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RESEARCH ARTICLE

How we can mine asteroids for space food

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Abstract

To deeply explore the solar system, it will be necessary to become less reliant on the resupply tether to Earth. An approach explored in this study is to convert hydrocarbons in asteroids to human edible food. After comparing the experimental pyrolysis breakdown products, which were able to be converted to biomass using a consortia, it was hypothesized that equivalent chemicals found on asteroids could also be converted to biomass with the same nutritional content as the pyrolyzed products. This study is a mathematical exercise that explores the potential food yield that could be produced from these methodologies. This study uses the abundance of aliphatic hydrocarbons in the Murchison meteorite (>35 ppm) as a baseline for the calculations, representing the minimum amount of organic matter that could theoretically be attributed to biomass production. Calculations for the total carbon in solvent-insoluble organic matter (IOM) represent the maximum amount of organic matter that could theoretically be attributed to food production. These two values will provide a range of realistic yields to determine how much food could theoretically be extractable from an asteroid. The results of this study found that if only the aliphatic hydrocarbons can be converted into biomass (minimum scenario) the resulting mass of edible biomass extractable from asteroid Bennu ranges from 5.070×10^7 g to 2.390×10^8 g. If the biomass extraction process, however, is more efficient, and all IOM is converted into edible biomass (maximum scenario), then the mass of edible biomass extractable from asteroid Bennu ranges from 1.391×10^9 g to 6.556×10^9 g. This would provide between 5.762×10^8 and 1.581×10^{10} calories that is enough to support between 600 and 17 000 astronaut life years. The asteroid mass needed to support one astronaut for one year is between 160 000 metric tons and 5000 metric tons. Based on these results, this approach of using carbon in asteroids to provide a distributed food source for humans appears promising, but there are substantial areas of future work.

Contents

Introduction

Space food is an area of intense research effort (Weiss, 1972; Mizuno and Weiss, 1974; Calvin and Gazenko, 1975; Grover *et al*., 2022; Pandith *et al*., 2022). The ability to create human-edible food in space is a key achievement that can foster economic exploitation of the asteroid belt (Gertsch, 1992; Sommariva, 2015; Ehresmann and Herdrich, 2017; Calla *et al*., 2018) as well as being a requirement for long-term human space exploration (Fritsche *et al*., 2018; James, 2018). Current technologies that can supply food to space travellers are dependent on consumables from resupply missions from Earth (e.g., dried (Venir *et al*., 2007; Park *et al*., 2009), freeze dried (Obrist *et al*., 2019), irradiated food (Pometto and Bourland, 2003) or frozen food (Geiges, 1996)). These systems are completely dependent on Earth resupply and thus far from optimized for energy or economics. For example, food demands for a Mars mission for six astronauts will weigh around 12 tons without packaging (Park *et al*., 2012). To explore further than Mars would entail massive quantities and masses of food. Even with SpaceX's relatively low cost of $2720 per kilogram to lift into space (Cobb, 2019), a less costly and more sustainable method is preferred. Recycling of air, water and waste will likely also be essential, but such systems are used in the context where waste mitigation includes the jettison or storage of these products, which ultimately leads to the need for resupply missions (Boscheri *et al*., 2021). To deeply explore the solar system, it will be necessary to become less reliant on the resupply tether to Earth (Sercel *et al*., 2018).

Farming in space, on an external base, may be possible but is extremely complex (Monje *et al*., 2003; Tibbetts, 2019; De Pascale *et al*., 2021). Bioregenerative life support systems are also a promising approach (Douglas *et al*., 2021). These include methods of food production from almost classical crop cultivation and animal farming (including insects) to innovative microalgae (Yang *et al*., 2019), and mushroom cultivation (Manukovsky *et al*., 1997). There have been significant advances in vegetable production systems in space onboard the International Space Station. For example, the Vegetable Production System (aka Veggie), is a space garden that has grown eight different types of edible leafy greens since 2014 (Massa *et al*., 2017). The Advanced Plant Habitat (APH) has shown similar success growing plants in a closed and automated system (Monje *et al*., 2020). Bioregenerative systems designed to mimic elements of Earth's biological systems (namely microbial ecologies) (Hendrickx *et al*., 2006; Fahrion *et al*., 2021), however, are far from mature (Kliss *et al*., 2000).

Protein storage is a particular concern since methods to store it can compromise quality (Bychkov *et al*., 2021). All of these approaches, however, require an initially considerable input of resources from Earth and may well require periodic resupply. These virtual tether to Earth strategies are expensive and will become less viable the further humanity moves out into space. What if humanity could acquire the raw materials to make food in space? This article investigates ways to do just that using new techniques developed to recycle plastic waste into food on Earth, and extrapolating these techniques to the theoretical application of converting asteroidal material into food (Petsch *et al*., 2001; Byrne *et al*., 2022; Schaerer *et al*., 2022; Waajen *et al*., 2022, 2024).

Recently, Waajen *et al*. (2024) examined this process by growing anaerobic microbial communities on the CM2 carbonaceous chondrite Aguas Zarcas as the sole carbon, energy and nutrient source, successfully demonstrating that microbial communities can metabolically transform carbonaceous asteroidal material as a potential resource. Furthermore, Bryne *et al*. (2022) demonstrated that potentially human-edible biomass could be produced from bacterial consortia acting on the pyrolytic breakdown products of high-density polyethylene plastics. Although Byrne's work is focused on the recycling of plastic waste, the idea of leveraging bacterial inocula to produce potentially edible biomass from initially inedible precursors is germane to the need to produce food in space (similar to synthetic

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biological processes described by Waajen *et al*., 2024). This article will outline an approach to providing human-edible food – and calculate theoretical yields – employing naturally occurring organic compounds commonly found in specific types of meteorites: the carbonaceous chondrites. Carbonaceous chondrite meteorites likely originate from the most abundant class of asteroid in our solar system, the C-class, which tend to be most abundant in the outer main asteroid belt (Vilas and Gaffey, 1989; DeMeo *et al*., 2015). In addition to their relatively high organic chemical content, some carbonaceous chondrites can contain as much as 10.5 wt% water (Rivkin *et al*., 2002). Selected asteroids could provide the raw materials – organic compounds and water – that when processed by bacterial consortia in bioreactors, would form the basis of an extra-terrestrial food-supply chain.

The mass of potentially available organic compounds in some C-class asteroids will be calculated to provide 100% of the caloric requirements for a human for one year. Furthermore, calculations will be made to determine how many years a single asteroid could theoretically sustain an astronaut. Based on the current biomass yields from bioreactors on Earth, future work will be provided to enable this path as a sustainable source of food for space travellers.

Background

Meteorites

The most abundant source of information available regarding asteroid composition is from the analysis of meteorites, which are – for the most part – fragments of asteroids. Meteorites are classified based on their mineralogical and petrological characteristics, as well as their whole-rock chemical and O-isotopic compositions. The main classifications are chondrites, primitive achondrites and achondrites. Within each of these main classifications are multiple sub-classifications. For example, there are currently 15 recognized groups of chondrites: 8 carbonaceous (CI, CM, CO, CV, CK, CR, CH, CB), 3 ordinary (H, L, LL), 2 enstatite (EH, EL) and R and K chondrites (Weisberg *et al*., 2006). Each sub-group is believed to have sampled a separate parent body or asteroid. There are also individual chondritic meteorites that may share some, but not all, of the characteristics of one of these sub-classifications. These may remain as ungrouped or unique or they may be associated with one of the established sub-classifications but identified as outliers by designations such as C-ungrouped (Grady *et al*., 2002; Mittlefehldt, 2002; Yesiltas *et al*., 2022).

Carbon compounds in meteorites and their distribution in carbonaceous chondrites

Grady and Wright (2003) provide a very useful overview of the major carbon phases seen in meteorite groups. The carbonaceous chondrites, particularly the CI, CM and some related ungrouped C-chondrites contain the highest concentrations of organic compounds, up to ~ 5 wt% (Kissin, 2003; Pizzarello *et al*., 2006). In ordinary chondrites and the achondrites, carbon is usually seen in inorganic forms, occurring as carbonates or carbides, as well as in elemental form as graphite or, more rarely, diamond. Ordinary chondrites, in general, contain less total organic carbon than carbonaceous chondrites, with values ranging from 0.03 to 0.2 wt% (Alexander *et al*., 1989; Makjanic *et al*., 1993). The carbon content of achondrites can range from 0.003 to as much as 7 wt% but is also typically in inorganic forms (Alexander *et al*., 2017).

Extensive reviews of the possible origins and modifications of extra-terrestrial organic compounds is given by various authors (e.g., Ehrenfreund and Charnley, 2002; Elsila *et al*., 2016; Glavin *et al*., 2018; d'Ischia *et al*., 2021; Alexander, 2022; Furukawa *et al*., 2023). The variety and isotopic diversity of the organic compounds seen in carbonaceous meteorites indicates an initial interstellar and circumstellar formation with subsequent secondary modification on their parent body in the presence of water (Botta and Bada, 2002; Pizzarello *et al*., 2006). Water, in the form of ice, was accreted into primitive asteroidal bodies along with organic compounds and anhydrous minerals such as olivines and pyroxenes (Rubin *et al*., 2007; Le Gillou and Brearly, 2014). Later heating, caused by the radioactive decay

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of Al26 and/or energetic impacts with other asteroidal bodies, melted the ice and provided the energy to drive the modification of the organic pre-cursors (Grimm and McSween, 1989; Nakamura, 2005; Lee *et al*., 2016). Keil (2000) provides an overview of heating on meteorite parent-bodies. The circulating water also altered the primary anhydrous silicate minerals, yielding a variety of secondary hydrous phyllosilicates (saponites, smectites, serpentines) as well as carbonates, oxides and sulphides. The phyllosilicates form the bulk of the matrix: 84.3% by volume in the Murchison meteorite and 71.2% by volume in Tagish Lake (Bland *et al*., 2004). The CI, CM and C-ungrouped meteorites also commonly contain carbonates (e.g., calcite, dolomite), oxides (e.g., magnetite) and sulphides (e.g., troilite, pyrrhotite, pentlandite) (Bland *et al*., 2004). A historical review of the study of organic compounds in meteorites is provided by Botta and Bada (2002).

The organic material in meteorites can be divided into two types: solvent-soluble organic material (SOM) and solvent-insoluble organic material (IOM). The SOM is composed of a wide variety of compounds such as ketones, alkanes, carboxylic and amino acids, methane, as well as polycyclic aromatic hydrocarbons (Grady and Wright, 2003; Pizzarello *et al*., 2006). Solvents often used for the extraction of SOM include water, for the extraction of amino acids, and benzene or benzene/methanol mixtures (Pizzarello *et al*., 2001; Sephton, 2002). Sephton and Gilmour (2000) provide a summary of organic moieties which have been identified in the CM-type meteorite, Murchison. The IOM comprises most of the organic compounds in carbonaceous chondrites; approximately 70% in the Murchison CM-type and as much as 99% in the Tagish Lake C-ungrouped meteorite (Pizzarello *et al*., 2006; Alexander *et al*., 2017). Elemental compositions of the IOM in the Murchison and Tagish Lake meteorites are given as $C_{100}H_{70}N_3O_{12}S_2$ and $C_{100}H_{46}N_{10}O_{15}S_{4.5}$ respectively (Pizzarello *et al*., 2006).

The IOM is typically in the form of complex, cross-linked macromolecules resembling types of terrestrial kerogens (Botta and Bada, 2002; Pizzarello *et al*., 2006; Alexander *et al*., 2017). See 'Kerogens as analogs for IOM', below, for more discussion of terrestrial kerogens. Sephton and Gilmour (2000) provide a summary of organic moieties which have been identified in the CM-type meteorite, Murchison, that include aromatic hydrocarbons, phenols, carboxylic acids among many others as well as O, S and N bearing moieties. These compounds are bound together into a larger structure by aliphatic linkages. Derenne and Robert (2010) proposed a model of the macromolecular structure of IOM in the Murchison CM-type carbonaceous chondrite.

In most studies, the IOM is separated from the mineral matrix of a meteorite by demineralization with acids (HCl, HNO, HF). Cody *et al*. (2002) modified the traditional method with the addition of fluorine-salts to overcome issues arising from the use of hydrofluoric acid. Smith and Kaplan, however, noticed that only ~45–80% of the C in bulk carbonaceous chondrites can be accounted for by the reported IOM, SOM, and carbonate abundances, the rest of which is lost during isolation of the IOM (Smith and Kaplan, 1970).

Alexander *et al*., provide a thorough review of studies done in determining the morphologies and distribution of IOM in meteorite matrices and also discuss those studies done *in situ* (Alexander *et al*., 2017). The IOM occurs, generally, in two forms: as sub-micrometric grains or flakes, often referred to as 'fluffy' (Garvie and Buseck, 2006), and as solid or hollow spherical, semi-spherical or tubular aggregates often referred to as nanoglobules. Nakamura *et al*. (2023) reported on the *in situ* occurrence of nanoglobules in the Tagish Lake meteorite. The fluffy material is typically amorphous and often found intimately associated with the abundant phyllosilicate minerals in the meteorite matrix. Short, vein-like structures have also been reported and may be the result of migration and subsequent modification of the pre-cursor organic material during the secondary, post-accretion phase in the asteroidal parent-body.

Kerogens as analogues for IOM

The IOM found in carbonaceous meteorites is often broadly compared with some terrestrial kerogens in terms of its insolubility in common solvents, its elemental composition and structure (Alexander *et al*., 2017). Terrestrial kerogens are defined as insoluble organic matter formed from the remains of algae,

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zoo- and phytoplankton, and/or vascular plants, usually found in sedimentary rocks in petroliferous basins (Curiale, 1986; Vandenbroucke and Largeau, 2007). The organic material in sedimentary rocks undergoes progressive alteration with increasing depth of burial. Initially, bacterial activity and low-temperature chemical reactions occur during diagenesis. Increasing temperature during catagenesis and later metagenesis produces a continuum of thermal maturation (Sanei, 2020). Thermal maturation leads to the production of a variety of substances including coal, bitumens (asphalt), oil and methane. Bitumens have also been proposed as analogues of cometary and asteroidal organic compounds (Moroz *et al*., 1998). In *The Origins of Petroleum,* Walters (2007) provides a review of the history and classification of kerogens. Tarafdar and Sinha (Tarafdar and Sinh, 2019) also review the formation of coal as well as hydrocarbons derived from kerogens.

Along the continuum of thermal maturation, characteristic changes occur. Behar and Vandenbroucke (1987) produced structural models showing the progressive alteration of kerogens during their maturation. Kerogens become increasingly aromatic while bitumens become more aliphatic in character (Craddock *et al*., 2015). There are also characteristic variations in the ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C). Van Krevelen (1961) used these elemental ratios to classify coal, but this method is now widely used in classifying kerogens and their products. Such plots are typically referred to as van Krevelen diagrams. Four kerogen types are recognized: Type I, generated from algal and bacterial remains (algal kerogens); Type II, generated from zoo- and phytoplankton (planktonic kerogens); Type III, from vascular plants (humic kerogens) and Type IV (residual kerogens). Types I and II often occur in shales. Type III kerogens commonly occur as varieties of coal which can, on occasion, be interlayered with Type I and II bearing shales. Type 4 kerogens are often found as degraded surface deposits associated with coal (Vandenbrouke, 2003; Walters, 2007; Ławniczak *et al*., 2020) (Fig. 1).

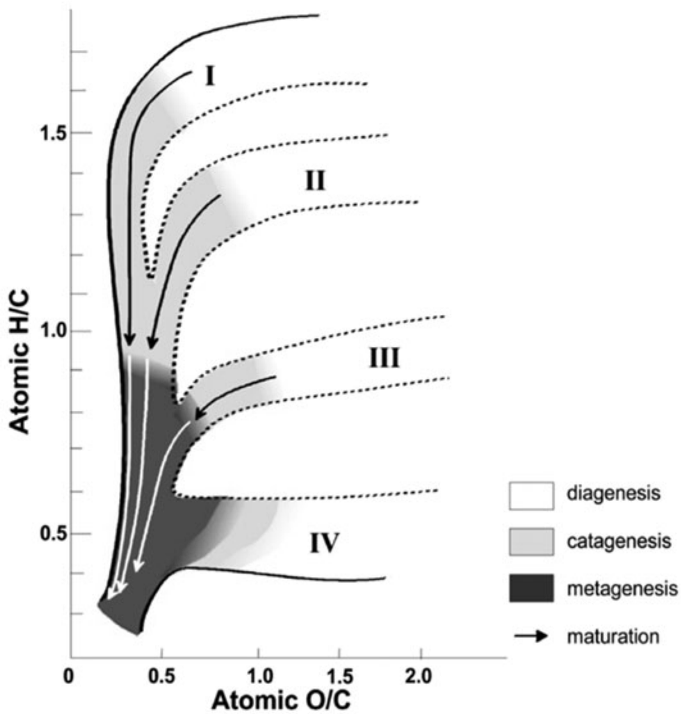

Figure 1. *van Krevelen type diagram showing the categorization of kerogen types based on their H/C and O/C atomic ratios (modified from Walters, 2007).*

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The major elements in the composition of both IOM and terrestrial kerogens are C, H, O, N and S. The elemental compositions of the IOM in the Murchison and Tagish Lake meteorites are $C_{100}H_{70}N_3O_{12}S_2$ and $C_{100}H_{46}N_{10}O_{15}S_{4.5}$, respectively (Pizzarello *et al.*, 2006). From these general formulae the H/C are 0.7 (Murchison) and 0.46 (Tagish Lake). The O/C ratios are 0.12 and 0.15, respectively. Naraoka *et al.* (2004) report H/C values of IOM extracted from 9 CM-type meteorites ranging from 0.11–0.72 (Table 1). The H/C and O/C of most terrestrial kerogens are notably higher, but some types are similar to those of Murchison and Tagish Lake, falling within the range of type 3 and type 4 kerogens (Behar and Vandenbrouke, 1987; Pathak *et al.*, 2017) (Fig. 2).

Despite the abundance of C-complex asteroids, carbonaceous meteorites are rather rare in collections on Earth. Of the approximately 27 000 known meteorites on Earth, only about 5% are carbonaceous chondrites, or approximately 1350 specimens. Of this number, approximately 733 specimens are of the CI, CM and C-ungrouped types of greatest interest. Of these, 633 are CM-type. Most are significantly under 1 km in weight (Simkus *et al.*, 2019). The sample sizes used by Naraoka *et al.* (2004) ranged from 0.5–1 g. Obtaining significant amounts of appropriate meteorite samples is possible but entails considerable cost. Therefore, future studies on the conversion of asteroidal matter into food should initially involve experimentation with selected kerogens instead, which will provide a more cost-effective alternative.

Table 1. *The organic components in the least metamorphosed carbonaceous chondrites: CI (Ivuna-like), CM (Mighei-like), CR (Renazzo-like), and Tagish Lake*

	CI	CM	CR	Tag. Lake
Matrix (vol.%)	100	~50	~30	~80
Bulk C (wt.%)[a]	3.7	2.0	1.2	4.1
C in IOM (wt.%)[b]	2.1	0.96	0.48	1.8
Amino acids	0.1–6.9[c]	<0.1–71[d]	~1–320[e]	<0.1–5.4[f]
Aromatic hydrocarbons		3[d]	16[g]	≥1[h]
Aliphatic hydrocarbons		>35		5_j
Monocarboxylic acids		~100–700[i]	26–90[g]	40.0[h]
Hydroxy- and dicarboxylic acids		14–15	212[g]	17.5[h]
Purines and pyrimidines		1.3		
Basic N-heterocycles		7		
Amines	14[j]	5–7[j]	103[g]	<0.1[h]
Alcohols		11		
Aldehydes and ketones		27		
Sulphonic acids		68		≥20[h]
Phosphonic acids		2		
Polyols		>8[k]		

Empty fields indicate unavailable data. Concentrations are based on chromatographic peak intensities and include compounds identified by reference standards and mass spectra. The CM data are from Murchison CM2 meteorite (updated from Botta and Bada (2002)), unless otherwise noted. The abundances are in μg/g (ppm), except where indicated. Table is adapted and modified from Alexander *et al.* (2017).

[a]Averages from Alexander *et al.* (2012).

[b]Averages for recovered IOM from Alexander *et al.* (2007; 2014).

[c]Range of the abundances in Orgueil and Ivuna (Ehrenfreund *et al.*, 2001; Burton *et al.*, 2014a).

[d]Range of abundances in Y-791198 (Naraoka *et al.*, 1988; Shimoyama and Ogasawara, 2002; Glavin *et al.*, 2010; Burton *et al.*, 2014b).

[e]Range of abundances in EET 92042, GRA 95229, and GRO 95577 (Martins *et al.*, 2007; Glavin *et al.*, 2010).

[f]Range for different lithologies of Tagish Lake (Glavin *et al.*, 2012; Hilts *et al.*, 2014).

[g]Abundances in GRA 95229 (Pizzarello *et al.*, 2008; 2012).

[h]SOM from Tagish Lake Pizzarello *et al.* (2001).

[i]Range of abundances (Yuen and Kvenvolden, 1973; Huang *et al.*, 2004).

[j]From Aponte *et al.* (2014; 2015).

[k]Lower limit for glyceric acid in Murchison (Cooper *et al.*, 2001).

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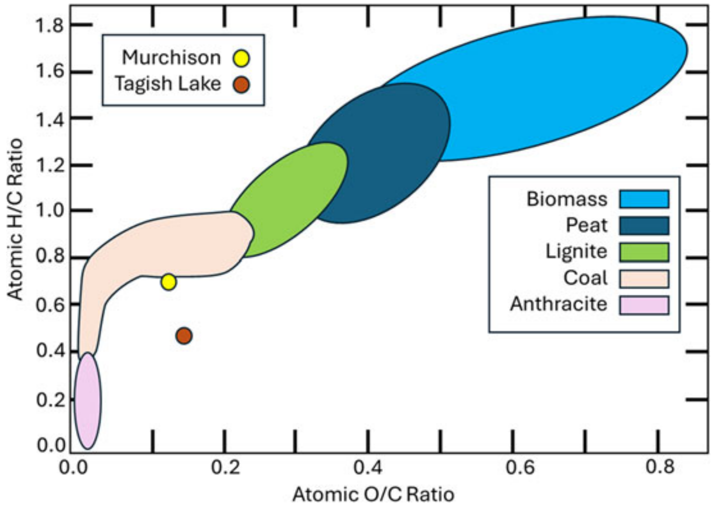

Figure 2. *van Krevelen coalification diagram comparing H/C and O/C ratios differences among coals and biomass (Jenkins* et al.*, 1998) compared to the elemental compositions of the IOM in the Murchison and Tagish Lake meteorites (Pizzarello* et al.*, 2006).*

Asteroids containing organic compounds

Reflectance spectra studies have proposed a strong link between the CI, CM and certain C-ungrouped meteorites and the C-complex of asteroids (Vilas and Gaffey, 1989). Although not distributed uniformly within the asteroid belt, the C-complex asteroids are the most numerous (DeMeo *et al*., 2015). A connection has also been proposed between the Ch-class asteroids – a subset of the C-complex defined by Bus and Binzel (2002) – and CM-type (Rivkin *et al*., 2015). Estimates of the number of Ch-type asteroids in the population of near-Earth objects (NEOs), with diameters greater than 1-km, are 53 ± 27. If no minimum size constraints are applied, these numbers rise to 700 ± 350 (Rivkin and DeMeo, 2019). The recent success of two sample return missions – OSIRIS-REx (NASA) and Hyabusa2 (JAXA) – to the NEO asteroids 101955 Bennu and 162173 Ryugu demonstrate that, although technically demanding, it is possible to access such asteroids (Lauretta *et al*., 2017; Nakamura *et al*., 2023; Potiszil *et al*., 2023).

To illustrate the potential of the approach outlined in this article, theoretical production values are calculated below based on the asteroid 101955 Bennu. Bennu has been chosen since it is the target asteroid for the OSIRIS-REx sample return mission (Lauretta *et al*., 2017). Asteroid Bennu is about 500 m in diameter, which is small for an asteroid (Peña *et al*., 2020). Bennu is an excellent candidate for comparison for four reasons: (1) it is has spectral features consistent with a carbon-rich (presumably carbonaceous chondrite meteorite-like) composition (Simon *et al*., 2020; Ferrone *et al*., 2021; Kaplan *et al*., 2021), (2) it is a near-earth asteroid meaning that it is feasible to reach and return from the asteroid (as proven by the OSIRIS-REx and Hayabusa2 missions), (3) its mass is very well understood after nearly 2 years of study during the mission (77.6 million metric tons), and (4) studies are underway to determine the asteroid's composition. Thus, the potential of Bennu will be analysed as a human food source. To estimate the amount of usable organic material which may be within asteroid Bennu, values from the extensively studied Murchison CM-type meteorite will be used as a proxy. Dozens of studies have explored the organic compound composition of these samples (Studier *et al*., 1972; Cronin and Pizzarello, 1990; Callahan *et al*., 2011; Botta and Bada, 2002; Oba *et al*., 2022).

Microbial assimilation of kerogens and related organic compounds

Since the majority of organic compounds in carbonaceous meteorites, and presumably their asteroidal parent-bodies, are insoluble, work in the field of microbially mediated coal-bed methane (CBM)

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production is of particular interest for this proposal. Wang *et al*. (2019) studied the effects of microbial activity in the generation of CBM from a Chinese coal deposit, showing that significant quantities of biomethane were produced. A detailed study by Vick *et al*. (2019) on the microbial assimilation of coal identifies several of the principal phyla involved and also explores the optimization conditions for enhanced production. Reviews of work in the biogeneration of CBM are also provided by Ritter *et al*. (2015) and Colosimo *et al*. (2016). Gao *et al*. (2011) studied the effects of bacterial consortia to act on leonardite, a type 4 kerogen, in the production of humic acid for biofertilizers. There are also intriguing recent studies of direct bacterial assimilation of carbonaceous chondrite material. In 2022, Waajen *et al*., found that naturally occurring bacterial consortia could metabolize carbon from the Cold Bokkeveld CM-type carbonaceous chondrite. In 2024, Waajen *et al*., used a sample of the Aquas Zarcas CM-type carbonaceous chondrite and found that bacterial consortia could use the meteoritic material exclusively as a source of carbon as well as energy and nutrients. In both studies, bacteria were able to directly transfer meteoritic carbon into biomass. The 2022 study explored the possibilities of carbonaceous meteoritic material supporting early life on Earth. The 2024 study also explores this as well as suggesting the possible use of bacteria in processing asteroids for future human activities.

Methods

Byrne *et al*. (2022) demonstrated the ability of pyrolysis to produce microbially biodegradable intermediate compounds from high-density polyethylene (HDPE). Pyrolysis uses high temperatures to break down plastics into lower-molecular-weight hydrocarbons (Gracida-Alvarez *et al*., 2018). These lower-carbon length hydrocarbons are more easily degraded by microorganisms, particularly for carbon lengths on the order of C10 – C40 (Ji *et al*., 2013). The hydrocarbons produced by pyrolysis by Byrne *et al*. (2022) were analysed with gas chromatography/mass spectrometry (GC/MS) to quantify the residual compound concentrations of alkenes. In an ideal scenario, the pyrolysis results would be compared to the organic compounds available in high carbon carbonaceous meteorites to determine if the asteroid compounds contain the same potentially human edible biomass identified by Byrne *et al*. (2022).

In the Murchison meteorite ~70% of the organic compounds comprise IOM. Studies of the precise breakdown of this IOM, in terms of specific compounds and quantities, are severely limited. Therefore, it is impossible to accurately determine what proportion of organic material in meteorites matches the types of compounds that can be converted into food, such as the low-C chain aliphatic hydrocarbons identified by Byrne *et al*. (2022). Instead, the calculations in this study will use the abundance of aliphatic hydrocarbons in the Murchison meteorite (>35 ppm, Table 1) as a baseline for the calculations, representing the *minimum amount of organic matter that could theoretically be attributed to protein production.* This minimum value assumes that only the aliphatic hydrocarbons present in asteroids will be effectively converted into biomass. *C*alculations for the total C in IOM represent the *maximum amount of organic matter that could theoretically be attributed to food production*. This is a pure theoretical exercise considering the lack of scientific literature on this topic. The maximum value assumes that all IOM is capable of being effectively converted into biomass. Together, these two values will provide a range of realistic yields to determine how much food could theoretically be extractable from an asteroid. To determine how many grams of biomass could be produced from this organic matter, the mass balance calculations from Byrne *et al*. (2022) are used.

The following calculations determine the biomass extractable from an asteroid (b) given the initial mass of the asteroid (m_a), the proportion of organic material (O) of the asteroid (From Table 1, adapted from Alexander *et al*. (2017)), and the proportion of organic compounds that are in the pyrolysis list in Byrne *et al*. (2022) that can be converted into proteins. In the minimum scenario, $O = 0.0035$ to represent the concentration of aliphatic hydrocarbons in the Murchison meteorite (>35 ppm, Table 1), and in the maximum scenario $O = 0.096$ to represent the concentration of IOM in the Murchison meteorite (0.96 wt %, Table 1).

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First, the mass of organic material present in asteroid (m_o) is given by:

$$m_o \text{ (grams)} = m_a \text{ (grams)} \times O \text{ (unitless)} \tag{1}$$

Next, the proportion of mass extractable for food production from asteroid (e) is:

$$e \text{ (unitless)} = \frac{m_p \text{ (grams)}}{m_i \text{ (grams)}} \tag{2}$$

where, m_p is the mass attributed to protein production (Table 1, Byrne *et al.* (2022)) (grams) and m_i is the initial mass of pyrolysis product (Table 1, Byrne *et al.* (2022)) (grams).

Finally, the biomass extractable from asteroid (b) is thus:

$$b \text{ (grams)} = m_o \text{ (grams)} \times e \text{ (unitless)} \times k \text{ (unitless)} \times 0.008 \tag{3}$$

where k is the conversion constant, which is currently 0.2 because the conversion efficiency from plastic to biomass is approximately 20% (Byrne *et al.*, 2022). At present, it is unclear if the conversion efficiency for organic material in asteroids would be similar to that for plastics. For the purposes of this mathematical exercise the assumption is that the conversion efficiency will be the same, however, this may have to be corrected in future studies after testing.

However, this calculation alone would be an oversimplification because of the inefficiencies of extracting resources from a planetary body via in-situ resource utilization (ISRU). Most ISRU technologies have primarily focused on the extraction of oxygen for life support and propellant production (e.g., Taylor and Carrier, 1992; Bennett *et al.*, 2020; Schlüter and Cowley, 2020; Linne *et al.*, 2021; Guerrero-Gonzalez and Zabel, 2023) so there are not good estimates for what the efficiency of an ISRU technology for extracting organic material from an asteroid would be. One potential analogue for these calculations is the method of bioleaching to extract rare earth elements (REE) from rock. Rasoulnia *et al.* (2021) conducted a critical review of the process and found that the total REE leaching efficiency varied significantly depending on the process parameters, from as low as 0.08% in bastnäsite-bearing rock (the mineral bastnäsite is the most abundant primary source of REEs (Wang *et al.*, 2017)) to 80% for extraction from the mineral zircon. Given these extreme uncertainties, the resultant value from equation (3) is multiplied again by 0.008 to simulate a low extraction efficiency similar to results from Zhang *et al.* (2018) in the extraction from bastnäsite-bearing rock.

Caloric intake requirements differ among astronauts due to size and other factors such as age, metabolism, and gender (Stemonstration Nutrition, NASA, https://www.nasa.gov/stem-content/stemonstrations-nutrition/). For these calculations, an average of 2500 calories (C) per day or 912 500 calories per year will be assumed. These calorie totals will be used for converting biomass yield to astronaut life-years. Plastics converted to biomass in the lab were analysed by Eurofins Food Chemistry Testing Madison, Inc to determine the calory-content of the biomass (c), as well as specific breakdowns of fat content, carbohydrates, fibre and protein[1].

The results of this analysis show that 100 g of biomass contains a total of 442 calories (c), 137 of which were from fat. The breakdown is as follows:

- 15.2% fat by acid hydrolysis
- 44.4% total carbohydrates
- 35.9% total dietary fiber
- 31.9% protein ($N \times 6.25$) Dumas method
- 7.07% ash
- 1.35% moisture by M100_T100

[1] https://www.eurofinsus.com/food-testing/services/testing-services/nutrition-analysis/

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The total calories (C) produced from the biomass extractable from an asteroid (b), given the calories per 100 g of converted biomass determined by Eurofins food analysis (c) is:

$$C\ (\text{calories}) = \left(\frac{c\ (\text{calories})}{100\ \text{grams}}\right) \times\ b\ (\text{grams}) \tag{4}$$

The number of astronaut-life years (y) that the biomass extractable from an asteroid (b) could support considering a recommended diet consisting of 2500 calories per day or 912 500 calories per year is:

$$y\ (\text{years}) = \frac{C\ (\text{calories})}{912,500\ \text{cal/year}} \tag{5}$$

The first set of calculations will determine what mass of edible biomass *(b)* can be obtained if asteroid Bennu were completely broken down. The mass of asteroid Bennu is $7.329 \pm 0.009\ \times 10^{10}$ kg, or $7.329\ \times 10^{13}$ g (Scheeres *et al*., 2019).

Finally, equation (3) can be solved to determine the initial asteroid mass (m_a) required to produce a specific amount of human edible biomass. In equation (6), O is the proportion of organic material in asteroid (0.0035 [min] and 0.096 [max]; (Alexander *et al*., 2017)), and e is the proportion of mass extractable for protein from asteroid (equation (2)).

$$m_a\ (\text{grams}) = \frac{b\ (\text{grams})}{(O\ (\text{unitless}) \times\ e\ (\text{unitless}) \times\ k\ (\text{unitless})\ \times\ 0.008)} \tag{6}$$

Results

Mass of edible biomass extractable from asteroid Bennu

Following equation (1) the *minimum* estimate of m_o is 2.565×10^{11} g and the maximum estimate is 7.036×10^{12} g, which is roughly a factor of three. Next, equation (2) is used to determine what proportion of mass is extractable for food production *(x)*. To do this, assumptions are made using experimental results from Byrne *et al*. (2022) of pyrolysis of different organic materials. Specifically, then if pyrolysis breakdown products were able to be converted to biomass using the consortia that equivalent chemicals found on asteroids could also be converted to biomass with the same nutritional content as the pyrolyzed products. Using results from equations (1) and (2), the mass of edible biomass extractable from Bennu is determined (b). The results are summarized in Table 2, calculated in grams. If only the aliphatic hydrocarbons can be converted into biomass (*minimum scenario,* $O = 0.0035$) the resulting mass of edible biomass extractable from asteroid Bennu ranges from 5.070×10^7 g to 2.390×10^8 g. If the biomass extraction process is more efficient, and all IOM is converted into edible biomass (*maximum scenario,* $O = 0.096$), then the mass of edible biomass extractable from asteroid Bennu ranges from 1.391×10^9 g to 6.556×10^9 g. These ranges of values are due to differences in calculations from Byrne *et al*. (2022) to determine what mass is attributed to food production.

Total astronaut life-years sustainable

Based on the food analysis by Eurofins, the total calories extractable from asteroid Bennu is calculated (equation (4)). From this, equation (5) is used to calculate the minimum and maximum amount of time in years this could sustain an astronaut for, assuming NASA's standard diet of 2500 calories per day is maintained. The average results for the minimum scenario (only aliphatic hydrocarbons are converted into biomass) is over 631 astronaut life years, and the average results for the maximum scenario (all IOM are converted into biomass) is over 17 000 astronaut life years (Table 3).

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Table 2. *Calculations of the proportion of mass that is extractable for food production (*x*, equation (2)) and the minimum / maximum expected biomass that is extractable from asteroid Bennu (*b*, equation (3))*

	Initial mass of pyrolysis product	Mass attributed to protein production	Proportion of mass extractable for protein	Mass of edible biomass from Bennu (min)	Mass of edible biomass from Bennu (max)
Equation			2	3	3
Units	g	g	proportion	g	g
Variable			x	b_{min}	b_{max}
Inoculum group					
Farm compost	0.17	0.021	0.12	5.070×10^7	1.391×10^9
Bete Grise sediment	0.17	0.023	0.14	5.553×10^7	1.523×10^9
Spurr River sediment	0.17	0.043	0.25	1.038×10^8	2.847×10^9
Mackinac mud	0.17	0.054	0.32	1.304×10^8	3.576×10^9
Fall Run stream sediment	0.17	0.084	0.49	2.028×10^8	5.562×10^9
Caspian Sea sediment	0.17	0.099	0.58	2.390×10^8	6.556×10^9
		Average	**0.32**	$\mathbf{1.304 \times 10^8}$	**3.576** $\times 10^9$

Mass Balances for the pyrolysis products are from Byrne *et al.* (2022).

In addition to these calculations that are specific to the mass of asteroid Bennu, estimates can be made using the same equations to determine the asteroid mass (m_a) required to sustain an astronaut for a single year (assuming an annual diet consisting of 912 500 calories). The results are 206 448 g of biomass is required to sustain an astronaut for one year to obtain the required 2500 calories per day.

On average, to feed an astronaut for one year would require over 160 million grams of asteroid (> 160 000 metric tons) in the minimum-efficiency scenario or over 5 million grams of asteroid (> 5000 metric tons) in the maximum-efficiency scenario (Table 3). For reference, the mass of asteroid Bennu is 77.6 million metric tons.

Discussion

The values obtained for the amount of asteroid mass that need to be processed to provide food for a single astronaut are large, but if human exploration of the solar system is to be done, it provides a potential path to doing so. Based on the results of this study, this approach appears promising but there are substantial areas of future work. First, the plastics recycling to food projects currently sponsored by DARPA have a number of ways to target human edible biomass (DARPA Cornucopia programme, https://www.darpa.mil/program/cornucopia) that can be leveraged for applying the same basic mechanisms to space. To get useful (human diet) relevant biomass outputs a scalable open source bioreactor has been developed (Hafting *et al.*, 2023) and is being used to produce biomass that is being tested for chemical toxicity using an open source toolchain (Pham *et al.*, 2022). The next state of that work is to do animal trials to obtain U.S. Food and Drug Administration (FDA) Generally Recognized As Safe (GRAS) status under sections 201(s) and 409 of the Federal Food, Drug, and Cosmetic Act (the Act), (https://www.fda.gov/food/food-ingredients-packaging/generally-recognized-safe-gras) and then human trials.

Meteorites, particularly the carbonaceous type, are a precious and often limited resource. Fortunately, reasonable terrestrial analogues of meteoritic organic compounds (kerogens) are readily available. Future work on this topic could focus on these terrestrial analogues to develop effective

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Table 3. *Calculations of the total astronaut life years (min / max) sustainable based on the calories extractable from Bennu (C), assuming 100 g of edible biomass contains 442 calories (Eurofins analysis, c)*

	Total calories (C) from Bennu (min)	Total calories (C) from Bennu (max)	Total astronaut life years (min)	Total astronaut life years (max)	Asteroid mass required to sustain an astronaut for 1 year (min)	Asteroid mass required to sustain an astronaut for 1 year (max)
Equation	4	4	5	5	6	6
Units	calories	calories	years	years	g	g
Variable	C	C	y	y	m_a	m_a
Inoculum group						
Farm compost	2.241×10^8	6.147×10^9	246	6736	2.984×10^{11}	1.088×10^{10}
Bete Grise sediment	2.454×10^8	6.732×10^9	269	7377	2.725×10^{11}	9.934×10^9
Spurr River sediment	4.589×10^8	1.259×10^{10}	503	13 793	1.457×10^{11}	5.314×10^9
Mackinac mud	5.762×10^8	1.581×10^{10}	631	17 321	1.161×10^{11}	4.231×10^9
Fall Run stream sediment	8.964×10^8	2.459×10^{10}	982	26 944	7.461×10^{10}	2.720×10^9
Caspian Sea sediment	1.056×10^9	2.898×10^{10}	1158	31 755	6.330×10^{10}	2.308×10^9
Average	$\mathbf{5.762 \times 10^8}$	$\mathbf{1.581 \times 10^{10}}$	**631**	**17 321**	**161 773 882 912**	**5 898 006 148**

and efficient techniques and procedures, before moving on to actual meteorite samples. Thus, in parallel, the identical microbial consortia can be tested on terrestrial kerogens. To make space exploration more cost-effective, there is a reasonable possibility that essentials such as food and water could be produced from resources existing in certain C-class asteroids using ISRU technologies. The extracted water could also potentially be a source of oxygen (for breathing) and fuel (e.g., Taylor and Carrier, 1992; Bennett *et al*., 2020; Schlüter and Cowley, 2020; Linne *et al*., 2021; Guerrero-Gonzalez and Zabel, 2023). This study focuses only on the production of edible biomass. The essential idea of Byrne *et al*. (2022) to turn initially inedible precursors – post-consumer waste plastic – into edible biomass via microbial assimilation in bioreactors is the basis of this approach. In place of plastics, terrestrial kerogens can be used as the initial carbon source for future studies. Kerogens with H/C ratios in the same range as IOM will be selected. Considerable experimentation will be required to develop the techniques to achieve this, which will require the use of considerable amounts of study material. Fortunately, some types of abundant terrestrial kerogens could provide reasonable analogues of IOM.

Future studies will initially use terrestrial kerogens, however, a fundamental guiding principle is to design processes that mimic an extraterrestrial installation that relies on resources found in space. The use of acidic demineralization to extract IOM is unfeasible since it would involve regularly transporting enormous quantities of highly reactive chemicals as well as the disposal of the spent acids. The aim is to ensure that the only heavy-lift requirements in the initial stages of the development of an asteroidal base would be the processing equipment. Other inputs would be certain dry chemicals necessary to provide essential electrolytes for the bacterial innocula.

Future work

Potential theoretical stages are:

- Review the ethical issues of asteroid mining.
- Assess how to collect asteroids and bring them to the desired space settlement for processing.
- Compare the theoretical efficiency of this process to recycling and upcycling space settlement's waste.
- Assess what other materials would be formed from the complete breakdown of an asteroid, and how these materials may be used.

Potential experimental stages are:

- Initial selection of kerogen samples and characterization
- Sample preparation (Vick *et al*., 2019)
- Bioreactor design and construction (Hafting *et al*., 2023)
- Innocula selection (Byrne *et al*., 2022; Schaerer *et al*., 2022)
- Periodic assessment of innocula activity via headspace gas production
- Determination of optimal or peak reaction periods
- Separation of innocula from reactants
- Testing of resultant biomass for potential toxins (Breuer *et al*., 2021)
- Assessment of resultant biomass and protein yields
- Testing nutritional value of resultant biomass and development of feasible balanced diets (Pham *et al*., 2022)

Concurrent potential experimental stages will be:

- Distillation and purification of water from phyllosilicate minerals
- Testing any pyrolytic effects of distillation temperatures on the kerogen samples (i.e., would distillation significantly alter the kerogen composition affecting bacterial assimilation)
- Sample preparation of actual carbonaceous meteorite samples (5–10 g maximum) to test dry mineral separation techniques (e.g., magnetic separation to remove magnetic oxides and possibly some sulphides) to produce a phyllosilicate/IOM concentrate.

The ability of bacteria to assimilate a wide range of naturally occurring terrestrial organic compounds provides a reasonable basis to investigate if the same is true for extraterrestrial organics. If possible, then the ultimate aim of producing food from existing resources found throughout the solar system is achievable, using the approach of Byrne *et al.* (2022) and going beyond synthesis from carbon dioxide (Alvarado *et al.*, 2021; Martínez *et al.*, 2021a). This work also has larger implications on Earth. It may provide alternative means to produce edible biomass from inedible precursors and support current activities in this area of research on alternative foods (Baum *et al.*, 2015; Martínez *et al.*, 2021b; 2021c) or resilient foods (Schipanski *et al.*, 2016; Gracida-Alvarez *et al.*, 2018; Linder, 2019). This opens up new potentially economic pathways for supplying basic nutrients during times of great distress such as famines or other natural or human-created disasters that cripple normal food supplies (Denkenberger and Pearce, 2014, 2015, 2016; Denkenberger *et al.*, 2017).

In addition to the testing of terrestrial kerogens, various analyses and trials will be conducted on the biomass to further this research, such as:

- Toxins analysis on biomass;
- Animal studies on biomass;
- Human trials on biomass;
- Then test bioreactor project with real asteroids and repeat toxin, animal and human trials;
- Test bioreactor in space with asteroid material;
- Develop solar-powered asteroid crusher.

Conclusions

After comparing the experimental pyrolysis breakdown products, which were able to be converted to biomass using a consortia, it was hypothesized that equivalent chemicals found on asteroids could also be converted to biomass with the same nutritional content as the pyrolyzed products. The results of this study found that if only the aliphatic hydrocarbons can be converted into biomass (minimum scenario) the resulting mass of edible biomass extractable from asteroid Bennu ranges from 5.070×10^7 g to 2.390×10^8 g. If the biomass extraction process, however, is more efficient, and all IOM is converted into edible biomass (maximum scenario), then the mass of edible biomass extractable from asteroid Bennu ranges from 1.391×10^9 g to 6.556×10^9 g. This would provide between 5.762×10^8 and 1.581×10^{10} calories that is enough to support between 600 and 17 000 astronaut life years. The asteroid mass needed to support one astronaut for one year is between 160 000 metric tons and 5000 metric tons. Based on these results, this approach of using carbon in asteroids to provide a distributed food source for humans exploring the solar system appears promising, but there are substantial areas of future work required.

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