

Solar-energy driven solid-state fermentation for continuous flow bioethanol production

Betina Tabah^a, Indra Neel Pulidindi^a, Venkateswara Rao Chitturi^b, Leela Mohana Reddy Arava^b, Aharon Gedanken^{a*}

^aDepartment of Chemistry, Bar-Ilan Institute of Nanotechnology and Advanced Materials (BINA), Ramat-Gan 52900, Israel

^bDepartment of Mechanical Engineering, Wayne State University, Detroit, MI 48202, USA

e-mail: gedanken@mail.biu.ac.il

Introduction

Why alternate fuels?

- Depleting fossil fuels
- Non-uniform distribution of fossil fuels
- Growing population
- CO₂ emissions

Why bioethanol?

- ❖ Carbon neutral
- ❖ Renewable and sustainable
- ❖ Tested transportation fuel

Why solar energy?

- ☐ Sustainable energy source
- ☐ Economically and environmentally benign

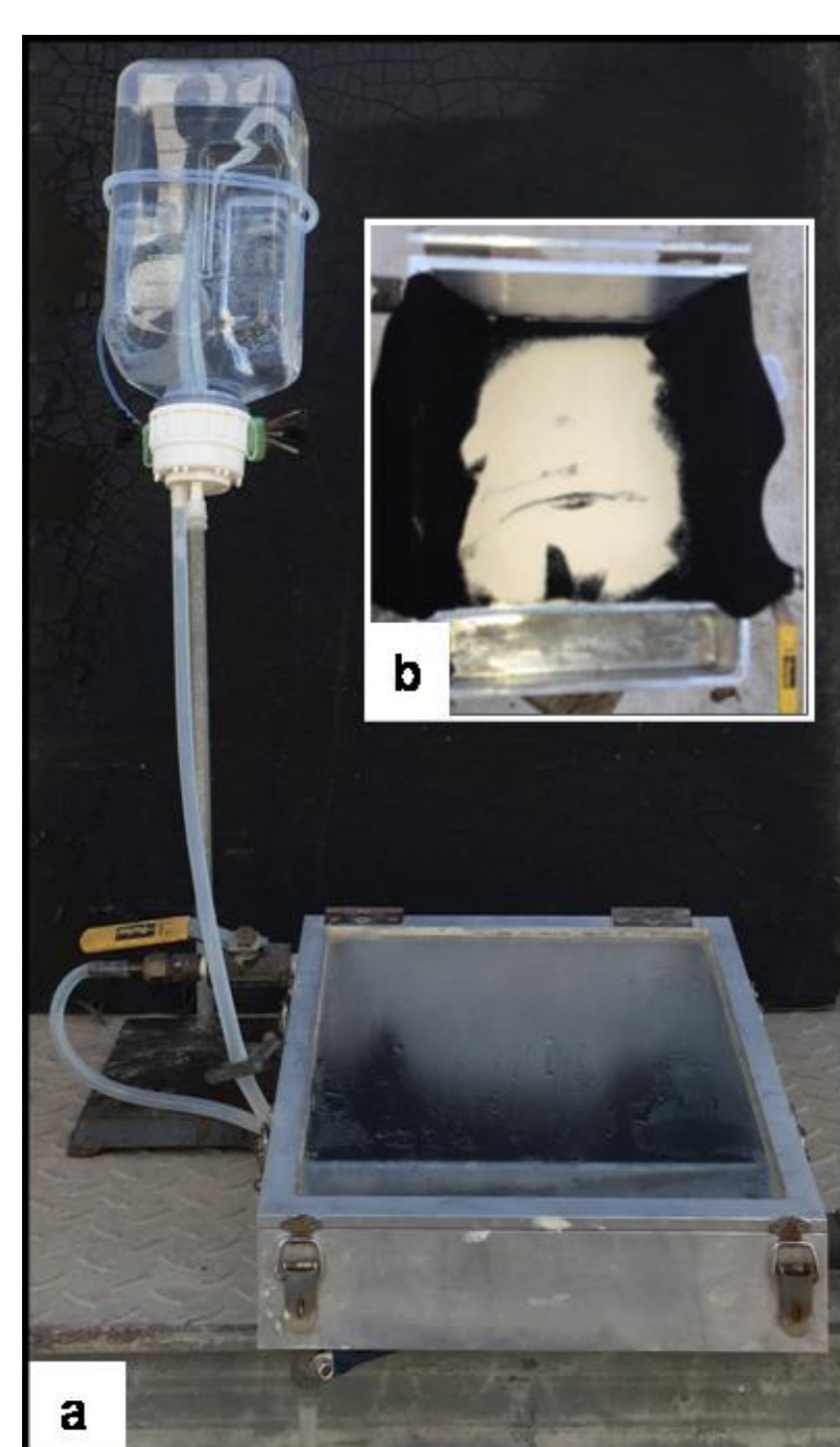
Why solid state fermentation (SSF)?

- ☀ Lower energy requirements
- ☀ Less waste water production
- ☀ Microbial cultures are closer to their natural habitats
- ☀ Reduced use of catalyst (yeast)

Why solar reactor?

- ☀ Continuous flow SSF process driven by solar energy for production of bioethanol
- ☀ *In situ* separation of ethanol from the yeast bed by evaporation-condensation

Experimental

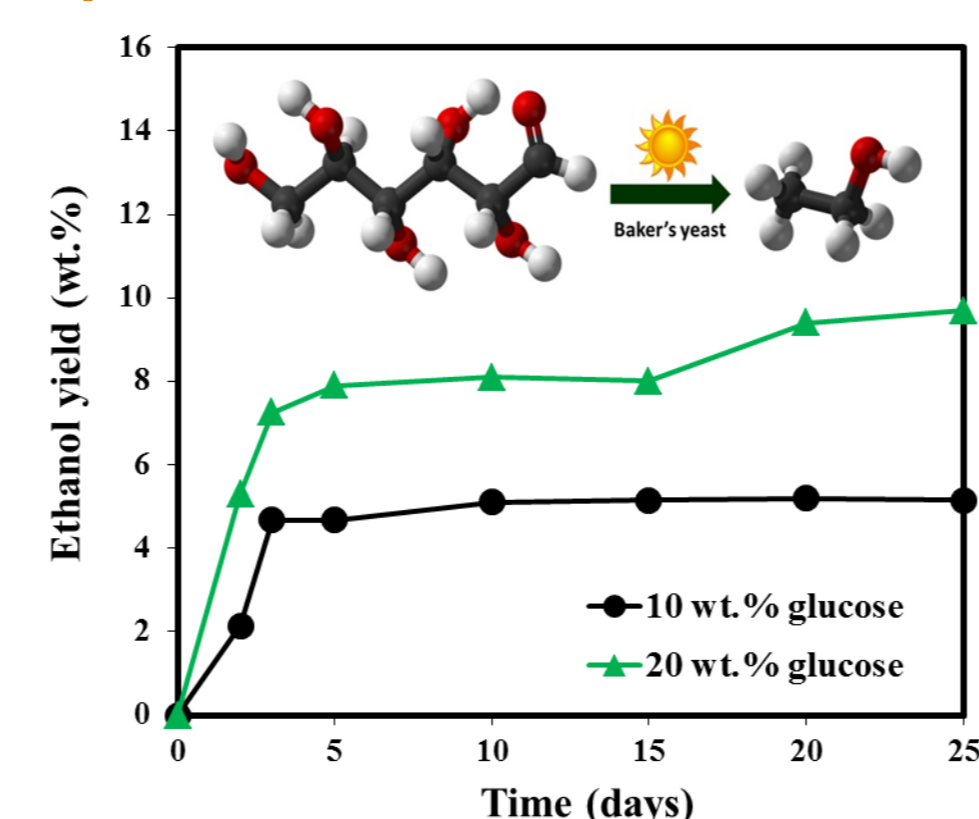


a) Solar reactor with D-glucose reservoir, b) open reactor with instant baker's yeast on activated carbon cloth (Kyno®)

- The reactor was fabricated using lightweight and non-corrosive aluminum blocks
- The geometry is crucial for effective production and separation of ethanol
- The height was kept much lower than the base to facilitate the condensation of ethanol vapor

Results

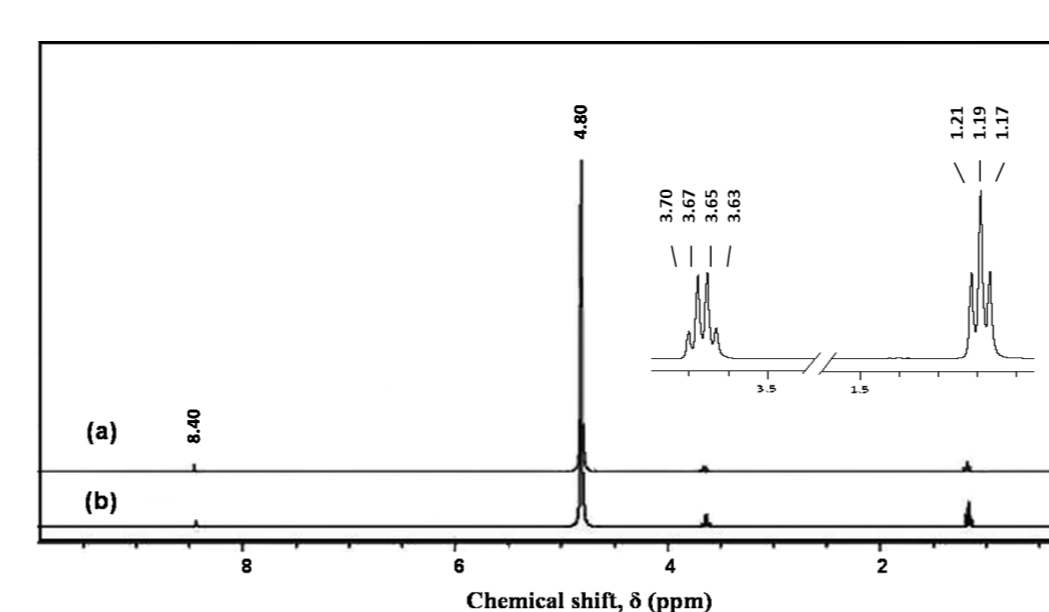
Continuous flow bioethanol production in the solar reactor



Time on stream studies of ethanol yield (wt.%)

- The average temperature was 20 °C for day and 13 °C for night
- The average ethanol yield from 10 wt.% glucose feed was 4.7 wt.% (1 M, 91.2% of the theoretical yield)
- The average ethanol yield from 20 wt.% glucose feed was 8.7 wt.% (1.9 M, 85.5% of the theoretical yield)

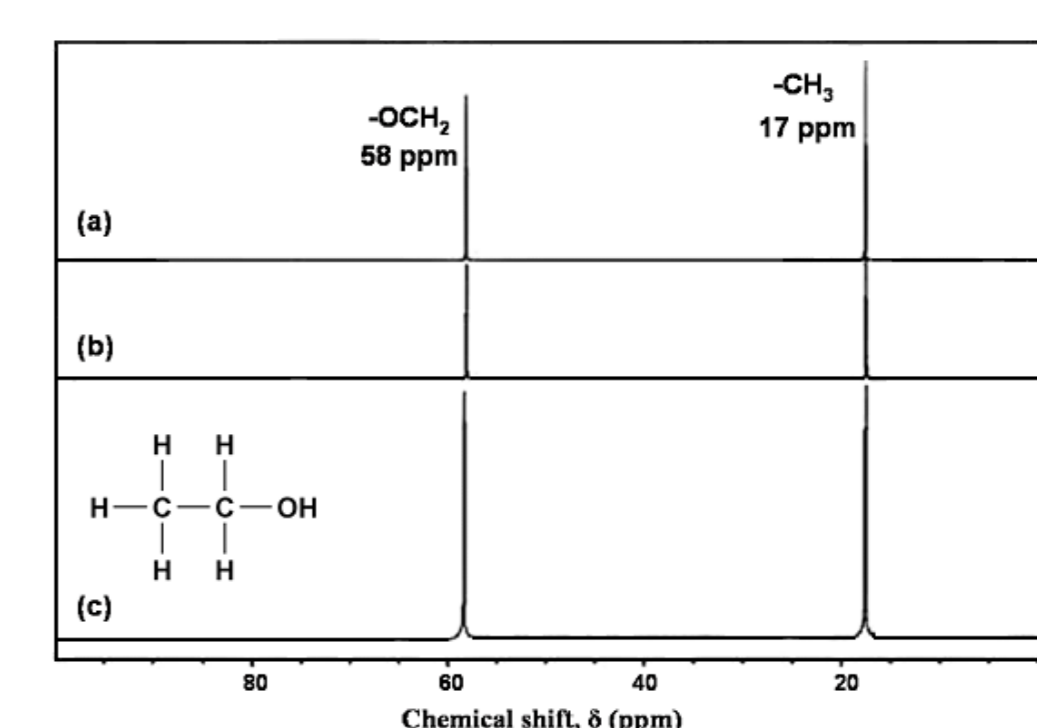
¹H NMR analysis of the product



¹H NMR spectra of ethanol produced from (a) 10 wt.% glucose (1.1 M, 25th day) and (b) 20 wt.% glucose (2.1 M, 25th day,) solutions

- Peaks centered at 1.19 (3H, t) and 3.66 ppm (2H, q) indicate the presence of ethanol (8.40 ppm: internal standard (HCOONa), 4.80 ppm: solvent)
- No reaction by-products (glycerol or acetic acid) in the analytes indicates the product purity (only aqueous ethanol) and its possible direct use for energy related applications

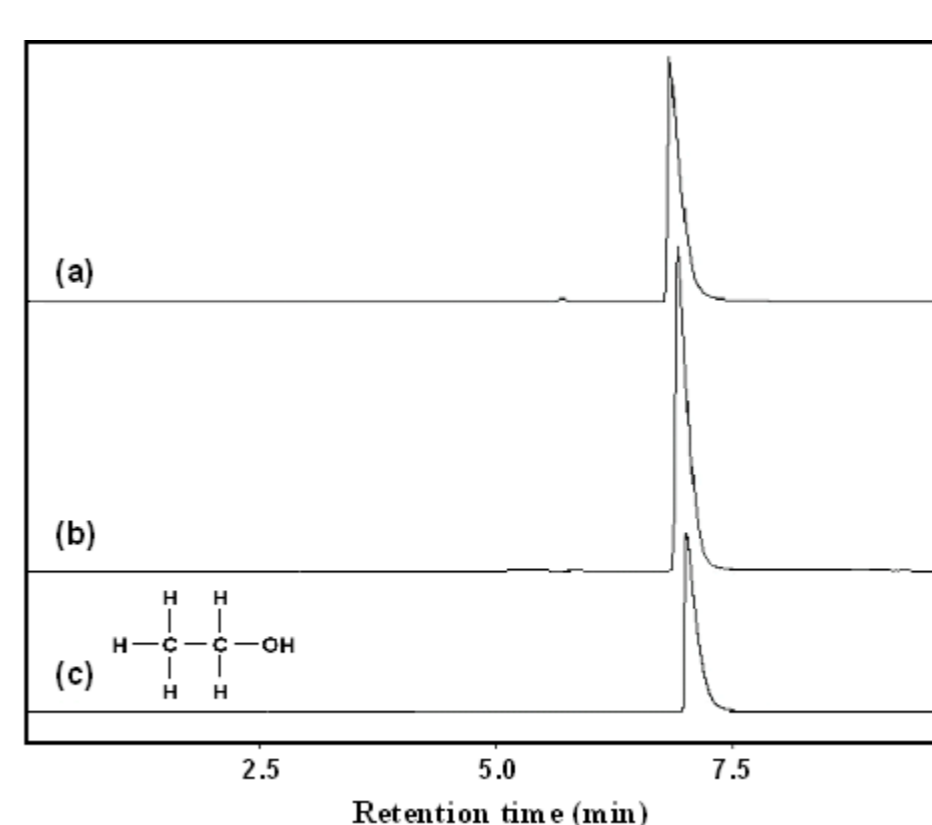
¹³C NMR analysis of the product



¹³C NMR spectra of ethanol produced from (a) 10 wt.% glucose (1.1 M, 10th day), (b) 20 wt.% glucose (1.8 M, 10th day), and (c) authentic ethanol

- Peaks of -CH₃ group at 17 ppm and -OCH₂ group at 58 ppm indicate the presence of ethanol
- The absence of glucose, yeast, and by-products signifies the role of solar radiation in separating the aqueous ethanol from the fermentation broth by means of evaporation-condensation

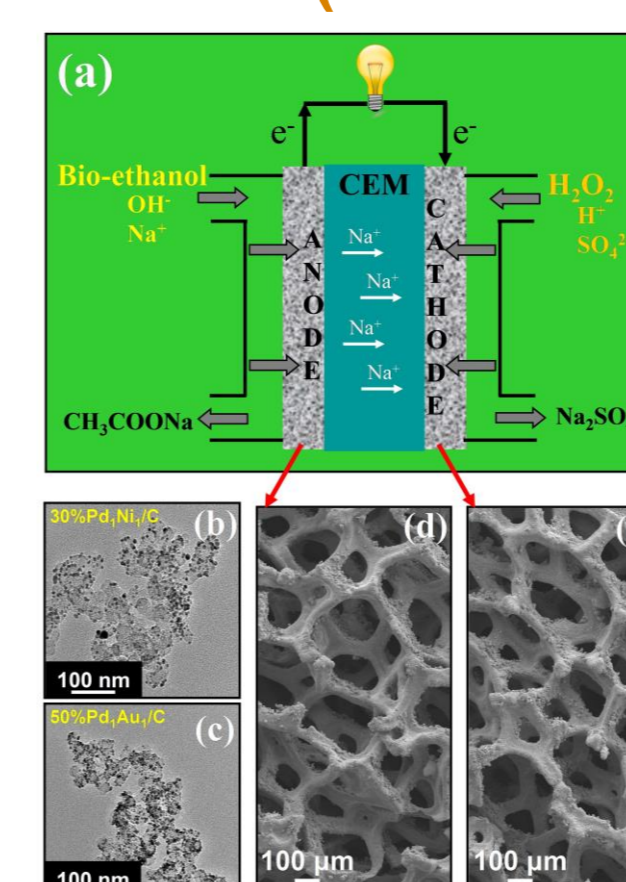
GC analysis of the product



Gas chromatograms of ethanol from (a) 10 wt.% glucose (1 M, 25th day), (b) 20 wt.% glucose (1.9 M, 25th day), and (c) authentic ethanol

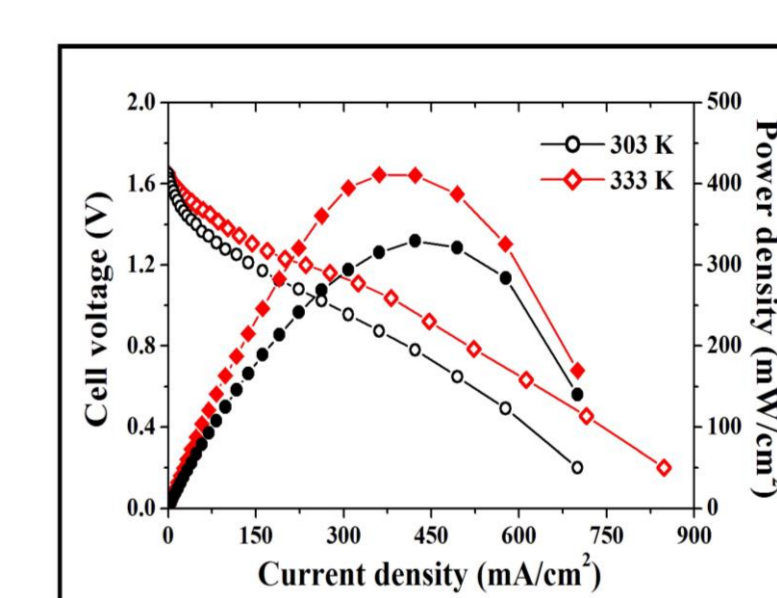
- The peak at 6.9 min retention time confirms the presence of ethanol
- The results of GC analysis agreed well with ¹H NMR analysis, confirming the authenticity of the methodology used for ethanol estimation

Alkaline-acid direct ethanol fuel cells (AA-DEFCs)



- AA-DEFCs is composed of alkalized bioethanol and acidified H₂O₂, separated by a cation-conducting membrane (a)
- Particle size for 30 wt.% Pd₂Ni₇/C and 50 wt.% Pd₂Au₂/C catalysts was 5-6 nm (TEM, b and c)
- 3D-structured electrodes facilitated the diffusion of reactant species and improved the active surface area for redox reaction (SEM, d and e)

AA-DEFCs measurements



I-V polarization and power density curves of AA-DEFCs operated at 303 and 333 K

- Open circuit voltage was 1.65 V (65.5% voltage efficiency) at both temperatures
- When the temperature increased from 303 to 333 K, the max. power density increased from 330 to 410 mW/cm²
- Enhanced performance is due to the faster kinetics of ethanol oxidation and H₂O₂ reduction, improved membrane conductivity, and increased reactant delivery and product removal rates

Conclusions

- ✓ Solar-energy driven solid-state continuous flow ethanol production process was developed
- ✓ There was no polluting effluent due to the solid-state fermentation
- ✓ Separation of ethanol from the fermentation broth was possible soon after its formation by evaporation-condensation process (at ~20 °C)
- ✓ No traces of reactant, catalyst or by-products were observed in the product (only aqueous ethanol)
- ✓ High ethanol yields (~90% of the theoretical yield) were achieved without electricity consumption
- ✓ Same biocatalyst (*S. cerevisiae*) was used for a long time (two months) without loss in the activity
- ✓ The produced bioethanol was demonstrated as a potential sustainable fuel for direct ethanol fuel cells