MycoGourmet at Artemis I. Ermanoski[1a], C. Tatalovich[1b], R. Ghotkar[2c], J. E. Miller[1d], E. B. Stechel[3e]; [1]Arizona State University LightWorks® and School of Sustainability, PO Box 878204, Tempe, AZ 85287; [2]Mechanical Engineering, School for the Engineering of Matter, Transport, & Energy, ASU; [3]ASU LightWorks® and School of Molecular Sciences, PO Box 878204, Tempe, AZ 85287; [a]ivan.ermanoski@asu.edu, [b]Christina.Tatalovich@asu.edu, [c]rghotkar@nlr.gov, [d]Jim.E.Miller@asu.edu, [e]Ellen.Stechel@asu.edu

Introduction: *In-situ* resource utilization (ISRU), including food production, is a crucial need for a sustainable, expanding human presence beyond low-earth orbit (LEO). This need has long been recognized by NASA and resulted in decades of research under the Controlled Ecological Life Support System (CELSS) program. CELSS achieved tuber yields corresponding to an **e**lectricity-**t**o-**c**alories **p**hotosynthetic conversion efficiencies ($\eta_{ETC,P}$) of up to 2%.[1,2] More recent, though sparse research has pushed $\eta_{ETC,P}$ to ~4%,[3] not including ancillary inputs, illustrating the well-understood limits of photosynthesis.

In this paper we evaluate through experiments and models the concept of producing sustainable space food cultivating edible fungi on ISRU-derived abiotic substrates, where the proximal energy source is chemical, not light (Figure 1). By not relying on photosynthesis, the established and sole bedrock of our food system, our concept represents a fundamentally new cultivation approach, with significant upside potential.

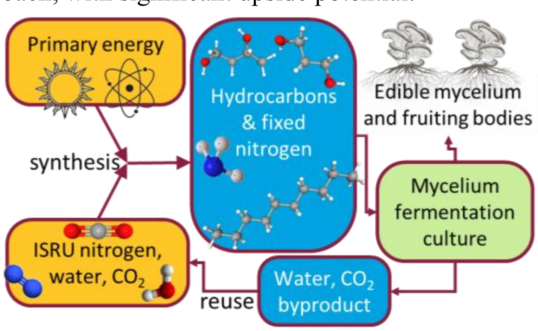

Figure 1. Myco-Gourmet process illustration.

Background: For the experimental aspect of answering these questions, our primary focus is on white rot fungi (WRF), with hundreds of edible species and dozens either commercially cultivated or commercially harvested wild.[4] In addition to many WRF being well-established foods with excellent nutritional profiles, they are also unique in their ability to break down lignin and other recalcitrant hydrocarbons and incorporate the products into their biomass.[5] This ability suggests a potential metabolic cross-compatibility with simple but energy-rich hydrocarbons that can be straightforwardly synthesized on a large scale from CO_2 and water, using re-newable energy.

Gastronomically well-known and prized WRF include shiitake (*Lentinula edodes*), common oyster mushroom (*Pleurotus ostreatus*), blue oyster mushroom (*P. columbinus*), phoenix oyster mushroom (*P. pulmonarius*), aspen oyster mushroom, (*P. populinus*), king oyster mushroom (*P. eryngii*), wood ear (*Auricularia auricula-judae*), and maitake (*Grifola frondosa*)—among many others. Oyster mushrooms are of particular interest as their mycelium is conclusively known to be edible with minimal processing[6] and contains lower peptide toxin concentrations than in the usually consumed fruiting bodies, as well as secondary metabolites with po-tential health benefits. Of this group of WRF we chose several for our study, with the addition of turkey tail (Trametes versicolor), used in traditional medicine, focusing on mycelium cultures, the rapid growth life stage of the filamentous vegetative structure of fungi, which is of most interest in the food production con-text.[7]

Our choice of hydrocarbons was guided by three criteria. First was a fit into entry points into the fungi lignin metabolism, to insert at those points hydrocarbons that are already part of WFR metabolic lignin decompo-sition or are structurally and/or functionally similar. Second was the feasibility of economically synthesizing them from CO^2 and water. Finally, of key relevance for food applications, is to use benign and preferably already considered food-safe hydrocarbons.

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The first WRF metabolism entry point are molecules resulting from the external removal of carboxyl and methoxy groups from monolignols by WRF extracellular enzymes. These include phenols, quinones, and benzene triols (three hydroxyl groups). The concern with class of molecules is synthesis difficulty and general toxicity concerns regarding compounds with aromatic rings.

In this study we probed on a second entry point into the WRF metabolism, molecules internal to mycelium cells, though likely before the central metabolism. We focused on C2 to C6 open-chain hydrocarbons with oxygen moieties, as they appear to be the result of a series of ring openings and other reactions, such as: alcohols, ketones or aldehydes, or acids, such as ethanol, acetaldehyde, acetic acid, butanol, diols, etc., as well as phenols, polyols, and similar. These and others are simpler molecules, far more amenable to industrial synthesis than the first group, with many of them toxicologically benign and largely separable from biomass via simple rinsing or centrifuging.

Results and discussion: To conclusively prove that growth on hydrocarbons is feasible, we conducted liuid-culture experiments, where the only biomass was the fungi inoculum itself. We achieved consistent liquid culture growth, showing that biomass carbon and nitrogen, such as carbohydrates and peptone, are not necessary for mycelium growth.

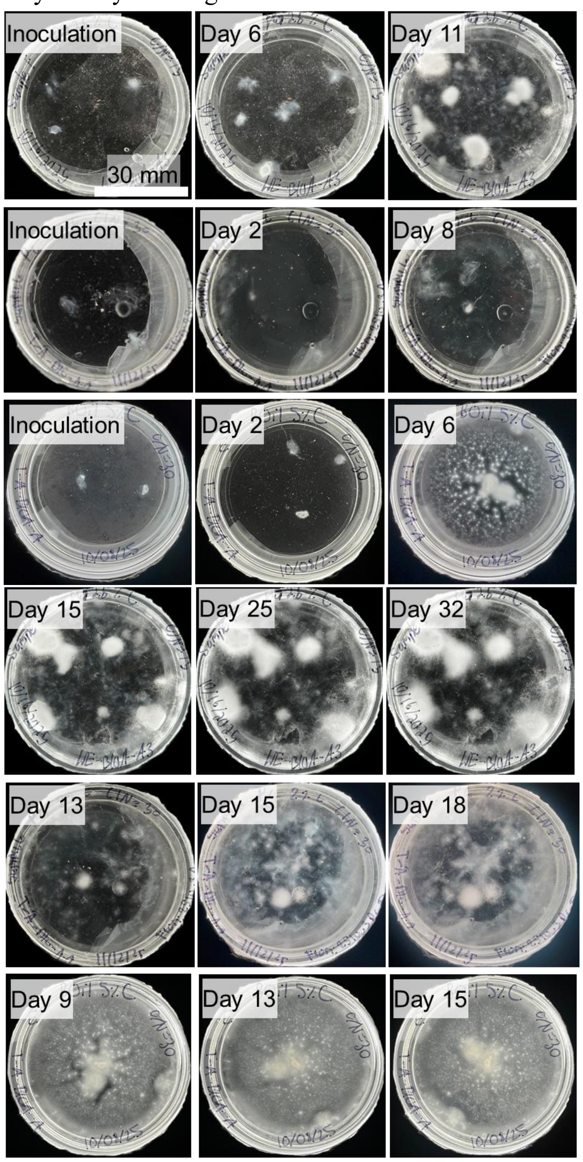

Figure 2. Liquid culture *A. auricula-judae* mycelium growth on 2.5%C propylene glycol, for C/N = 15 g/g (top), *T. versicolor* on 2%C propylene glycol, C/N=30 g/g (middle), and *T. versicolor* on 5%C mineral oil, C/N=30 (bottom).

We further measured **HC**-**t**o-**m**ycelium carbon and **e**nergy conversion efficiencies, the latter reaching $\eta_{HCTM\text{-}E}$~30%, suggesting what may be possible. Assuming scale-up and optimization consistently achieves $\eta_{HCTM\text{-}E}$~35%, and taking η_{ETHC}~60%, we arrive at an estimated **e**lectricity-**t**o-**c**alories efficiency of **f**ungi of $\eta_{ETC,F}$~21%. While these values need careful HC-specific refinements that depend on the synthesis particulars from CO_2 and water, this is an exceptionally high efficiency by any food energy conversion standard and 5x higher than the highest achieved by photosynthetic crops (tubers).

ETC efficiencies are directly relevant to power input and powerplant mass. Taking photovoltaic (PV) efficiencies of ~35%, fungi grown on HCs could reach a ~10% solar-to-food energy efficiency. Feeding an astronaut consuming 3000 kcal/day of food, independent of external supplies, would therefore require an electrical input of ~1.4 kW. Assuming PV operating 50% of the time in 1.36 kW/m^2 sunlight, less than 3 m^2 (~8 kg) of PV area, i.e., ~5 days of food mass equivalent would be sufficient for the purpose.

Eually importantly, rapid doubling times of t_{2x}~4 days in these static 2D experiments indicate s ignificant potential for a high volumetric production density, potentially comparable to that in existing microfungi mycelium fermentation, indicating that bioreactors of about volume of an astronaut would be sufficient to feed each astronaut.

Conclusions: We report the first successful cultivation of common edible mushroom-bearing fungi mycelium using solely abiotically synthesizable hydrocarbons and urea as carbon and nitrogen sources.[8] We show through experiments and analysis the potential for a nearly hundredfold land and water need decrease compared to staple crops. These results provide a solid foundation for a transformative rethinking of food production at Artemis and other locations beyond LEO.

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