A flexible microbial co-culture platform for simultaneous utilization of methane and carbon dioxide from gas feedstocks

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HIGHLIGHTS

• A co-cultivation technology that converts, CH4 and CO2, into microbial biomass.
• Robust bacterial growth on biogas and natural gas feedstocks.
• Continuous co-cultivation without air or O2 feed to support CH4 oxidation.
• A flexible co-culture technology constructed from genetically tractable bacteria.

ABSTRACT

A new co-cultivation technology is presented that converts greenhouse gasses, CH4 and CO2, into microbial biomass. The methanotrophic bacterium, Methylomicrobium alcaliphilum 20z, was coupled to a cyanobacterium, Synechococcus PCC 7002 via oxygenic photosynthesis. The system exhibited robust growth on diverse gas mixtures ranging from biogas to those representative of a natural gas feedstock. A continuous processes was developed on a synthetic natural gas feed that achieved steady-state by imposing coupled light and O2 limitations on the cyanobacterium and methanotroph, respectively. Continuous co-cultivation resulted in an O2 depleted reactor and does not require CH4/O2 mixtures to be fed into the system, thereby enhancing process safety considerations over traditional methanotroph mono-culture platforms. This co-culture technology is scalable with respect to its ability to utilize different gas streams and its biological components constructed from model bacteria that can be metabolically customized to produce a range of biofuels and bioproducts.

1. Background

Microbial biomass is a clean, renewable energy source that can significantly diversify and sustain future energy and transportation fuel requirements (Elliott et al., 2015; Tian et al., 2014). Production of microbial biomass and targeted bioproducts often depends upon costly substrates, such as glucose or other sugars, that limit the economic viability of the process (Kumar et al., 2012; Rodríguez et al., 2014). In contrast, various trends in algal cultivation have promised to develop renewable bioprocesses that convert inorganic carbon (CO2/HCO3-) into microbial biomass using solar energy; however, process viability is often constrained by low biomass productivities and the inherent limitations of photosynthetic efficiencies (Grobbeelaar, 2010; Quinn and Davis, 2015). Natural gas or biogas derived CH4 represents an alternative, energy rich carbon source for generating microbial biomass and bioproducts (Kaluzhnaya et al., 2015; Sheets et al., 2016) yet O2 demands and mass transfer limitations remain challenging aspects for developing viable and safe bioprocesses (Rishell et al., 2004). Co-cultivation platforms of photoautotrophic and methanotrophic microbes represent a unique and promising option for concurrent capture of CO2 and CH4 within an integrated system (van der Ha et al., 2012).

CH4 and CO2 have the largest contributions to atmospheric radiative forcing caused by anthropogenic greenhouse gasses (GHG) (Robertson et al., 2000). Natural gas is an abundant resource that has played a central role in global energy production. Much of the natural gas that is co-produced with oil recovery (5 quadrillion BTU, ~5% of annual production) is unused, flared or vented representing a major GHG contribution that could be redirected and consumed as microbial feedstock (Fei et al., 2014). Biogas represents another major source of CH4 and is an important renewable
energy source that can be upgraded to a gaseous transportation fuel or combusted to generate electricity. However, biogas utilization is constrained because of its high upgrade costs and presence of contaminants such as H₂S and organosilicon (i.e., siloxanes). A large fraction of biogas produced is also being flared or vented into the atmosphere, representing yet another wasted product that could be redirected into microbial biomass and targeted bioproducts.

Many state-of-the-art biotechnologies are seeking to capitalize on the productivity and stability advantages gained through co-cultivation of microbial consortia (Bernstein and Carlson, 2012; Bernstein et al., 2012; Gilmore and O’Malley, 2016; Lindemann et al., 2016). This study presents new bacterial co-culture platform for concurrent conversion of CH₄ and CO₂ into biomass by employing a cyanobacteria-methanotroph binary culture. The co-culture technology is based upon robust metabolic coupling between oxygenic photosynthesis and methane oxidation. Continuous steady-state operation is achieved on the basis of light and O₂ limitation engineering which renders the platform flexible and scalable for the production of different bioproducts on cost-effective, renewable CH₄ feedstocks.

2. Materials and methods

2.1. Bacterial strains and media

Synechococcus sp. PCC 7002 and Methylomicrobium alcaliphilum 20z were grown under co-culture and axenic conditions. All cultures were grown in one of two previously described minimal salts media, P-medium (Khmelina et al., 1999) or A-plus medium (Stevens and Porter, 1980).

2.2. CH₄ feedstocks

Raw biogas was collected from an anaerobic digester (located in Outlook WA, USA) that was operated on dairy farm waste. The biogas composition was 58% CH₄, 42% CO₂, 0% O₂, and 0.3% H₂S as measured by a Landtec biogas 5000 m (Landtech, Dexter, MI). A synthetic natural gas feed stream of 80% CH₄, 17% N₂, and 3% CO₂ was made by mixing pure gas flows through calibrated rotameters. Importantly, the bacteria used to build this co-culture are amenable to metabolic engineering which renders the platform flexible and scalable for the production of different bioproducts on cost-effective, renewable CH₄ feedstocks.

2.3. Batch cultivation

The maximum specific growth rates on various biogas, CH₄, CO₂ and O₂ mixtures were obtained using sealed 30 ml Balch tubes incubated under constant 250 μmol photons m⁻² sec⁻¹ (fluorescent light). Each tube was charged with 8 ml A-plus medium (pH 8.0), sparged with an appropriate gas mixture, and sealed with the respective gas in the head-space maintained at 1 ATM. The optical density (OD₇₃₀nm) was measured over a 96 h period using a Spectronic 20D+ spectrophotometer (Thermo Spectronic, Thermo Fisher Scientific, Waltham, MA). Each culture Balch tube was inoculated to a starting OD₇₃₀nm = 0.028 ± 0.005. Co-cultures were inoculated with a 1:1 ratio of *M. alcaliphilum* and *Synechococcus* 7002, respectively.

2.4. Photobioreactor cultivation

Continuous cultivation was performed under chemostat mode by previously described methods (Beliaev et al., 2014; Bernstein et al., 2015). Briefly, di-chromatic (680 and 630 nm LEDs) photobioreactors were operated as light and O₂ limited chemostats using the New Brunswick BioFlo 3000 fermenter charged with a 5.5 L working volume diluted at a 0.03 h⁻¹, 30 °C, pH 8.0 and controlled for constant incident and transmitted irradiance (250 and 10 μmol photons m⁻² sec⁻¹, respectively). Cells were never exposed to dark conditions during these experiments. The control volume was sparged at 0.25 L min⁻¹ with a synthetic natural gas mixture, 80% CH₄, 17% N₂, 3% CO₂. Steady-state biomass concentrations were measured directly as ash-free cell dry weight (g AFCDW L⁻¹) as previously reported (Pinchuk et al., 2010). The volumetric gas mass transfer coefficient, kₐ = 5.32 h⁻¹, was directly measured in the reactor under abiotic conditions by the unsteady re-aeration technique. Dissolved O₂ concentration in the reactor was measured with a Clark O₂ electrode (InPro® 6800Series, Mettler Toledo International Inc., Columbus, OH). The in situ net rate of O₂ production was calculated from the steady-state mass balance through the bioreactor control volume (Eq. (1)).

\[ q₀x = D\left(\frac{[O₂]}{[O₂]} - [O₂]\right) + kₐ\left(k_{LPD}O_{in}^2 - [O₂]\right) \]  

The specific rate of O₂ production \( q₀ \), multiplied by the biomass concentration (\( x \)) is interpreted here as the net rate of O₂ production during photosynthesis (Bernstein et al., 2014) and is a function of the dilution rate (\( D \)), kₐ, dissolved O₂ concentration ([O₂]) and Henry’s law partitioning coefficient (\( k_{H} = 1.08 \text{mM atm}^{-1} \)). The specific rate of biomass production (\( q_x \), Cmmol biomass h⁻¹ gAFCDW⁻¹) was calculated by assuming the molecular weight of ash free dry biomass (AFDW) to be 24.59 gAFDW Cmol⁻¹ (Roels, 1980). The net rate of photosynthesis was also determined as a function of incident irradiance (P-I curve) by collecting axenic *Synechococcus* 7002 cells from the bioreactor and measuring the volumetric O₂ production rates as a function of ‘white light’ (tungsten incandescent) inside an oxygraph chamber (Hansatech, Norfolk, UK) coupled to a 2 π quantum sensor (LI-2105SA Photometric Sensor, LI-COR Biosciences, Lincoln, NE). The P-I curve was fit to the Jasby-Platt (Eq. (2)) using a parametric nonlinear regression (Jasby and Platt, 1976).

\[ P = P_{max} \cdot \tanh \left( \frac{I}{I_c} \right) \]

The net volumetric rate of oxygenic photosynthesis (\( P \)) was estimated as a function of incident irradiance (\( I_c \)) by fitting to the single response variable (\( k_1 \)), which represents the theoretical saturating irradiance of photosynthesis. The maximum net volumetric rate of oxygenic photosynthesis (\( P_{max} \)) is a constant that was directly measured from the P-I curve.

2.5. Flow cytometry and imaging

The relative abundances of *Synechococcus* 7002 and *M. alcaliphilum* cells were determined by flow cytometry using a BD Influx Fluorescence Activated Cell Sorter (FACS, BD Biosciences, San Jose, CA). Upon harvesting, the cells were immediately treated with 50 mM Na₂EDTA (Sigma-Aldrich) and gently pipetted to disrupt large aggregates and then fixed with 2% paraformaldehyde. Using the 488-nm excitation from a Sapphire LP laser (Coherent Inc., Santa Clara, CA) at 100 mW, samples were analyzed using a 70-μm nozzle. Optimization and calibration of the FACS was performed before each analysis using 3 μm Ultra Rainbow Fluorescent Particles (Spherotech, Lake Forest, IL). The ratio of the two distinct populations of cells within a mixed microbial community were identified from 50,000 recorded cells via size and complexity gates using Flojo (Flojo, LLC Ashland, OR) flow cytometry software. Microscopic images were acquired on a Zeiss LSM 710 Scanning Confocal Laser Microscope (Carl Zeiss MicroImaging GmbH, Jena,
Germany) equipped with an alpha Plan-Apochromat 100x/1.46 Oil DIC M27 objective. *M. alcaliphilum* cells were visualized by SYBR Gold Nucleic Acid Gel Stain (Invitrogen, Grand Island, NY) at 529–555 nm. *Synechococcus 7002* was visualized by phycocyanin/chlorophyll auto-fluorescence measured at 655–685 nm. Structured illumination microscopy (SIM) was performed on a Zeiss Elyra S1 microscope using an alpha Plan-Apochromat 100x/1.46 oil-immersion objective. Excitation of SYBR Gold (Thermo Fisher) and phycocyanin/chlorophyll auto-fluorescence was achieved using 488 nm and 642 nm laser excitation, respectively. Emission bandpass filters were 495–550 nm and Long Pass 655 nm, respectively. The two excitation/emission color channels were recorded consecutively. Within each color channel, the raw data contained 3 rotations, 5 phases and 0.1 μm spacing z stack images. The super-resolution images were then reconstructed from raw images using ZEISS Efficient Navigation (ZEN) 2012 software to provide 2D and 3D projections or Volocity (Perkin Elmer). Confocal and SIM images were used to obtain the cell size measurements made along the major and minor axis. Cell volume calculations for each organism were carried out using the equation for an ellipsoid, 

\[ V = \frac{4}{3} \pi ab^2 \]

where \( a \) is the minor axis, and \( b \) is the major axis. The relative biomass content of each organism in the co-culture was calculated using the Eq. (3), where \( v_1 \) and \( v_2 \) are the cell volumes of each organism, \( r_1 \) and \( r_2 \) are the measured population ratios.

\[ B_1 = \frac{v_1r_1}{(v_1r_1 + v_2r_2)} \]  

3. Results and discussion

3.1. Oxygenic photosynthesis drives conversion of biogas to biomass

*M. alcaliphilum* and *Synechococcus 7002* co-cultures, that were fed raw biogas, sustained longer periods of growth and achieved higher biomass concentrations compared to the *M. alcaliphilum* axenic control (Fig. 1). The axenic *Synechococcus 7002* cultures were viable and grew rapidly on raw biogas as the sole carbon source. *Synechococcus 7002* reached stationary phase rapidly (~45 h) likely due to depletion of CO2. The co-culture continued to grow through the duration of the 96 h experiment and showed linear growth with time that was a signature of O2 limitation. Longer periods of co-culture growth were sustained by the intrinsic supply of photosynthetically derived O2 required for CH4 oxidation.

The composition of gas effected the growth properties of each axenic and co-culture batch experiment (Fig. 2). The highest specific growth rate and maximum OD730 was observed for axenic *Synechococcus 7002* cultured in biogas, 0.601 ± 0.002 h⁻¹ and 0.545 ± 0.006, respectively. Supplementation of 20% O2 to the biogas decreased the specific growth rate of axenic *Synechococcus 7002* by 49%. Incubations under a 97% CH4 and 3% CO2 headspace resulted the highest co-culture specific growth rates and maximum OD730, 0.505 ± 0.005 h⁻¹ and 0.532 ± 0.017, respectively. The co-culture exhibited higher maximum biomass loads (OD730) but slightly lower specific growth rates as compared to the axenic *M. alcaliphilum* controls cultured under analogous conditions. Increased CO2 supplementation (to 50% in pure CH4) decreased the growth performance of all axenic and co-cultures as compared to biogas or higher CH4 composition feeds indicating that high inorganic carbon concentrations inhibits microbial growth in the system.

These batch results, obtained on biogas and variable gas compositions, highlight the versatility of the cyanobacteria-methanotroph co-culture technology while utilizing a renewable CH4 and CO2 feedstock for producing microbial biomass. This technology harnesses a metabolic coupling interaction between oxygenic photoautotrophs and methanotrophs that is naturally occurring in many terrestrial and aquatic ecosystems (Le Mer and Roiger, 2001; Milucka et al., 2015). The bioengineering applications of coupled microbial photosynthesis and methane oxidation are promising and have previously been investigated using waste-water enrichment cultures (Van der Ha et al., 2011) and co-cultures driven by non-axenic green algae (van der Ha et al., 2012). The current study differs from previous investigations in multiple respects. First, this new co-culture technology is constructed from pure cultures of genetically tractable bacteria, *Synechococcus 7002* and *M. alcaliphilum 20z* (Ojala et al., 2011; Xu et al., 2011a). Also, previous co-culture studies utilized a synthetic biogas substrate (van der Ha et al., 2012) as compared to the tests presented here on raw biogas feedstock, sourced from an anaerobic digester operated on dairy waste. The current system displayed robust growth on raw biogas, containing trace H2S, that can inhibit microbial growth (Ge et al., 2014).

3.2. Continuous cultivation on a synthetic natural gas mixture

The co-culture was supported under steady-state conditions in a LED-illuminated chemostat sparged with the synthetic natural gas mixture, 80% CH4, 17% N2 and 3% CO2. The total biomass load, held at a dilution rate of 0.3 h⁻¹, was 0.68 ± 0.01 gCdw L⁻¹ (mean of 5 measurements over 3 residence times). The species-specific abundances and steady-state specific rates were determined via cell counting (FACS) and microscopy-enabled measurements of cell sizes (Fig. 3). The steady-state mass fractions of *Synechococcus 7002* and *M. alcaliphilum* were 0.562 ± 0.003 and 0.438 ± 0.01, respectively.

During steady-state co-cultivation, the source of O2 required for CH4 oxidation and *M. alcaliphilum* growth, was supplied by oxygenic photosynthesis. The dissolved O2 concentration, inside the chemostat control volume, was negligible (0.56 ± 0.01 μM). Hence, *M. alcaliphilum* was O2-limited and thereby limited by the rate of photosynthesis performed by light-limited *Synechococcus 7002* cells. Under this metabolically coupled steady-state, the rate of O2 consumption was equal to the net rate of photosynthetic
The specific rate of \( \text{O}_2 \) production (0.781 ± 0.002 mmol \( \text{O}_2 \) gcdw \( \text{C}^0 \)/C0h \( \text{C}^0 \)) was calculated from the dynamic recovery of dissolved \( \text{O}_2 \) concentration in the absence of \( \text{CH}_4 \) oxidation, by replacing \( \text{CH}_4 \) flow with a volumetric equivalent of \( \text{N}_2 \) gas (Fig. 4A).

The specific rate of co-culture biomass production, on a carbon mole (Cmol) basis, was 1.22 Cmmol gcdw \( \text{C}^0 \)/C0h \( \text{C}^0 \). The minimum specific rates of \( \text{CO}_2/\text{HCO}_3^- \) and \( \text{CH}_4 \) uptake were calculated to be 0.686 ± 0.003 and 0.535 ± 0.001 Cmmol gcdw total h \( \text{C}^0 \) for \( \text{Synechococcus} \) 7002 and \( \text{M. alcaliphilum} \), respectively (Fig. 4B). Based on the metabolic coupling requirement, it is reasonable to assume that the \( \text{M. alcaliphilum} \) biomass production rate is controlled by the input of actinic light at environmental conditions near the experimental set points and thus its growth can be modelled as a simple function of incident irradiance (I). Eq. (4) describes this relationship and makes use of parameter estimates obtained by the data presented in Fig. 5.

\[
R_{\text{Met20z}} = Y_{X/\text{O}_2} \cdot P_{\text{max}} \cdot \tanh \left( \frac{I}{I_k} \right) \tag{4}
\]

The volumetric biomass productivity of \( \text{M. alcaliphilum} \) (\( R_{\text{Met20z}} \)) is dependent on the biomass-to-\( \text{O}_2 \) yield, \( (Y_{X/\text{O}_2}) \) that was assumed to be constant at the measured value of 0.68 Cmol biomass produced per mole \( \text{O}_2 \) consumed (Fig. 5C). This yield constant was predicted from the mid-log batch phase of axenic \( \text{M. alcaliphilum} \) growth in the photobioreactor supplemented with \( \text{O}_2 \) at a partial pressure of 0.17 ATM and it showed 99.4% agreement with the independent measurement taken from the co-culture steady-state, 0.683 ± 0.002 Cmol \( \text{M. alcaliphilum} \) biomass produced per mole \( \text{O}_2 \) consumed. The maximum volumetric rate of oxygenic photosynthesis (\( P_{\text{max}} \)) and theoretical saturating irradiance (\( I_k \)) were parametrized from the \( \text{Synechococcus} \) 7002 P-I curve (Fig. 5A and Eq. (2)) and were 12.55 l MO\( \text{O}_2 \) min \( \text{C}^0 \) and 337 \( \mu \text{mol photons m}^{-2} \text{s}^{-1} \), respectively. The model was able to
make a relatively accurate prediction for the *M. alcaliphilum* biomass productivity by accounting for the incident irradiance (260 μmol photons m⁻² s⁻¹) and control volume (5.5 L) used to establish the metabolically coupled steady-state in the chemostat photobioreactor. The predicted volumetric biomass productivity for the *M. alcaliphilum* component of the population was 1.82 Cmol h⁻¹ which showed 90% agreement with the independently obtained bioreactor measurement of 2.026 ± 0.006 Cmol h⁻¹. Similarly, the net volumetric rate of photosynthesis predicted by the Jassby-Platt term (Eq. (2)) was 2.68 mmol O₂ h⁻¹ which showed a 90.6% agreement with the independent measurement taken from the photobioreactor at steady-state, 2.962 ± 0.009 3.15 mmol O₂ h⁻¹. The minor discrepancies between the predicted and measured productivities (<10% variance) are likely related to the difference in light quality used between the photobioreactor (dichromatic LED light) and the oxygen chamber (‘white’ incandescent light). The upper bound for *M. alcaliphilum* biomass productivity corresponds to the theoretical saturating irradiance (Iₛ = 337 μmol photons m⁻² s⁻¹) under the assumption that the observed metabolic coupling will continue to be controlled by O₂-limitation of methanotrophic growth at higher irradiances than the 260 μmol photons m⁻² s⁻¹ that was explicitly tested in the chemostat. The predicted maximum *M. alcaliphilum* biomass productivity was 2.14 Cmol h⁻¹ and based on the saturating, hyperbolic shape of the P-I curve, obtained from *Synechococcus* 7002, this value is expected to remain constant with increasing irradiances beyond Iₛ. Similarly, the peak respiration rate for *M. alcaliphilum* was assumed to be equal to the maximum net rate of oxygenic photosynthesis of *Synechococcus* 7002 illuminated Iₛ and was estimated to be 3.15 mmol O₂ h⁻¹.

Based on the experimental measurements, the illuminated areal biomass productivity of the system was 33.04 ± 0.55 Cmol h⁻¹ m⁻² and the individual productivities of *Synechococcus* 7002 and *M. alcaliphilum* were, 18.57 ± 0.09 and 14.47 ± 0.04 Cmol h⁻¹ m⁻², respectively. Photosynthetic cultures are often expressed on an areal basis to reflect their intended application in solar or hybrid LED/solar lighting. Although the bench-scale chemostat demonstration of this co-culture technology was not optimized for solar-irradiance inputs, the LED-illuminated prototype reactors achieved a relatively high biomass productivity 19.5 ± 0.3 μg dw m⁻² day⁻¹. This high areal productivity was achieved despite the conservative dilution rates chosen for proof-of-concept demonstration. Further process optimization has great potential to achieve the 25 μg dw m⁻² day⁻¹ target set forth by a recent report outlining the biomass production goals of the U.S. Department of Energy (Davis et al., 2016). Future optimization and scaling of this, and similar processes, will need to consider other factors such as dynamic environmental conditions (specifically diel cycles for solar powered systems) and the biological responses to minor components in raw natural gas. Although the components of natural gas other than CH₄ differ by reservoir, they are typically composed of a mixture of volatile organic (VOC) compounds including paraffins, napthenes and aromatics that have the potential to inhibit bacterial growth and metabolism (Abuhamed et al., 2004; Gilman et al., 2013). VOCs thereby represent yet another reduced carbon source that might be utilized as a substrate in future expansions of this co-culture toward more complex, multi-functional microbial consortia.

### 3.3. Future directions

This co-culture technology, as currently reported, is a prototype platform that can be customized to produce a range of bioproducts concurrently with microbial biomass. *Cyanobacterium* *Synechococcus* 7002 is of keen interest to industrial biotechnologists as a metabolically tractable (*Xu et al.*, 2011b), highly productive microbe (*Bernstein et al.*, 2016) that has been demonstrated as a chassis for producing terpenoids (*Davis et al.*, 2014), sugars (*Xu et al.*, 2013) and fatty-acid biodiesel precursors (*Kuo and Khosla*, 2014). Similarly, *M. alcaliphilum* and related methanotrophs are amenable to metabolic engineering and synthesis of value-added bioproducts such as single cell proteins, poly-3-hydroxybutyrate (PHB), methanol and fatty-acid biodiesel precursors (*Kalyuzhnaya et al.*, 2015). Microbial biomass itself is a promising bioproduct that can be used as feedstock in modern catalytic conversion technologies such as hydrothermal liquefaction (Chen et al., 2014; Elliott et al., 2015) and other thermochemical conversion methods (*Balat et al.*, 2009) that produce biocrudes with comparable characteristics to petroleum crude oils (*Vardon et al.*, 2011). In this manner, the ability of multi-species microbial consortia to collaborate for the efficient capture and conversion of CH₄ and CO₂ represents a tremendous opportunity for biotechnologists and engineers to continue investigating.

### 4. Conclusion

The results presented here highlight the versatility of a cyanobacteria-methanotroph co-culture technology capable of
for engineering custom bioprocesses that concurrently remediate GHGs that are environmentally-toxic waste products generated by current energy production activities.

Conflict of interests

The authors have no conflicts of interest to declare.

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References


Fig. 5. Batch growth data for axenic Synechococcus 7002 (Syn7002) and M. alcaliphilum (Met20z) cultures used to parameterize coupled growth and photosynthesis kinetics. A) A P-I curve obtained on Syn7002 cells harvested from the bioreactor. All data points from biological duplicate measurements are plotted and fit with the Jassby-Platt model; dotted lines represent the 95% confidence limit bounds. B) Batch growth dynamics of Met20z showing the biomass concentration (on a carbon mole basis) and dissolved O2 data points with dark black boundaries represent those in mid-log phase. C) The mid-log phase biomass concentration plotted against O2-consumed; the linear slope of this relationship was used to calculate the biomass-to-O2 yield for Met20z.


Kuo, J., Khosla, C., 2014. The initiation ketosynthase (FabH) is the sole rate-limiting enzyme of the fatty acid synthase of Synechococcus sp. PCC 7002. Metab. Eng. 22, 53–59.


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