SAND2020-10159C

# High-protein algal bioproducts:
An economic and environmental sustainability review and risk analysis

Carlos Quiroz-Arita [1], Somnath Shinde [1], Sungwhan Kim [1], Eric Monroe [1], Philip T. Pienkos [2], Lieve M.L Laurens [2], Jason Quinn [3], Nick J. Nagle [2], Eric P. Knoshaug [2], Jacob S. Kruger [2], Tao Dong [2], Ryan W. Davis [1*]

[1] *Sandia National Laboratories, Livermore, CA; *rwdavis@sandia.gov*
[2] *National Renewable Energy Laboratory, Golden, CO*
[3] *Colorado State University, Fort Collins, CO*
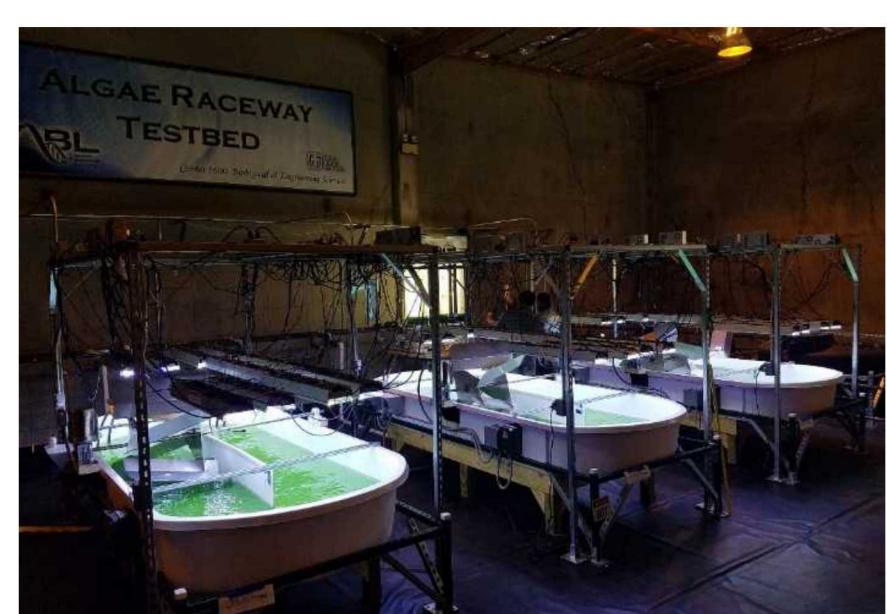
Sandia National Laboratories
Algae Raceway Testbed

NREL Facility

Abstract

This review identifies the most relevant sustainability findings related to the processing of proteinaceous algal biomass and potential pathways to improve life cycle assessment (LCA) and techno-economic analysis (TEA) metrics, including life-cycle carbon dioxide equivalent (CO_2eq), energy, cost, and minimum selling price (MSP). We reviewed several state-of-the-art processes, including cell disruption, protein solubilization, protein precipitation and purification, and protein concentration. Because protein is often the most prominent biochemical component of photoautotrophic algal biomass, this review focuses on options for protein valorization. We evaluated displacement of proteinaceous products by algal-bioproducts, including ruminant feed, aquaculture feed, protein tablets, and biopolymers and biopolyesters, with prices in the market ranging from 1.9 to 120 $ kg^{-1} protein, placing these in a framework for biomass production. Our review reveals a discrepancy in the metrics of sustainability reported in the literature because of differences in proteinaceous biomass process selection, TEA assumptions, LCA system's boundaries, product preparation units, and input uncertainty. For instance, the MSP of ruminant and non-ruminant feed ranges from 0.65 ± 0.56 to 2.9 ± 1.1 $ kg^{-1} protein, and bioplastics' MSP ranging from 0.97 to 7.0 $ kg^{-1} protein. Regarding LCA metrics, there is limited research on life cycle energy in proteinaceous biomass concentration and bioproduct systems, reported at 32.7 MJ $kgprotein^{-1}$, for animal feed displacement. However, direct energy consumptions of specific unit operations are well-studied in the literature. Animal feed emissions in the literature report negative fluxes, representing environmental benefits, as low as -3.7 $kgCO_2$eq kg^{-1} protein and positive fluxes, i.e., global warming potential, as high as 12.8 $kgCO_2$eq kg^{-1} protein. There is limited research on bioplastics life cycle emissions reported at 0.6 $kgCO_2$eq kg^{-1} protein. In general, the studies to date of algae-derived protein bioproducts showed similar life cycle emissions to soybean meals, nylon, polymers, and polystyrenes, ranging from 0.39 to 9.67 $kgCO_2$eq kg^{-1} protein. To assess the risk associated with algal-protein bioproducts input variations, we used a Monte Carlo methodology to simulate scenarios with probabilities of sustainability performance. This review and the Monte Carlo analysis assess and demonstrate the scenarios that improve economic and environmental sustainability metrics in high-protein algal bioproducts systems.

Sustainability review and risk analysis

To assess the risk associated with algal-protein bioproducts input variations, we used a Monte Carlo methodology to simulate scenarios with probabilities of sustainability performance
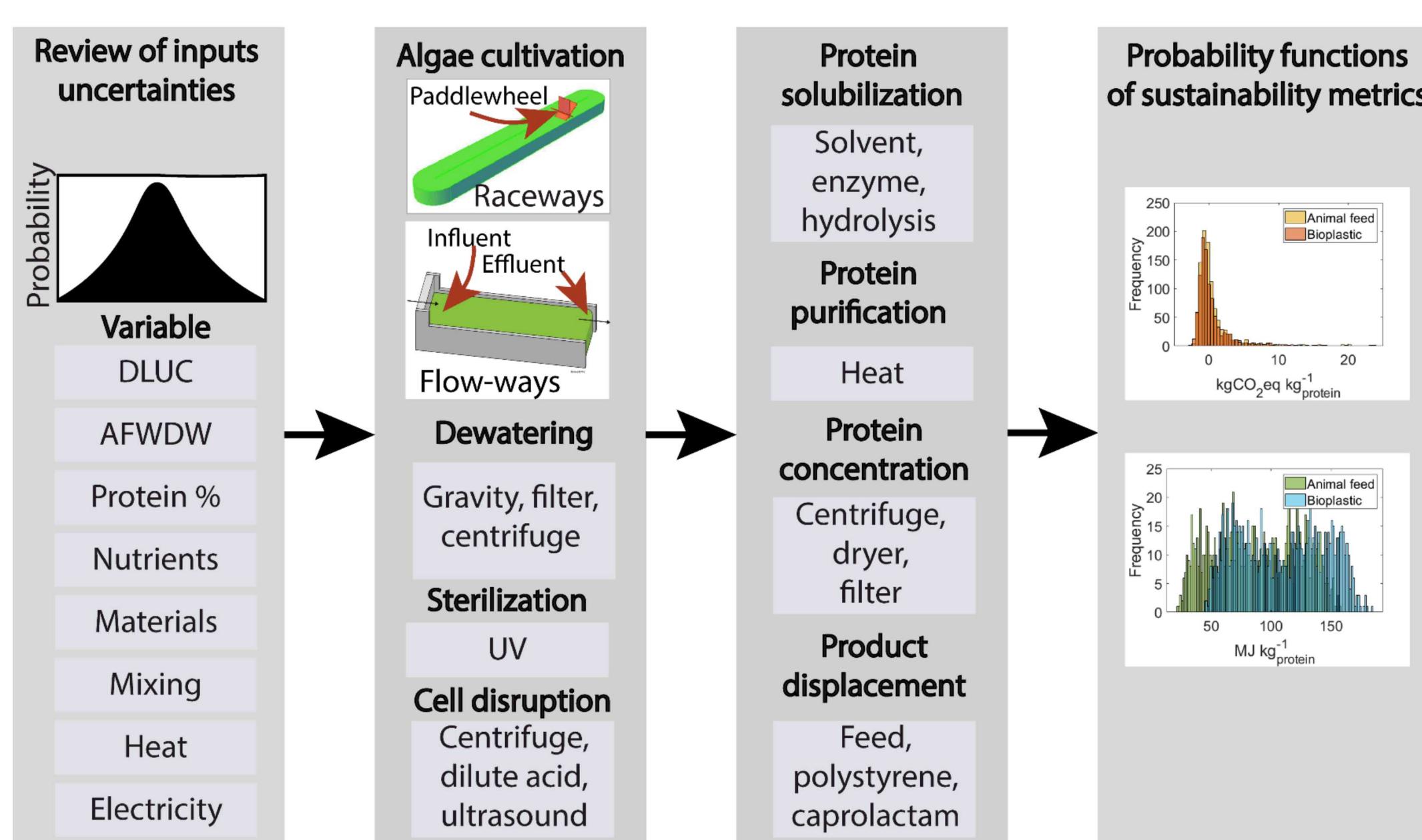
Direct land-use change **(DLUC)** in barren land areas
Ash-free dry weight **(AFDW)** algae productivity
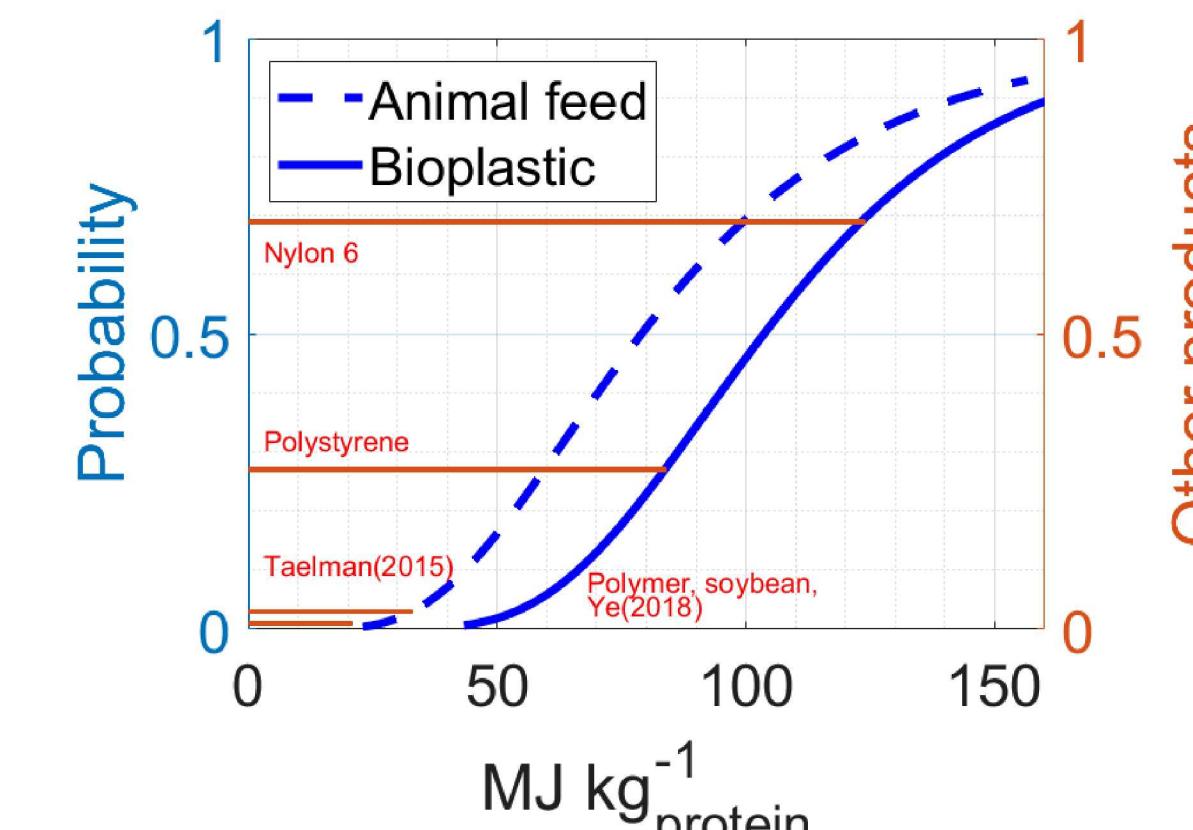
Results

Products from high-protein biomass offers broad portfolio basis for sustainable societal contributions
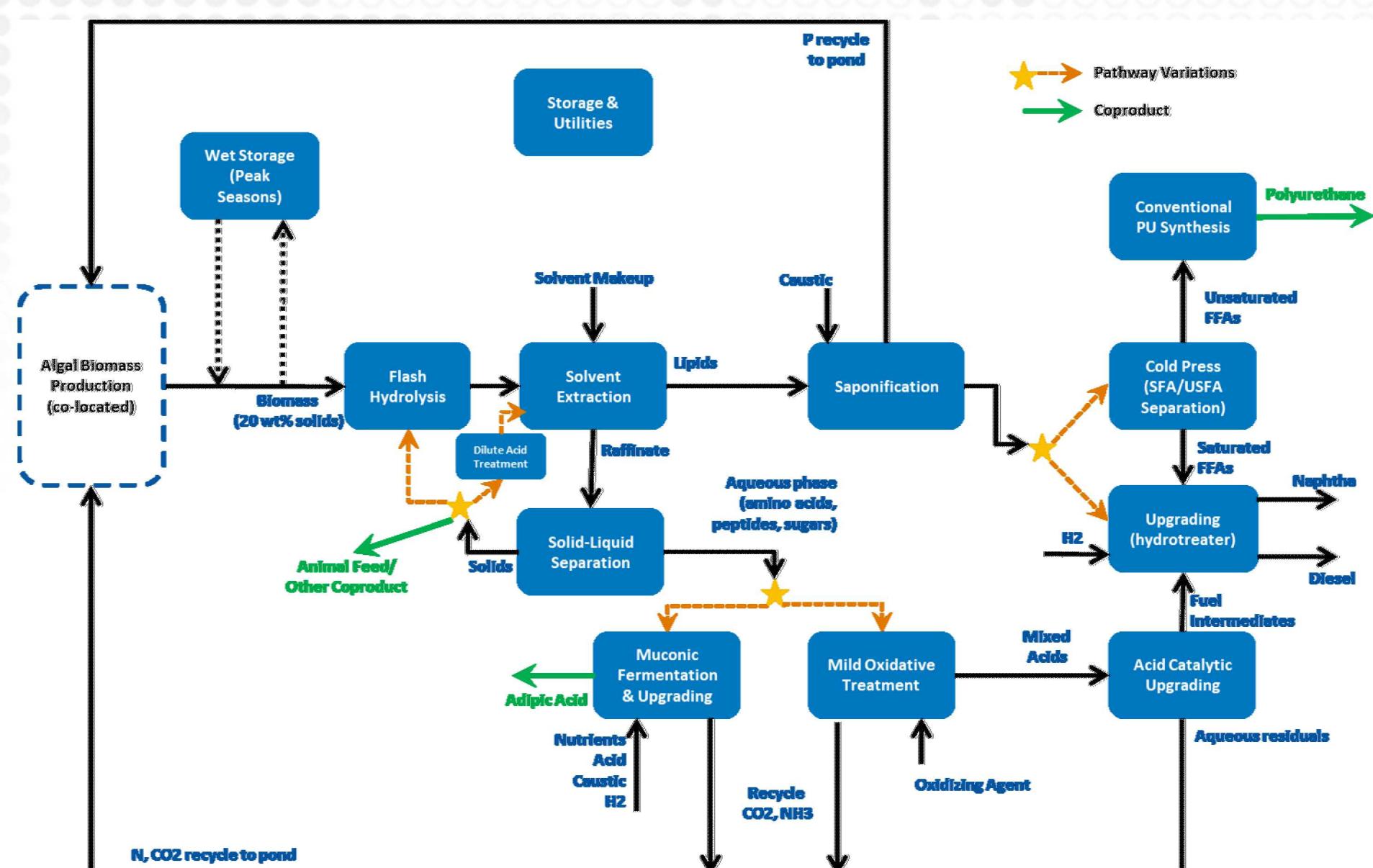

Conceptual process-flow integration for valorizing high-protein algal biomass in a bioenergy context (*i.e.* alongside fuels in a biorefinery configuration)

Probabilistic results show that more than 50% of scenarios will demand life cycle energy consumptions lower than Nylon 6

- Nylon 6 life cycle energy values are equal to a 67% probability of algae-derived bioplastic
- Algae-derived protein tablets reported in the literature assumed best-case scenario obtaining the lowest life cycle energy
- The Monte Carlo analysis demonstrates that 50% of algae-derived animal feed and bioplastics will consume life cycle energy less than 100 MJ kg^{-1} protein

Probabilistic results show that more than 50% of scenarios can result in negative-net life cycle CO_2eq emissions
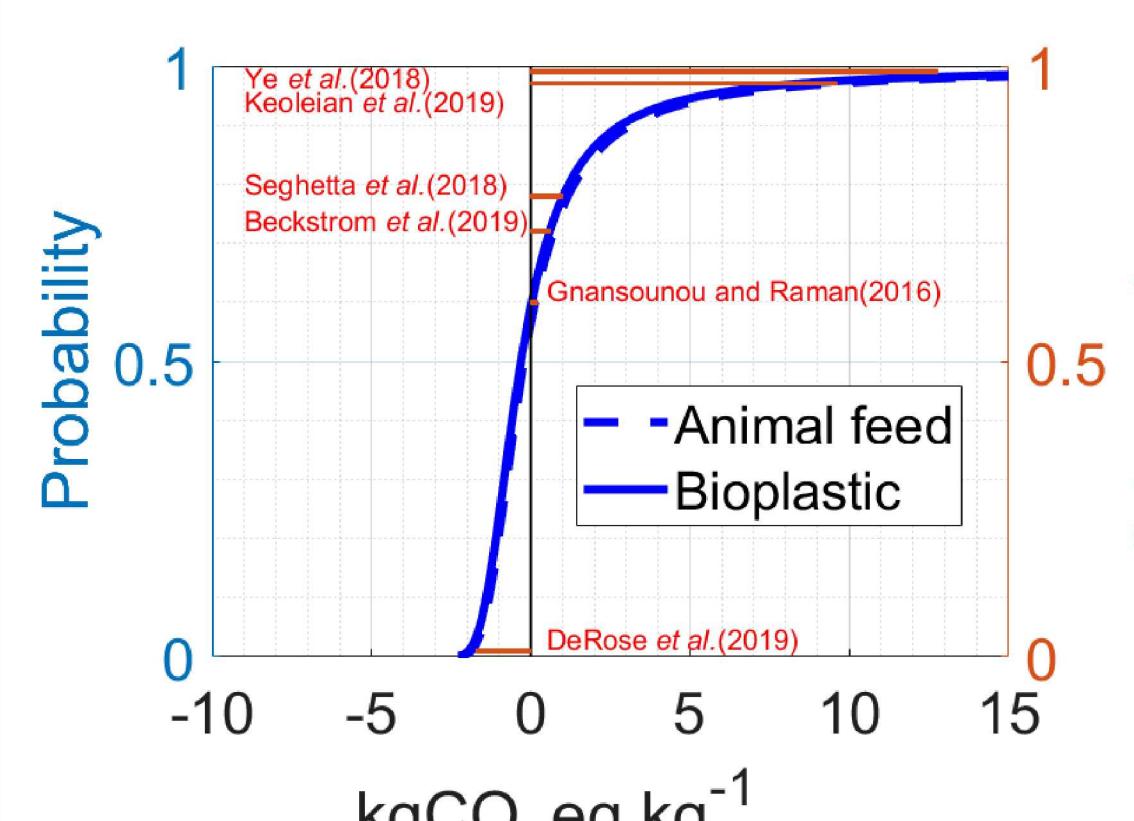
- Algae-derived protein tablets reported in the literature (Chensong et al. 2018) assumed the worst-case scenario obtaining the highest life-cycle CO_2eq
- Protein recovery from benthic polyculture showed negative life-cycle CO_2eq (DeRose et al. 2019)
- The Monte Carlo analysis demonstrates that ~50% of algae-derived animal feed and bioplastics can produce CO_2eq lower than values reported by other authors

Conclusions

- Most sustainability studies neglected uncertainties that are highly sensitive in metrics of sustainability, including DLUC, protein content, and specific energy consumption in cultivation, cell rupture for bioproduct recovery, and conversion processes
- Model inputs' uncertainties and the probabilistic results that provide environmental benefits in high-protein algal bioproducts systems
- Probabilistic life cycle energy results demonstrated that environmental benefits are more likely to achieve in scenarios displacing animal-feed and high resource-intense products (e.g., nylon 6 and polystyrene)
- Probabilistic life cycle CO_2eq emissions showed that negative-net carbon pathways are possible under best conditions for cultivation, protein content, low-energy intense processes, and carbon capture and utilization in the form of bioproducts stocks

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration