

A Review: Using Pyrolysis and its Bioproducts to Help Close the Loop in Sustainable Life Support Systems

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The next step in human exploration of space is beyond low Earth orbit and possibly to sites such as the Moon and Mars. Resupply of critical life support components for missions such as these are difficult or impossible. Life support processes for closing the loop of water, oxygen and carbon have to be identified. Currently, there are many technologies proposed for terrestrial missions for waste, water, air processing and the creation of consumables. There are a variety of different approaches, but few address all of these issues simultaneously. One candidate is pyrolysis; a method where waste streams can be heated in the absence of oxygen to undergo a thermochemical conversion producing a series of bioproducts. Bioproducts like biochar made from non-edible biomass and human solid waste can possibly provide valuable benefits such as waste reduction, regolith fertilization for increased food production, and become a consumable for water processing and air revitalization systems. Syngas containing hydrogen, carbon monoxide and carbon dioxide, can be converted to methane and dimethyl ether to create propellants. Bio-oils can be utilized as a heating fuel or fed to bioreactors that utilize oil-eating microbes.

I. Introduction

The goal of expanding the human race beyond low-Earth orbit will require the development of regenerable life support systems. Key components to this system will be utilizing solid waste streams such as inedible plant biomass, paper, feces, and plastic etc. in such a way to create useful consumables that would be used to support other aspects of the life support loop. This loop will most likely integrate both biological and physicochemical practices in order to reach a required system stability and dependability while minimizing mass and volume requirements crucial to space systems¹.

Many methods have been considered for dealing with solid waste streams, one such method is pyrolysis which is the process of thermal decomposition in an oxygen-free environment. This process holds several advantages over other methods for space waste management. As succinctly stated by Serio et al.²:

- 1) It can be used for all types of solid products and can be easily adapted to changes in feedstock composition
- 2) The technology is relatively simple and can be made compact and lightweight and thus is amenable to spacecraft environments.
- 3) It can be conducted as a batch, low pressure process, with minimal requirements for feedstock preprocessing.
- 4) It can produce several useable products from solid waste streams (e.g. CO₂, CO, H₂O, H₂, NH₃, CH₄, etc.).
- 5) The technology can be designed to produce minimal amounts of unusable byproducts.
- 6) It can produce potentially valuable chemicals and chemical feedstock; (e.g. monomers, hydrocarbons, nitrogen rich compounds for fertilizers)
- 7) Pyrolysis will significantly reduce the storage volume of the waste materials while important elements such as carbon and nitrogen can be efficiently stored in the form of pyrolysis chare and later recovered by gasification or incineration when needed.

Much has been done regarding development of spacecraft suitable pyrolysis systems and utilizing gases as propellants³⁻⁷ therefore; this paper will propose the utilization of biochar in biological and physicochemical systems that are currently being suggested for space applications.

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II. Biochar and Space Crop Production

Biochar (Figure 1) is a carbon-rich byproduct of pyrolysis. It is highly porous and would be made from organic waste such as inedible biomass and feces. When used as a soil amendment, biochar has been reported to boost soil fertility and improve soil quality by raising soil pH, increase moisture holding capacity, attract beneficial microbes, improve soil cation exchange capacity and retain nutrients within the soil⁸⁻⁹. Another benefit associated with the use of biochar as a soil amendment is its ability to sequester carbon from the atmosphere and transfer it to the soil¹⁰⁻¹¹. Biochar may persist in soil for millennia because of its resistance to microbial decomposition and mineralization. This particular characteristic of biochar depends strongly on its properties, which is affected in turn by the pyrolysis conditions and type of feedstock used in its production¹².



Figure 1. Biochar's high carbon content and porous nature can help soil, and possibly regolith, retain water, nutrients and microbes. Source CNN.

To reduce the amount of cargo required on long term space mission to the Moon or Mars, it is vital to utilize in situ resources. Moon and Mars regolith can be used as a substrate for plant growth and as a support for microbial populations in the degradation

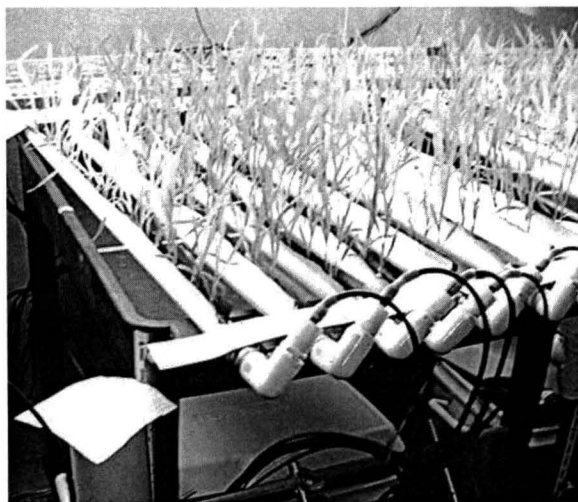


Figure 2. Wheat production utilizing a microporous tube nutrient deliver system at the Space Life Sciences Lab, Kennedy Space Center, FL Source NASA.

of wastes. Use of indigenous lunar regolith as a terrestrial-like soil for plant growth could offer pH buffering capacity, a solid support substrate for rooting support, source of macro and micro nutrients and provide storage and retention of these elements. The regolith could, with a suitable microbial population, play a role in waste renovation; much like terrestrial waste applications directly in soils (composting). Issues associated with potentially toxic elements, pH, nutrient availability, air and fluid movement parameters, and cation exchange capacity of lunar regolith could possibly pose a risk for plant growth¹. Amending the regolith with biochar could mitigate this problem.

What method shall be used to grow these plants? Hydroponic systems utilizing micro-porous tube membrane system (Figure 2) where regolith and biochar could be used as plant rooting media could be used. It was found that sweetpotato plants grown in such a system with Turface, granulated clay, used as media had significantly smaller storage roots and reduced foliage than those grown in nutrient film technique (NFT). It was concluded that this reduction in storage root mass could have been due to nutrient availability within the system¹³. Given biochar's ability to improve soil quality, its use here could significantly improve crop biomass production.

Another possible method to utilize biochar in plant growth systems is in the Vegetable Production Unit (VPU) VEGGIE which is a deployable plant growth unit, developed by Wisconsin based Orbital Technologies Corporation (Orbitec) to be used on board the International Space Station (ISS). It is capable of producing salad-type crops while providing lighting and nutrient delivery. It utilizes heat sealed pillows which allow for passive watering, which contain rooting media and Osmocote fertilizer (Figure 3). These pillows could be filled with a ratio of biochar and regolith or rooting media.

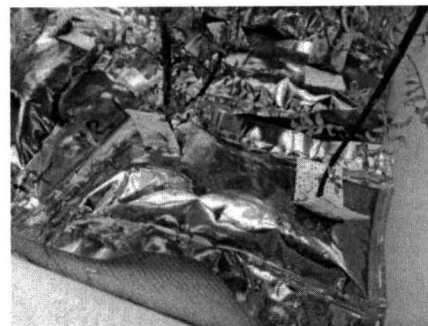


Figure 3. VEGGIE plant rooting pillow.

Utilization of this biochar as an amendment to regolith could improve the regolith's ability to support plant life. It is important, however, to determine and define pyrolysis methods (using pyrolyzers developed for space applications) and waste streams to optimize plant growth in using simulated Mars and Lunar regoliths.

III. Biochar for Waste Water Reclamation

Comparable to activated carbon, biochar can serve as a sorbent for water processing. It is already proving to be a low cost water filtration option in developing countries²⁴. Biochar filters work through the process of adsorption. For water treatment, the large porosity and high surface area of biochars provide many reactive sites for the attachment of dissolved compounds. These reactive sites can bind to targeted hazardous contaminants. Biochar can sometimes have greater sorption ability than natural soil organic matter due to its greater surface area, negative surface charge and charge density¹⁴. Biochar can not only efficiently remove many cationic chemicals including a variety of metal ions, but also sorb anionic nutrients such as phosphate ions, though the removal mechanism for this process is not fully understood⁸. A study showed that modified biochars have the potential to effectively remove a variety of organic contaminants, naphthalene, nitrobenzene and *m*-dinitrobenzene from water as a sorbent¹⁵. Lead and atrazine was sorbed with manure derived biochar¹⁶ and NH_4^+ was effectively sorbed from water utilizing biochar¹⁷.

Could a filter unit of biochar serve as a prefilter for waste water systems? Currently, the Water Recovery System on board the ISS consists of a Urine Processor Assembly (UPA) and a Water Processor Assembly (WPA) where a low pressure vacuum distillation process is used to recover water from urine. The UPA has issues with calcium buildup causing malfunctions within the unit. There are ongoing studies to determine if ion exchange resins can be utilized to remove this calcium, along with other elements from ISS ersatz brines¹⁸. Carbon filters cannot help with this issue, but can be used to reclaim necessary nutrients for plant growth.

Recycling water used for personal hygiene will be necessary in a closed, space-based system. Incorporation of human hygiene water (gray water) into hydroponic plant production systems, and subsequent recovery of the water transpired by the plants, is one potential means for water purification and recycling. The use of plants, and the active microbial community associated with their roots, for water processing would eliminate the need for physical-chemical treatment or a bioreactor and the concomitant resupply of physical components, (i.e., filters, etc.) Hydroponic systems have been proven to successfully remove anionic surfactants¹⁹⁻²¹. But there have been cases where phytotoxicity resulted from excessive amounts of surfactant in the system²². Could biochar prefilters be used to remove some of this surfactant? There have been limited studies done proving that biochar does have anionic exchange capacity²³. But if hydroponic methods are not viable for a particular reason, spent biochar used in a waste water system could be utilized. The sorbed phosphate and sulfate could be available for plants to use thusly.

IV. Biochar for Air Revitalization

It's no secret that odors and off gassing of equipment and experiments can become a problem in enclosed spaces. One can only imagine what kind of odors can develop during a six month journey to Mars so air revitalization is very important.

Currently, on board ISS, the system for atmospheric scrubbing is the Trace Contaminant Control System (TCCS). The TCCS utilizes a three tiered approach to air revitalization: physical adsorption, thermal catalytic oxidation and chemical adsorption. Most contaminants are adsorbed in the charcoal bed assembly (CBA) which contains granular activated charcoal treated with 10% phosphoric acid for ammonia removal. Contaminants not easily removed by the CBA undergo thermal catalytic oxidation in the catalytic oxidizer assembly (COA). Operating at 400°C, the COA catalytically oxidizes contaminants to carbon dioxide and water²⁴. In February 2001, the CBA was returned to the ground from the ISS after 14 months of service and being operational for 74% of that time. The charcoal within the unit was analyzed for ammonia and volatile organic compound loading. Based on this data and archival data of the ISS atmosphere, the service interval was increased to 4.5 years for a crew of three and 2.25 years for a crew of six²⁵. It stands to reason that if the number of crew increased, this system would require more frequent servicing because of increased load.

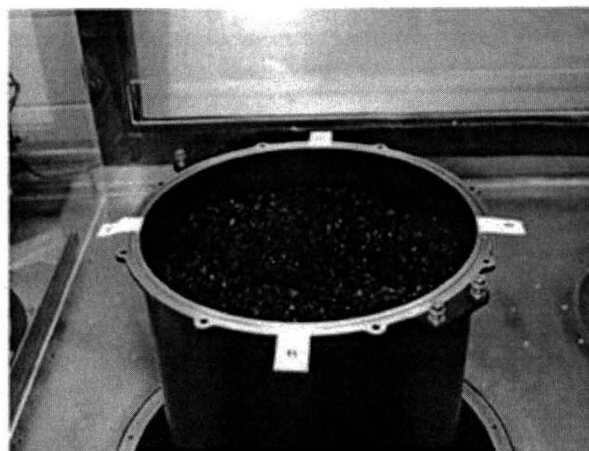


Figure 4. ISS charcoal bed assembly. Source NASA.

The ability to replace or regenerate spent charcoal in this unit during long duration missions would be a huge benefit. Testing on biochars produced utilizing simulated spacecraft waste streams would be required.

Developments of new air processing methods are underway. These systems use photocatalytic oxidation (PCO) reactors (Figure 5) to break down air contaminants. This system would replace the thermal catalytic oxidation unit that is currently used. To date, ammonia removal has not been determined, but is within experimental scope. If it is determined that these units cannot remove ammonia, a CBA would be required. At that time, experimentation with filters created with pyrolyzed biochar could be examined.

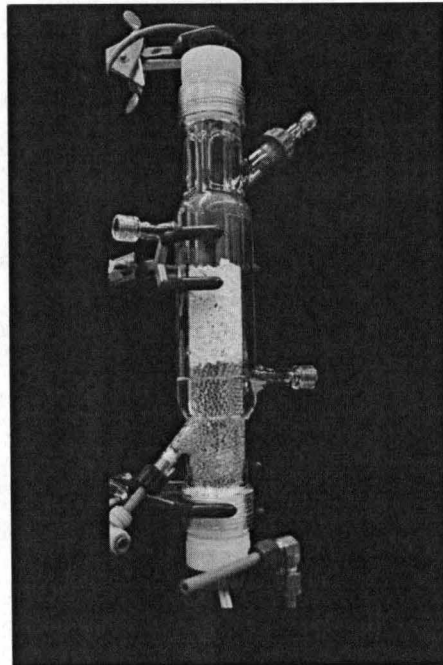


Figure 5. PCO quartz reactor containing silica-titania for air revitalization located at the Space Life Science Lab, Kennedy Space Center, FL.

V. Alternative Methods for Waste Water Processing

What if pyrolysis of waste streams yield undesirable byproducts such as oils or greases? Byproducts that would require further costly and/or time consuming post processing in order to make it viable for use could be fed to bioreactors. Biological reactors are an important part of Advanced Life Support Systems since they require little space and are energy efficient²⁶⁻²⁸. Membrane aerated bioreactors (MABR) have been widely studied for use in a spacecraft environment³²⁻³⁴. These types of reactors exhibit higher transfer efficiencies reduced stripping of volatile contaminants from wastewaters, and the ability to support an attached biofilm for fixed film applications. They are of particular interest in development of biological water processors for space applications, where separation of phases (gas/liquid) is essential³³⁻³⁵. So far, reactors that specialize in bacterial nitrification, which is an important element of the solution to water resource limitations in extended space flight missions have been suggested for spaceflight. Here, nitrifiers convert volatile NH_3 to NO_3^- - eliminating the problem of volatile ammonia in the cabin, and the NO_3^- is potentially removable by another biological process, denitrification, leaving water that can be easily finished by physical-chemical means for reuse by the crew.

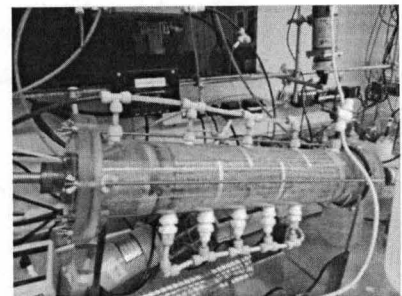


Figure 6. Nitrifying bioreactor Kennedy Space Center, FL.

Nitrifiers form biofilms on reactor surfaces, and the distribution of nitrifiers in biofilms (which can affect the efficiency of the process) is controlled by gradients of O₂ and NH₃.

Similar to these nitrifying bacteria, oil eating microbes could potentially breakdown undesirable pyrolyzed byproducts. With clever coaching from microbiologists, bacteria and other “bugs” can be put to work in to perform this task. MABR have been created to assimilate oil refinery waste water containing aromatic hydrocarbons and inorganic substances for long periods of time²⁹, clean up to 90% of cooking oil influent³⁰ and many other sources of oil contaminated waste water^{31,36}. All with varying levels of success.

VI. Conclusion

Disposable life support equipment will not be suitable for long duration, crewed missions away from low Earth orbit due to the resupply requirements. There is high cost associated with launching fresh supplies of air, water and expendable life support equipment to ISS and returning used equipment to Earth. On deep space missions in the future, such resupply will be impossible and it will not be possible to take along all the consumables required due to the large volume and mass required for a voyage of months or years. Regenerative life support hardware, which can be used repeatedly to generate and recycle the life sustaining elements, will be needed. The ability to create consumables during long trips will be essential to the success of long duration missions. Something as simple as biochar can have far reaching applications, if we seek to determine the correct parameters for use. Useful biochars are dependent on its physical and chemical properties. Therefore, the main challenge is to identify a biochar source, processing combination (using a spacecraft suitable pyrolyser) and application that will optimize its efficiency as a regolith amendment or waste processing component.

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