



Considerations For Waste-to-Base Future Research Paths

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What is Waste-to-Base (WtB)?

WtB is processing any waste into a compact, non-toxic, storable base material that is available for future use.

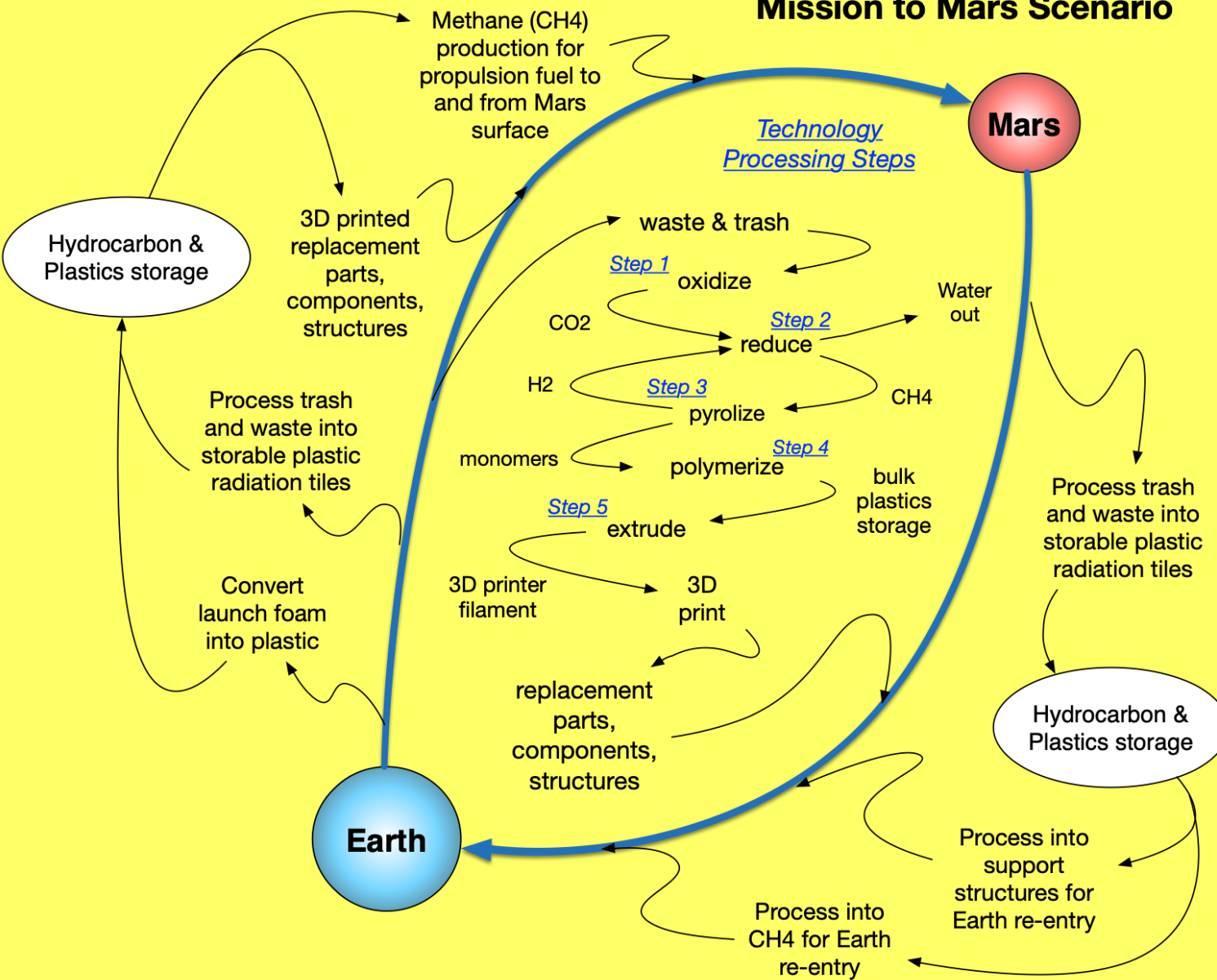
Why is WtB Important?

- A 1000 days Mars mission will generate significant amounts of waste
- Developing innovative technologies to reprocess low value waste into high value base products will enable a new WtB capability that can spawn innovative approaches to mission design
- Equipment, components, consumable goods, packaging, storage, and structures will be understood not only in terms of functional requirements, but also in terms of useful lifetimes and materials of construction.
- A new technical discipline - *reprocess engineering* - will grow from the intersection between chemical, mechanical, and systems engineering, mission design, and logistics planning.

Example Scenario



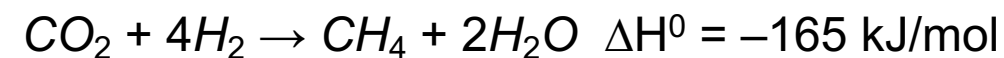
Mission to Mars Scenario



The processing steps are:

1. Oxidize waste and trash
2. Reduce the CO₂ with a Sabatier reactor thereby recovering oxygen and producing methane
3. Pyrolyze the methane to produce ethylene and recover hydrogen
4. Polymerize ethylene to produce solid polyethylene and other polymers
5. Extrude polymers into filament for 3D printing, or radiation shielding tiles, or propellant for thrusters, i.e., hybrid, resistojet, or pulse plasma

Sabatier reactor:





CrowdSourcing

- Gather low TRL concepts into workable solutions
- Under NASA's Space Technology Mission Directorate NASA Tournament Lab, NASA Conducted:
- The 'Waste to Base (WtB) Materials Challenge: Sustainable Reprocessing in Space'
- The WtB challenge consisted of four categories
 - trash
 - fecal waste
 - foam packaging
 - CO₂ processing.
- Submissions were gathered from participants world-wide
- Each category's solicitation is given in the paper

The Waste to Base Challenge received 256 submissions from 41 different countries

NASA Waste Wwaste to Base Challenge I Media Coverage (Selection)

Date	Source	Headline	URL	Country	Reach
1-29-2022	The Guardian	Nasa asks public to help solve waste recycling for Mars trip	https://www.theguardian.com/science/2022/jan/29/nasa-asks-public-to-solve-waste-recycling-mars-trip	United Kingdom	302,500,000
1-24-2022	Q104.3-FM	NASA Needs Ideas On How To Recycle On Mars? Contest!	https://q1043.iheart.com/featured/marc-the-cope-coppola/content/2022-01-24-nasa-needs-ideas-on-how-to-recycle-on-mars-contest/#:~:text=NASA%20wants%20help%20with%20ideas,year%20crewed%20mission%20to%20Mars	United States	26,000,000
1-24-2022	HotHardware	NASA Waste To Base Challenge Puts Up \$24K In Prizes To Invent A Space Recycling System	https://hothardware.com/news/nasa-waste-to-base-challenge	United States	1,380,000
1-21-2022	ZDNet	NASA wants to convert waste into space gold	https://www.zdnet.com/article/nasa-wants-to-convert-waste-into-space-gold/	United States	9,800,000
1-20-2022	Sputnik News	Per Recycling Ad Astra: NASA Seeks New Ideas About Managing Fecal Waste in Space	https://sputniknews.com/amp/20220120/per-recycling-ad-astra-nasa-seeks-new-ideas-about-managing-fecal-waste-in-space-1092397562.html	Russia	42,300,000
1-20-2022	Aroged	NASA announces a competition for the best ideas on how to dispose of waste during an expedition to Mars	https://www.aroged.com/2022/01/20/nasa-announces-a-competition-for-the-best-ideas-on-how-to-dispose-of-waste-during-an-expedition-to-mars/	United States	1,400,000
1-20-2022	Gaming Deputy	NASA is looking for businesses to build toilets and recycling systems on Mars	https://www.gamingdeputy.com/nasa-is-looking-for-businesses-to-build-toilets-and-recycling-systems-on-mars/	Unknown	161,373

1-19-2022	Daily Mail	Could YOU design a toilet for a trip to Mars? NASA challenges entrepreneurs to invent a way for astronauts to relieve themselves comfortably on the nine-month journey to the Red Planet	https://www.dailymail.co.uk/sciencetech/article-10404051/NASA-challenges-entrepreneurs-design-toilet-trip-Mars.html	United Kingdom	357,200,000
1-19-2022	Space.com	NASA wants your ideas to reuse trash and waste on a Mars mission	https://www.space.com/nasa-reuse-trash-waste-mars-mission	United States	16,800,000
1-19-2022	leonarddavid.com	Waste Not! Mars Crowdsourcing Competition – Ideas Wanted	https://www.leonarddavid.com/waste-not-mars-crowdsourcing-competition-ideas-wanted/	United States	1,800,000
1-19-2022	The Science Times	NASA Offers Challenge and Reward In Finding Solution For Waste, Trash Sustainable Reprocessing In Mars and Other Space Missions; How to Join	https://www.sciencetimes.com/articles/35664/20220120/nasa-wants-to-reuse-trash-waste-for-mars-other-space-missions.htm	United States	508,670
1-18-2022	Travel + Leisure	You Could Help a Future NASA Mars Mission — Here's How	https://www.travelandleisure.com/trip-ideas/space-astronomy/space-waste-solution-nasa-mars-mission	United States	8,940,000
1-18-2022	Universe Today	NASA and HeroX Want to Convert Waste in Space and Monitor Air-Quality Here on Earth	https://www.universetoday.com/154049/nasa-and-herox-want-to-convert-waste-in-space-and-monitor-air-quality-here-on-earth/	United States	1,650,000
1-18-2022	Scott Manley - YouTube	Spaceflight Kills Your Blood Cells, SpaceX's Big Balls and Other Deep Space Updates January 18th	https://www.youtube.com/watch?v=DcCdVj7zhk8	6,000	1,390,000
1-18-2022	Aviation Week	NASA, HeroX Kick Off Mars Mission Recycling Challenge	https://aviationweek.com/defense-space/space/nasa-herox-kick-mars-mission-recycling-challenge	United States	609,040



The trash-based WTB submissions span a wide range of ideas:

These include clothing manufacturing, clothes washing, shredding, composite production for additive manufacturing, and trash sorting mechanisms

Here is a summary of the awarded concepts

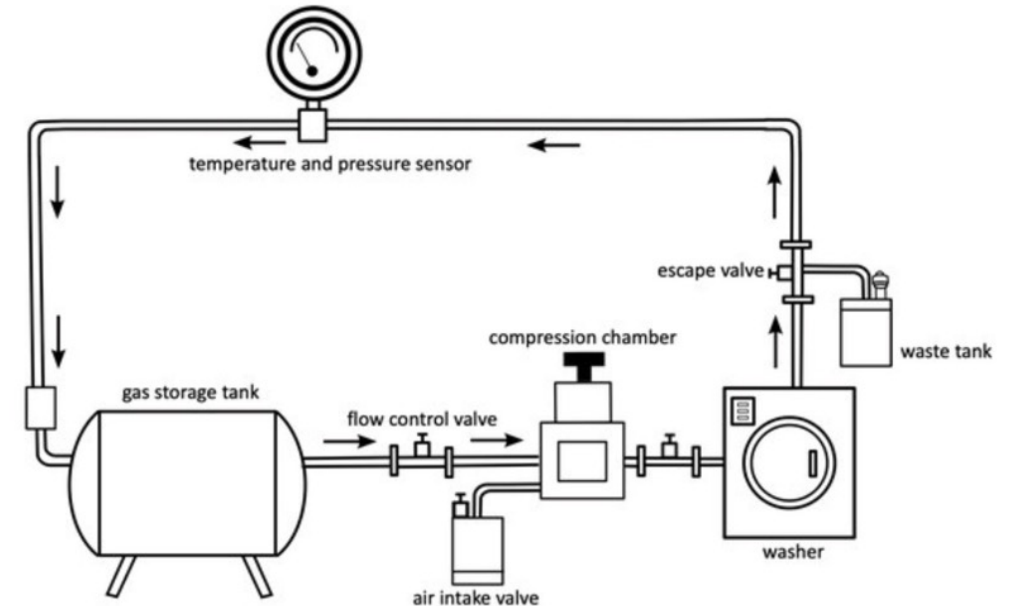


Cotton-based clothing pulped, mixed with microgreen seeds, and pressed into paper

- Cotton fabric is cut into small pieces and blended in water, forming a pulp.
- Microgreen seeds such as radish, broccoli, or kale are then mixed in and grown from the mixture
 - This application may not be very useful while in transit because of space limitations but could become important for surface habitat ecology

Supercritical carbon dioxide (CO₂) for clothes washing machine

- A small amount of soap/detergent can be used
- Operating conditions are 31.3C and 72.9 atm.
- After washing, the pressure and temperature are returned to standard conditions.
- The CO₂ vaporizes leaving the clothes clean and dry
 - There is concern with the equipment needs, safety, and power required to reach these high pressures, but it is an interesting concept





Shredder to consume nearly any type of solid waste

- Plastic, papers, packaging, soft metals, and trash are candidate materials
- Shredding it into tiny particles
- Then 3D printing the particles with a UV resin to create a composite object
 - However, there is concern with using shredders because they consume a lot of power, may become jammed, and have high mass and volume requirements

Tracer-based sorting separating different material even after shredding

- Inorganic tracer substances are added to a material when it is formed
- The substances fluoresce when excited with electromagnetic radiation
- The fluorescence can be quickly detected and can be used to identify an article or material
- A sorting mechanism is then used
 - This might be a good way to sort the trash for recycling even after shredding

The fecal-based awarded submissions usually included composting, anaerobic decomposition, or fermentation (chemical breakdown) methods

Here is a summary of the awarded concepts



- Use bioplastic bags for composting, tailor composting to harvest biodiverse microbes
- Heat sterilize feces for the safe transport of containers to proposed vertical composting reactors. Once fully decomposed, the remains are used as fertilizer
- Combine all waste, including metabolic for anaerobic decomposition. Afterwards use a centrifuge to separate the remains
- Feces contains about 10% fiber. Break down the fiber (cellulose) into the simpler sugar, glucose, by hydrolysis with boiling water and perhaps a small amount of mild acid. Glucose is then converted to starch and then to polylactic acid, PLA. PLA is a thermoplastic monomer suitable for 3D printing
- Another approach for feces decomposition is by alkaline hydrolysis. Here, feces are placed in a solution of water and alkaline chemicals, for example potassium hydroxide. The strong base solution will rapidly react with the feces when pressurized and heated to 150°C. A sterile solution of water, salt, and simple sugars will result



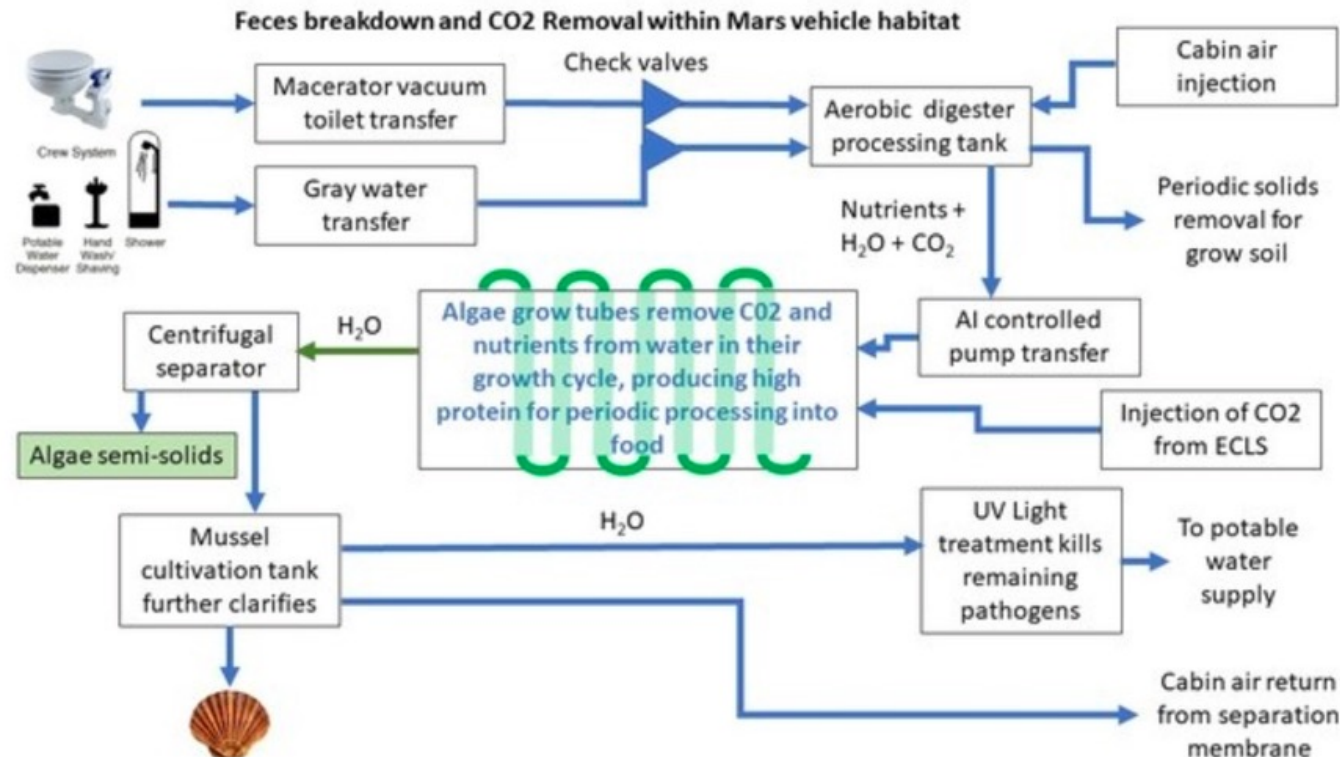
- Wet oxidation (WO), also called sub-critical water oxidation, is a process in which organic material is oxidized (typically by air) in the presence of liquid water
 - The critical point of water is at 374°C and 21.4 MPa (3104 psi). The WO reaction occurs at moderate temperatures of 150-370°C, below supercritical values
 - WO typically does not have 100% oxidation conversion efficiency, which can result in nitrogen remaining in solution as ammonia. This may be beneficial because ammonia can be used as a fertilizer
 - If full oxidation occurs, the resulting N₂ gas might be more difficult to further process or it could be used as a make up gas for other processes
- European Space Agency (ESA) project MELiSSA (Micro-Ecological Life Support System Alternative) is to create a closed-loop ecosystem to recycle waste into oxygen, water, and food with only the input of energy to drive the process
 - By using a variety of microbes to decomposes feces and brine, a complete re-use of all materials by fermentation can ideally be accomplished
 - Many low TRL concepts to be developed

- A dry-distillation method has also been proposed. Here the fecal matter is first dehydrated. Then it is heated using microwave radiation. Hydrogen, methane, carbon monoxide, and sulfuric acid gases are extracted in sequence, and this heating and gas extraction process is repeated five to ten times. Pure carbon results, which is then converted to graphene by acoustic treatment
- Another approach is to use an induction furnace to control pyrolysis heat-treatment temperatures. At lower temperatures (torrefaction), water is boiled off from the feces. As temperatures increase, methane gas is recovered. By using a variable temperature induction furnace, valuable resources of water, methane, and other gases can be recovered.
- Feces can also be consumed by microbes. The waste material is broken down by microbes while also producing biomass. The biomass is further processed into an edible (palatable) form for consistency, taste, and smell. While not being fed to humans, perhaps it can be used as an animal feedstock

Fecal: Decomposition Solutions



Proposed processor uses anaerobic digestion and then algae to remove CO₂ and nutrients. An eventual food source is developed.





The most used foam for spacecraft hardware protection is ZOTEK® F30 (density 30 kg/m³) and is distantly followed by Plastazote® LD45FR (density 45 kg/m³)

Both are thermoset, heavily cross-linked polymers that typically have no useful applications after being used as packing materials because they are so difficult, if not impossible, to decompose

This section investigates ways to find a new material or novel uses of existing ones.

Here is a summary of the awarded concepts



Chemical technique: substitution or addition of a molecule in the polymer chain that easily breaks its bonds resulting in depolymerization

- Only trace concentrations are needed. Mechanical strength is retained
- Monomer recovery is often energy-intensive, costly, and incompatible with complex mixtures
- Much industry research in this area. Review for space applications
- Works well with a wide spectrum of additives, including dyes, pigments, inorganic fillers, fiber reinforcing fabrics, and flame-retardants



Thermoplastic high density polyethylene (HDPE) with a small amount of in-chain functional groups added

- Typical recycling of pure HDPE occurs at temperatures above 600°C with a recovery yield of ethylene less than 10%
- However, the modified HDPE can be completely depolymerized in MeOH within 12 h (or in 2 h with catalyst) at 150 °C with a recovery rate of more than 96%

Thermoset plastics polymerized using dynamic covalent diketoenamine bonds

- Recovery of monomers occurs at ambient temperature in 5.0 M H₂SO₄ or HCL solutions
- Complete depolymerization occurs in less than 12 hours, with pure triketone and amine monomers recovered with >90% yield



Use polyvinylidene fluoride (PVDF) in string form and weaving it into useful materials

- When the material is no longer needed, it can be untangled and knitted for reusability

Reduce packing material volume with Orbeez™

- These small, jelly-like balls are super-absorbent polymers and are commonly used as a children's toy.
- They can grow up to 100 times their original size when submerged in water
- Desorption commonly occurs by heating in direct sunlight or in an oven and occurs in about an hour to a few days
- When filled they provide shock protection, radiation shielding, and a recoverable water source. They can also be used as a plant's water supply when placed in soil

Use a corn-based packing foam that's edible

- Seems unlikely the physical properties of such a foam could meet all the stresses of spaceflight
- Can easily be converted to a powder by a shredder, or perhaps more importantly, dissolved in water

Use thermoplastic polyether ether ketone (PEEK) as a foam packaging material

- Can be recycled for 3D printing
- Existing Essentium 3D printers accept it as feedstock
- Very costly

Use thermoplastics recycled into containers for hydroponics

- For Mars applications, a soft-walled system would be developed



Here is a summary of the awarded concepts

Removal of carbon dioxide by absorbents is well-known technology. However, the use of a catalyst to split carbon from CO₂ is a relatively new approach

- the catalyst Eutectic Gallium-Indium (EGaIn) as a liquid at 100 - 120°C splits carbon from CO₂ gas into solid carbon flakes
 - An equivalent portion of the metal gallium is consumed as gallium oxide.
 - Concern to not allow liquid gallium to contact aluminum, thereby severely weakening the aluminum's structural strength
- In a similar approach, a small amount of metallic cerium is mixed into liquid Galinstan. A small voltage potential is applied to facilitate the removal of carbon from CO₂ as flakes

A very novel technique split carbon from CO₂

- use an inductively coupled plasma at 2 mTorr to ionize the CO₂.
- Then the ionized CO₂ is accelerated in an electric field until it hits a gold surface to cleave off the carbon
- So far, the yields produced have been small

A photobioreactor is proposed that uses algae with artificial lighting to convert organic waste and CO₂ into oxygen and excess algae

- The organic waste is contained in a media, and the airborne algae is circulated around it in a mushroom-shaped container

Another approach uses seaweed for CO₂ processing, similar to how it is naturally processed on Earth

Finally, let CO₂ concentration increase and use its greenhouse effect as a Martian solar heating source

- It is unknown the amount of solar heating that can be developed and the expected concentration levels

Conclusions

Twenty-two winners received awards for this crowdsourcing effort. The ideas are very low TRL concepts that can hopefully be developed. The novelty of ideas is excellent.

- Trash processing: concepts varied from repurposing materials as a growing medium, grinding materials for 3D printing, ways to sort them, and oxidize (react) to simpler materials
- For fecal processing, many of the entries used some form of anaerobic digestion and heat treatment
- For foam & plastics, many concepts propose ways to chemically break down polymers into 3D printable monomers. Much of this technology will be driven by recycling needs on Earth, but space applications should also be considered
- For CO₂ processing, very novel ideas have been presented to cleave carbon from O₂. These technologies are still in their infancy but show promise

Overall, it has been a very rewarding experience to gather and compile these ideas. It is hoped that other researchers will be able to gain from them and help bring them to maturity



The authors thank the many involved for their assistance in judging the numerous entries for this crowdsourcing challenge, and to Ryon Stewart for much valuable insight, and finally to HeroX and Shane Jenkins for hosting the challenge.



Backup



The Guardian, MSN Money, Flipboard, Easy Branches, Bollyinside, NewsConcerns, Games4You, Jaituss.com, Latvia on 24, India on 24, Day to News.com, English News, Good Healine, Q104.3-FM, WAMX-FM, KOGA-FM, 93.7 The River, WWBB-FM, WRKH-FM, WCIB-FM, 941 KODJ Iheart, 929 The Bear Rocks Iheart, KKFG-FM, KGOR-FM, 93.3 The Eagle Classic Rock, KQHT-FM, KBGO-FM, WFQX-FM, KCOL-FM, 99.5 The Fox Iheart, WJQQ-FM, 98 Rockme Iheart, KKRQ-FM, WDSJ-FM, WBVB-FM, KPHT 955 Iheart, WKGR-FM, WTRY-FM, WRFX-FM, WQOL-FM, HotHardware, News Break, Geniushark, ZDNet, Sputnik News, Aroged, Gaming Deputy, Daily Mail , Flipboard, Opera News, Newstral, WhatsNew2day.com, xlbux, Travel Guides Buzz, Times of News - USA, Republic World, Space.com, ARCHYDE, WUSQ-FM, Heromag, Geeky.news, Games4You, PressNewsAgency, AllstartsUsa, EduPlus, Access TV Pro, Newsbreezer.com, India on 24, Asteroid.news, AVIOTA, jaituss.in, Go Builz, TalkFinanceOnline, Daily World Live, Tech Times, leonarddavid.com, The Science Times, Travel + Leisure, Yahoo! Lifestyle (US), Discover Magazine, Universe Today, Before It's News, Opera News, DayDayNews, Tweak Town, Jioforme, True Viral news, Israel on 24, Portal to the Universe, Scott Manley - YouTube, Aviation Week, NBC News (79.09M UVM)