 100% LL with pH adjustment via HCl (solid line) and 100% LL without pH adjustment (control, - - -); data represent means of triplicate cultures with standard deviations as error bars.

cell yield of the *Scenedesmus* isolate within LL were 91.2% and 92.8% that observed in BBM, respectively (Table 3). The mean growth rate of *C*. cf. *ellipsoidea* in 100% LL (0.67/day) was also similar to that in BBM (0.73/day). However, cell yield of the *Chlorella* isolate was severely inhibited, reaching only 44.9% of the cell yield recorded for BBM. Cell density values observed were almost twice as high in BBM and four times as high in HCl-adjusted LL for the *Scenedesmus* isolate as compared with the *Chlorella* isolate (Table 3). The LL used in this study supported a maximum volumetric productivity of 0.55 g/L/day of *S*. cf. *rubescens* biomass.

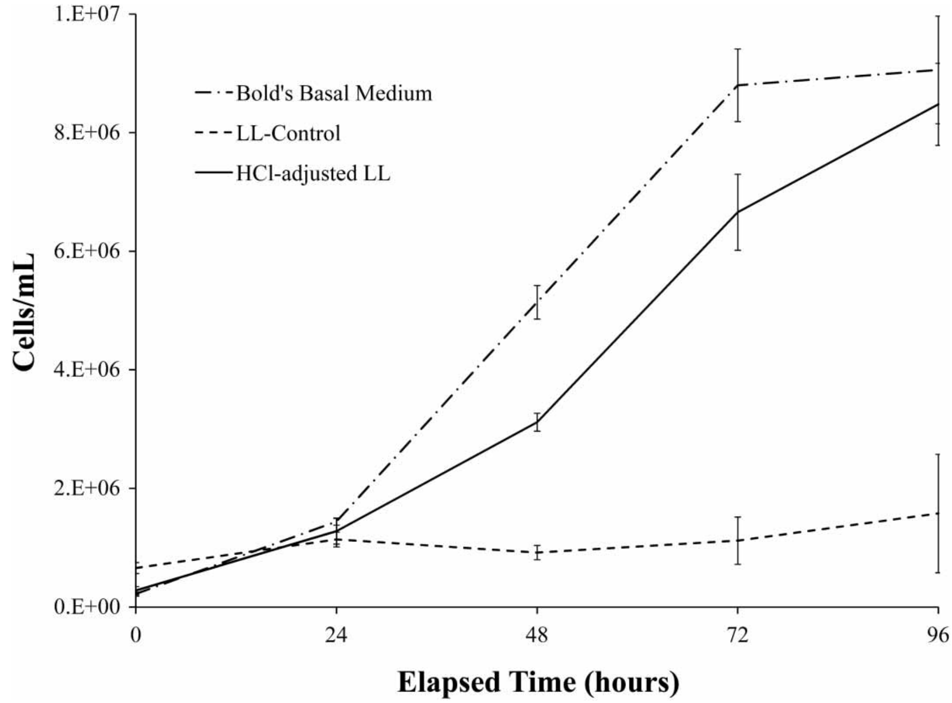

Figure 3. Cultivation of *S*. cf. *rubescens* in BBM. (-•-•-), 100% LL with pH adjustment via HCl (solid line) and 100% LL without pH adjustment (control, - - -); data represent means of triplicate cultures with standard deviations as error bars.

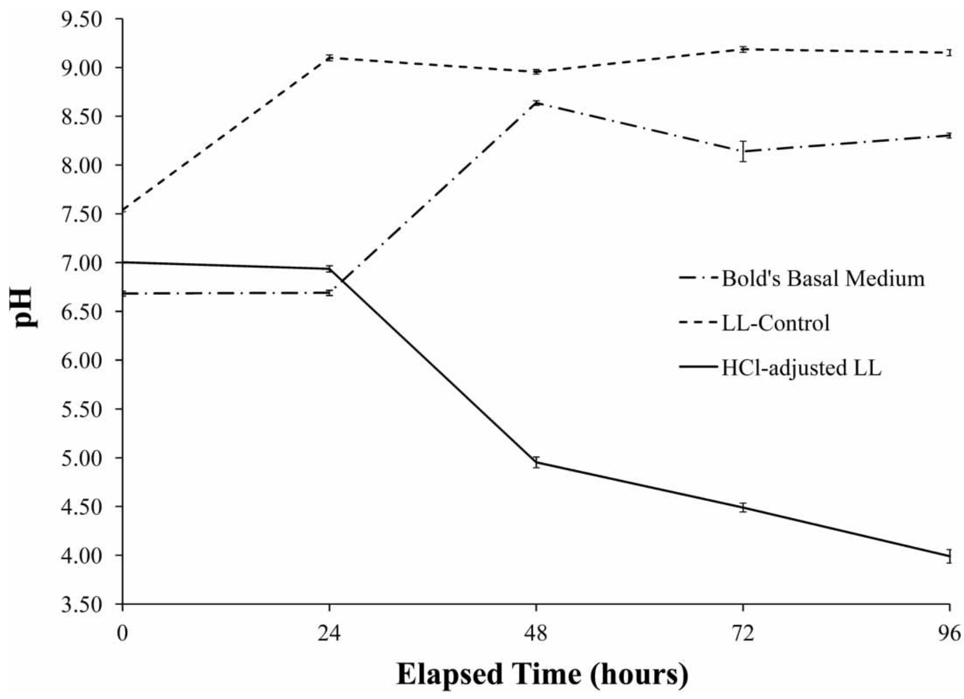

Figure 4. pH values during cultivation of *S*. cf. *rubescens* in BBM (-•-•-), 100% LL with pH adjustment via HCl (solid line) and 100% LL without pH regulation (control, - - -); data represent means of triplicate cultures with standard deviations as error bars.

Biomass and biofuel production potentials

Potential biomass production was estimated based on the mean elemental composition of algae biomass as reported in the extensive review by Healey.[25] It is recognized that large variations in the nitrogen content of algae biomass exist (1–14%), but 5.5% was taken as a mean estimate. ACSWL leachate can supply enough nitrogen for the production of 17.8 g/L of algae biomass at 5.5% N, roughly 20-fold higher than the potential biomass producible by BBM, 0.8 g/L (Table 4). Phosphorus in the ACSWL

Table 3. Growth rate and cell yield of algae isolates cultivated in 100% LL and BBM.

	C. cf. *ellipsoidea*		*S*. cf. *rubescens*	
Medium	LL	BBM	LL	BBM
Mean growth rate/day	0.67	0.73	0.83	0.91
Mean cell yield (cells/mL/day)	5.07E + 05	1.13E + 06	2.05E + 06	2.21E + 06
Final biomass (g/L)	0.285 ± 0.01	0.499 ± 0.02	1.33 ± 0.108	1.42 ± 0.142
Maximum biomass yield (g/L/day)	0.10 ± 0.007	0.15 ± 0.034	0.55 ± 0.084	0.58 ± 0.036

Notes: LL, HCl-adjusted landfill leachate; BBM, Bold's Basal Medium.

Table 4. Theoretical algae biomass potential based on medium composition and mean elemental concentration of algae.

		Algae biomass production potential	
Element	Average % in algae biomass [25]	LL (g/L)	BBM (g/L)
Nitrogen	5.5	17.8	0.8
Phosphorus	1.1	1.2	4.8
Potassium	1.73	56.6	6.1
Magnesium	0.56	15.7	1.3
Iron	0.59	2.7	0.2

Notes: LL, landfill leachate; BBM, Bold's Basal Medium.

leachate, however, limits the potential biomass to 1.2 g/L of algae biomass at 1.1% P, which is only 21% of the potential biomass based on the phosphorus in BBM. The LL from ACSWL had sufficient potassium and magnesium for algae growth of up to 56.6 and 15.7 g/L, respectively (Table 4). Based on the ACSWL leachate quality, the primary elemental limitations for algae biomass production on LL are phosphorus and iron, which limit the theoretical biomass potential to 1.2 and 2.7 g/L, respectively (Table 4). These levels of biomass production may be satisfactory as algal density in open pond cultivation systems is typically ~1 g/L.[3,26] Actual final biomass values obtained from the cultivation of *S*. cf. *rubescens* and *C*. cf. *ellipsoidea* in LL were 1.33 and 0.285 g/L, respectively (Table 3). When compared with BBM, ACSWL leachate is a superior medium for high algae biomass production based on macro-elemental composition.

Since LL production is extremely variable both temporally and spatially, 113,550 L/day/landfill was used as a normalized estimate.[27] Total waste nitrogen available from Florida LLs was estimated at 1.24 Gg N/year, based on 60 Class I MSW landfills in Florida,[28] an average leachate generation rate of 113,550 L/day/landfill site, and an average concentration of ammoniacal-nitrogen in Florida LLs of 500 mg-N/L.[14] Algae biomass production potential from this waste nitrogen was estimated at 22.6 Gg/year based on the mean elemental nitrogen composition of algae (5.5%) as reported by Healey.[25] Algae oil content was assumed to be a modest 20% with a density of 0.92 kg/L.[29] Conversion of algal oil to biodiesel was assumed to be only 80% efficient,[30] providing 3.33 gigaliter (GL) of algae-derived biofuel/year. This estimated biofuel production is equivalent to 63.3% of the total annual diesel consumption [31] or 6.75% of the total annual petroleum consumption [32] in the state of Florida.

Discussion

Algae have an unrealized potential in future biofuel production.[2,4,26] Utilization of algae as a feedstock for biofuel production must still overcome significant technological, biological, and resource sustainability challenges.[33,34] Primary concerns in the development of sustainable algae-based biofuels are the high demand for water, nutrients (fertilizers and inorganic carbon), and land resources.[7] The advancement of methods that address resource sustainability issues in producing algae-based biofuels is critical in realizing the potential contribution of algae. Pittman et al. [8] recently suggested that perhaps the only way that algae biofuels will become economically feasible, in comparison to today's cost of petroleum, is through the combination of algae feedstock production with bioremediation services. Bioremediation services offer both environmental and economic benefits in the cultivation of algae biofuels, leveraging a dual role in providing both waste mitigation and resource production.[9,35] Cultivating algae in LL will undoubtedly provide a tertiary (nutrient) remediation benefit, as described by Lin et al. [15] in the removal of total ammoniacal-nitrogen and orthophosphate in diluted LL. Additionally, there is also evidence to expect that many contaminants within LL may be biodegraded by algae.[36,37] However, previous reports of cultivation of algae within LL required dilution or extensive pretreatment to facilitate algae growth.[15,16] This study provides evidence that the cultivation of algae on high-ammonia LL, without dilution or extensive pretreatment is possible. Remediating environmental wastes provides additional economic incentives to the production of biofuels and additional support for a sustainable society.

The observed growth rates of *S*. cf. *rubescens* within BBM and LL were approximately equal, providing evidence that LL may have potential application as an algal growth medium. Observed growth rates of *S*. cf. *rubescens* (0.83/day) and *C*. cf. *ellipsoidea* (0.67/day) in 100% LL were 113% and 72% greater, respectively, than the growth rate for *Chlorella pyrenoidosa* (0.39/day) in 10% MSW LL reported by Lin et al.[15] Additionally, growth rates reported in the present study are significantly higher than the growth rates reported by Mustafa et al. [16] for *Scenedesmus quadricauda*, *Chlorella vulgaris*, and *Euglena gracilis* (0.18, 0.21, and 0.23/day, respectively) in 25% MSW LL which had undergone previous treatment through mechanical aeration in treatment ponds at the landfill site. Furthermore, no tested organisms in either study [15,16] were able to tolerate 100% LL.

Utilizing leachate without dilution or mechanical aeration pretreatment provides an abundant supply of nitrogen, a key fertilizer requirement for producing algae biomass. Ironically, the high nitrogen content in the tested LL is also implicated as the primary inhibitory compound (free ammonia), when pH is not adjusted (Figures 1 and 3). For both isolates, growth on LL was poor without pH adjustment, exhibiting the previously described toxicity impacts of LL.[18] Adjusting the pH with the strong acid, HCl, eliminated the toxicity of the leachate but may have practical drawbacks in application. The operational and environmental costs of utilizing HCl may detract from the benefit of using a waste resource and should be investigated further. Nonetheless, HCl is currently applied for pH control in on-site, full-scale nitrification/denitrification processes for leachate pretreatment at landfill facilities. It is expected that the utilization of an alternative acid for pH regulation would be as effective in regulating ammonia toxicity. Growth inhibition of *C.* cf. *ellipsoidea*, where the pH of the treatment medium continued to decrease after leachate neutralization with HCl, makes a case for the utilization of a pH controller to regulate the pH instead of initial neutralization. A continued decrease in pH is attributed to both the decreased buffering capacity of the LL after neutralization and the phenomenon of medium acidification due to cellular uptake of ammonium ions.[38] The *Chlorella* isolate showed less adaptation to LL as a growth medium than the *Scenedesmus* isolate, suggesting that there may be inhibitory compounds within the LL to which this isolate is more sensitive. Growth of the *Chlorella* isolate in the pH-adjusted treatment plateaued in correlation with medium acidification. From the observed data, it is not possible to distinguish between the impact of medium pH and possible growth inhibitors within the LL (e.g. refractory organic compounds, metals, etc.). It is expected that the majority of the reported COD for this mature LL is present as refractory organic compounds that are not readily degradable, but which may have significant biological effects. Cultivation of algae tolerant to these unknown compounds would provide conditions of oxygen saturation and may aid in the removal of these recalcitrant organics. The *Scenedesmus* isolate appeared to be unaffected by the potential inhibitory conditions of LL and was more tolerant of the pH change in the medium, emphasizing the suitability of *S.* cf. *rubescens* in favour of *C.* cf. *ellipsoidea*, under the described experimental conditions. No impact of acidic pH on growth was observed within the *Scenedesmus* culture. Indeed, cultures of the *Scenedesmus* isolate were observed growing at pH values <4 in preliminary trials (data not shown). Buffering the system may foster the growth of algae sensitive to pH fluctuations. However, cultivating an alga at an extreme pH may be advantageous in reducing culture contamination in outdoor growth systems, analogous to the cultivation of the alkaliphile *Spirulina*.[39]

The high nitrogen content of LL makes it an attractive N-source for industrial algae biomass production. Using MSW LL has the potential to reduce the nitrogen, water, and greenhouse gas emission footprints of algae biomass production. MSW landfills can supply wastewater, carbon dioxide (combustion of landfill gas), land area (tops of closed MSW landfill sites), and essential nutrients for the cultivation of algae biomass, which can be used for algae-based biofuels. Industrial production of algae biomass sited at landfill facilities can transform landfills from societal burdens to centres of resource generation and nutrient recycling.

Various toxic heavy metals may potentially be found in LL, depending on the site, materials landfilled, and age of the landfill.[17] Algae biomass may accumulate heavy metals, limiting the potential use of the biomass. On the other hand, certain species of algae with high affinities for valuable metal ions may provide a biological means of bio-mining LLs. In the production of biofuels, heavy metals are not expected to transfer from the algae biomass to the oil or gas produced by biofuel processing.

Algae biomass generated from LL cultivation can be used as a feedstock for several biofuels, depending on the species and cultivation conditions. Algae biomass can be converted to biofuels through anaerobic digestion (CH_4), fermentation (e.g. to ethanol, butanol, or hydrogen), or hydrothermal processing. Ammonia released through biomass processing can be recycled to algae cultivation. If high in lipids, the algae biomass can be refined into high-value liquid fuels such as biodiesel or jet fuel. Estimates of available nitrogen, biomass, and biofuel production highlight the potential of utilizing MSW LL for algal biomass production.

Conclusion

Experimental observations indicate that MSW LL may provide both water and nutrient resources for the production of algae-based biofuels. Displacing the use of potable waters and the energy embedded in synthetic fertilizer production can reduce both the cost and the environmental footprint of algae-based biofuels. Utilizing algae in a dual role of waste mitigation and biofuel production can be extended from commonly explored areas such as municipal sewage and agricultural wastes to applications in industrial and solid waste remediation. MSW landfills are currently the most commonly employed means of solid waste management and the liquid leachates generated at these facilities can provide abundant nitrogen for the production of algae biomass. This study provides evidence that the cultivation of algae on high-ammonia LLs, without dilution or extensive pretreatment, is possible. The LL used in this study supported a maximum volumetric productivity of 0.55 g/L/day of *S*. cf. *rubescens* biomass. Once algae biomass is sustainably and cost-effectively generated, several different process trains can be used to produce biofuels, such as anaerobic digestion, transesterification of neutral lipids, hydrothermal treatment, or combustion. The potential biofuel production from the total waste nitrogen available in LLs in Florida was estimated at 3.33 GL of algae-derived biofuel/year.

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References

[1] van Iersel S, Gamba L, Rossi A, Alberici S, Dehue B, van de Staaij J, Flammini A. Algae-based biofuels: a review of challenges and opportunities for developing countries, FAO Environment and Natural Resources Service Series 33 (2009), Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/docrep/012/i1199e/i1199e00.htm

[2] Stephens E, Ross IL, Mussgnug JH, Wagner LD, Borowitzka MA, Posten C, Kruse O, Hankamer B. Future prospects of microalgal biofuel production systems. Trends Plant Sci. 2010;15:554–564. http://dx.doi.org/10.1016/j.tplants.2010.06.003

[3] U.S. Department of Energy. National algal biofuels technology roadmap. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program; 2010. http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf

[4] Wigmosta MS, Coleman AM, Skaggs RJ, Huesemann MH, Lane LJ. National microalgae biofuel production potential and resource demand. Water Resour Res. 2011;47:W00H04-1–13. http://dx.doi.org/10.1029/2010WR009966

[5] Lardon L, Hélias A, Sialve B, Steyer J-P, Bernard O. Life-cycle assessment of biodiesel production from microalgae. Environ Sci Technol. 2009;43:6475–6481. http://dx.doi.org/10.1021/es900705j

[6] Clarens AF, Resurreccion EP, White MA, Colosi LM. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ Sci Technol. 2010;44:1813–1819. http://dx.doi.org/10.1021/es902838n

[7] National Research Council. Sustainable development of algal biofuels in the United States. Washington, DC: The National Academies Press; 2012. http://www.nap.edu/catalog.php?record_id=13437

[8] Pittman JK, Dean AP, Osundeko O. The potential of sustainable algal biofuel production using wastewater resources. Bioresour Technol. 2011;102:17–25. http://dx.doi.org/10.1016/j.biortech.2010.06.035

[9] Rawat I, Ranjith Kumar R, Mutanda T, Bux F. Dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Appl Energ. 2011;88:3411–3424. http://dx.doi.org/10.1016/j.apenergy.2010.11.025

[10] Wang L, Min M, Li Y, Chen P, Chen Y, Liu Y, Wang Y, Ruan R. Cultivation of green algae *Chlorella* sp. in different wastewaters from municipal wastewater treatment plant. Appl Biochem Biotechnol. 2010;162:1174–1186. http://dx.doi.org/10.1007/s12010-009-8866-7

[11] Peccia J, Haznedaroglu B, Gutierrez J, Zimmerman JB. Nitrogen supply is an important driver of sustainable microalgae biofuel production. Trends Biotechnol. 2013;31:134–138. http://dx.doi.org/10.1016/j.tibtech.2013.01.010

[12] Renou S, Givaudan JG, Poulain S, Dirassouyan F, Moulin P. Landfill leachate treatment: review and opportunity. J Hazard Mater. 2008;150:468–493. http://dx.doi.org/10.1016/j.jhazmat.2007.09.077

[13] Jones DL, Williamson KL, Owen AG. Phytoremediation of landfill leachate. Waste Manage. 2006;26:825–837. http://dx.doi.org/10.1016/j.wasman.2005.06.014

[14] Meeroff DE, Teegavarapu R. Interactive decision support tool for leachate management. Gainesville, FL: Hinkley Center for Solid and Hazardous Waste Management; 2010. http://www.hinkleycenter.org/images/stories/Meeroff_INTERACTIVE_DECISION_SUPPORT_TOOL.pdf

[15] Lin L, Chan GYS, Jiang BL, Lan CY. Use of ammoniacal nitrogen tolerant microalgae in landfill leachate treatment. Waste Manage. 2007;27:1376–1382. http://dx.doi.org/10.1016/j.wasman.2006.09.001

[16] Mustafa E-M, Phang S-M, Chu W-L. Use of an algal consortium of five algae in the treatment of landfill leachate using the high-rate algal pond system. J Appl Phycol. 2012;24:953–963. http://dx.doi.org/10.1007/s10811-011-9716-x

[17] Kjeldsen P, Barlaz MA, Rooker AP, Baun A, Ledin A, Christensen TH. Present and long-term composition of MSW landfill leachate: a review. Crit Rev Environ Sci Technol. 2002;32:297–336. http://dx.doi.org/10.1080/10643380290813462

[18] Cheung KC, Chu LM, Wong MH. Toxic effect of landfill leachate on microalgae. Water Air Soil Pollut. 1993;69:337–349. http://dx.doi.org/10.1007/BF00478169

[19] Reinhart DR, Townsend TG. Landfill bioreactor design and operation. Boca Raton, FL: Lewis Publishers/CRC Press; 1998.

[20] Eaton AD, Clesceri LS, Rice EW, Greenberg AE, Franson MAH, editors. Standard methods for the examination of water & wastewater, 21st ed. Washington, DC: American Public Health Association, American Water Works Association, Water Environment Federation; 2005.

[21] USEPA. Test methods for evaluating solid waste, physical/chemical methods (SW-846), Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response; 2007. http://www.epa.gov/epawaste/hazard/testmethods/sw846/online/index.htm

[22] Pfaff JD. Method 300.0, determination of inorganic anions by ion chromatography. Cincinnati, OH: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Office of Research and Development; 1993. http://water.epa.gov/scitech/methods/cwa/bioindicators/upload/2007_07_10_methods_method_300_0.pdf

[23] Andersen RA, Berges JA, Harrison PJ, Watanabe MM. Recipes for freshwater and seawater media: Bold's Basal Medium (BBM). In Andersen RA, editor. Algae culturing techniques. Boston, MA: Elsevier Academic Press; 2005. p. 437–438.

[24] Abeliovich A, Azov Y. Toxicity of ammonia to algae in sewage oxidation ponds. Appl Environ Microbiol. 1976;31:801–806. http://aem.asm.org/cgi/content/long/31/6/801

[25] Healey FP. Inorganic nutrient uptake and deficiency in algae. Crit Rev Microbiol. 1973;3:69–113. http://dx.doi.org/10.3109/10408417309108746
[26] Sheehan J, Dunahay T, Benemann J, Roessler P. A look back at the U.S. Department of Energy's aquatic species program: biodiesel from algae, NREL/TP-580–24190, Golden, CO: National Renewable Energy Laboratory; 1998. http://www.nrel.gov/biomass/pdfs/24190.pdf
[27] USEPA. Development document for final effluent limitations guidelines and standards for the landfills point source category, EPA-821-R-99-019, Washington, DC: U.S. Environmental Protection Agency, Office of Water; 2000. http://water.epa.gov/scitech/wastetech/guide/landfills/upload/2000_01_14_guide_landfills_final_technical_a.pdf
[28] FDEP. Solid waste management in Florida 2001–2002. Tallahassee, FL: Florida Department of Environmental Protection, Bureau of Solid and Hazardous Waste. http://www.dep.state.fl.us/waste/categories/recycling/SWreportdata/99-00.htm
[29] Weyer KM, Bush DR, Darzins A, Willson BD. Theoretical maximum algal oil production. Bioenerg Res. 2010;3:204–213. http://dx.doi.org/10.1007/s12155-009-9046-x
[30] Chisti Y. Biodiesel from microalgae. Biotechnol Adv. 2007;25:294–306. http://dx.doi.org/10.1016/j.biotechadv.2007.02.001
[31] FDACS. 2010 Florida motor gasoline and diesel fuel report. Tallahassee, FL: Florida Department of Agriculture and Consumer Services; 2011. http://www.freshfromflorida.com/offices/energy/docs/2010_Gasoline_Diesel_Report.pdf
[32] EIA. Total end-use energy consumption estimates, 1960–2010, Florida. Washington, DC: Florida, U.S. Energy Information Administration; 2011. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/tx/use_tx_FL.html&sid=Florida
[33] Pienkos PT, Darzins A. The promise and challenges of microalgal-derived biofuels. Biofuel Bioprod Bior. 2009;3:431–440. http://dx.doi.org/10.1002/bbb.159
[34] Scott SA, Davey MP, Dennis JS, Horst I, Howe CJ, Lea-Smith DJ, Smith AG. Biodiesel from algae: challenges and prospects. Curr Opin Biotechnol. 2010;21:277–286. http://dx.doi.org/10.1016/j.copbio.2010.03.005
[35] Wilkie AC, Edmundson SJ, Duncan JG. Indigenous algae for local bioresource production: phycoprospecting. Energ Sustain Dev. 2011;15:365–371. http://dx.doi.org/10.1016/j.esd.2011.07.010
[36] Hirooka T, Nagase H, Uchida K, Hiroshige Y, Ehara Y, Nishikawa J, Nishihara T, Miyamoto K, Hirata Z. Biodegradation of bisphenol a and disappearance of its estrogenic activity by the green alga *Chlorella fusca* var. *vacuolata*. Environ Toxicol Chem. 2005;24:1896–1901. http://dx.doi.org/10.1897/04-259R.1
[37] Muñoz R, Guieysse B. Algal-bacterial processes for the treatment of hazardous contaminants: a review. Water Res. 2006;40:2799–2815. http://dx.doi.org/10.1016/j.watres.2006.06.011
[38] von Wirén N, Gazzarrini S, Gojont A, Frommer WB. The molecular physiology of ammonium uptake and retrieval. Curr Opin Plant Biol. 2000;3:254–261. http://dx.doi.org/10.1016/S1369-5266(00)80074-6
[39] Lincoln EP, Wilkie AC, French BT. Cyanobacterial process for renovating dairy wastewater. Biomass Bioenerg. 1996;10:63–68. http://dx.doi.org/10.1016/0961-9534(95)00055-0