Design of Anaerobic Digestion Systems for Closed Loop Space Biomanufacturing

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Space biomanufacturing has the potential to substantially reduce the launch mass of long-duration manned missions. Active research areas include enhancing methane conversion to polyhydroxybutyrate by methanotrophs to enable 3D-printed mission tools. Because anaerobically digesting mission wastes can recycle essential carbon, this process can provide necessary biomanufacturing feedstocks like methane. Thus, this paper analyzes the costs and benefits of adding anaerobic digestion to aid space biomanufacturing. First, stoichiometry determines theoretical yield from inedible food biomass (e.g., the straw and husk of rice) and human waste. Thereafter, this work examines how digester design and operating conditions, including operating temperature, solid loading density, digestion duration, and pretreatment impact methane yield. This paper also studies numerous combinations of possible wastes. The work assesses impact through a systems engineering analysis that optimizes performance and specifications of this two-step process via the Equivalent System Mass (ESM) metric. ESM augments traditional shipped mass costs with those of pressurized volume, demanded power and thermal control, and needed crew time. This analysis helps quantify the extent of loop closure for space biomanufacturing and its trade-off with ESM, and finds that it is possible to close as much as one third of the loop. This paper also incorporates a parametric sensitivity analysis to highlight the positive impact that mission horizon increase has on anaerobic digestion viability.

Nomenclature

ALSSAT = Advanced Life Support Sizing Analysis Tool
C = thermal control demand
C_{eq} = mass-equivalence factor for thermal control
CT = daily time of crew operation
CT_{eq} = mass-equivalence factor for crew time
CUBES = Center for the Utilization of Biological Engineering in Space

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D = days of crew operation
ESA = European Space Agency
ESM = Equivalent System Mass
ISS = International Space Station
M = mass of shipment
MELiSSA = Micro-Ecological Life Support System Alternative
NASA = National Aeronautics and Space Administration
P = power demand
P_{eq} = mass-equivalence factor for power
PHB = polyhydroxybutyrate
S = startup energy demand for bioprocesses
S_{eq} = mass-equivalence factor for startup energy for bioprocesses
TMY = Theoretical Methane Yield
V = pressurized volume of shipment
V_{eq} = mass-equivalence factor for volume

I. Introduction

SPACE biomanufacturing is a viable approach to reducing mission cost[1-5] by supplementing physicochemical *in situ* resource utilization (ISRU) with biochemical ISRU. To this end, easily-accessible mission wastes that are rich in essential elements like carbon and nitrogen can augment available on-site resources. Recycling these essential elements reduces the demand for external resources, but the conversion of waste to value-added product can warrant additional logistics and shipped infrastructure. Longer duration missions that produce a large amount of inedible biomass from crop cultivation may find that waste recycling substantially reduces mission costs while still allowing for mission completion. On the other hand, shorter missions may not benefit from recycling because of relatively lower Earth shipment costs. Hence, a systematic analysis of trade-offs will ascertain the benefits of mission waste recycling, now for biomanufacturing missions, by assessing the extent of loop closure and associated expenditures.

Waste management in space encompasses various treatments and decisions that need comprehensive analysis[6]. We focus on anaerobic digestion of inedible plant matter and human waste to yield methane. Methane is unavailable at most space mission destinations, but it is a byproduct of anaerobic waste digestion[7-9]. Methane can be a feedstock to biomanufacture the polymer polyhydroxybutyrate (PHB), Figure 1(a), which can then serve as a filament in a 3D-printer to produce desired mission tools[4]. For this two-step process of anaerobic digestion and polymer production, we consider variations in process operating conditions, Figure 1(b), to minimize the mission cost per unit of polymer.

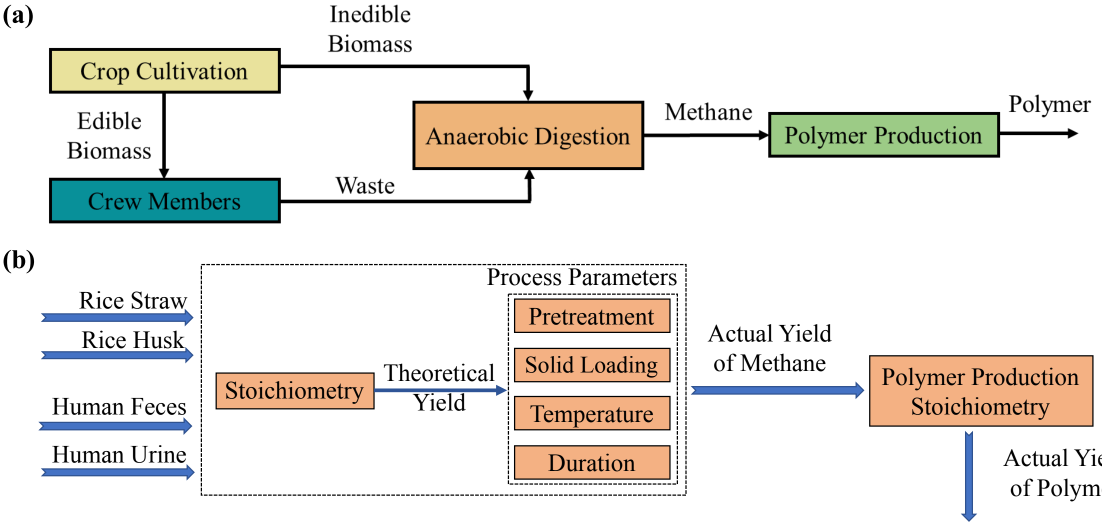


Figure 1: Paper overview. (a) Block diagram that shows how anaerobically digesting mission wastes can provide methane as a resource for polymer biomanufacturing. (b) The technical approach that is used to compute polymer yield.

To assess mission cost, we use the Equivalent Systems Mass (ESM) metric[10]. Studies exist[11-13] that use ESM to analyze the life support system provisions (air, water, biomass, and waste) for different missions. ESM is a weighted sum of mass, volume, power, thermal, and crew time needs of a mission or mission component. ESM insulates cost-analyses from inflation, exchange rate, and other monetary factors. Although there are ESM-based studies on anaerobic digestion of mission waste[14,15], our assessment of the extent of loop closure in a space biomanufacturing process, in conjunction with process parameter optimization, is novel. Our intellectual contributions are:

1. Quantification, by ESM, of the benefit of anaerobic digestion in closing the loop for space biomanufacturing.
2. Process optimization of anaerobic digestion at various operating points to produce methane as a feedstock in the polymer production process.
3. Analysis of mission horizon effect on the trade-off between anaerobic digestion in space biomanufacturing and the shipping of polymeric tools.
4. A sensitivity analysis of the critical parameters that drive the ESM of anaerobic digestion performance.

The remainder of this paper is as follows. Section II summarizes relevant literature, presents reaction stoichiometry, and describes investigated scenarios. Section III details the ESM cost for various sets of mission wastes and operating parameters. It also covers a sensitivity analysis on critical parameter values. Section IV contextualizes our Section III results.

II. Background

A. Related Literature Studies

The literature on mission waste handling and processing is rich. The Advanced Life Support Sizing Analysis Tool (ALSSAT)[16] includes lyophilization, warm air drying, plastic melt waste compaction, and sequential batch anaerobic composting to recover water from waste. Ref. 6 presents possible mission strategies of waste disposal through an airlock into space as well as waste processing into gases for venting or propulsion. The Trash to Supply Gas (TtSG) project[17] investigated processing techniques like pyrolysis, gasification, incineration, steam reforming, ozone oxidation, and catalytic wet air oxidation. These thermochemical processes each have different operating conditions and product-mix, and feature in NASA's Advanced Exploration System (AES) Logistics Reduction and Repurposing (LRR) project[18]. Conversion of trash into compact and stable tiles via a heat melt compactor (HMC) is also a plausible option[19]. While these thermochemical processes are very efficient and well-established, they require high temperature (at least around 100°C), and some require high pressure. Accordingly, an alternate approach is to employ biochemical treatment technologies that operate at mild conditions. Hence, anaerobic digestion of mission waste to yield value-added products is a promising strategy.

Anaerobic digestion sequentially and biochemically converts waste to biogas in the absence of oxygen[7-9]. This biogas is a mixture of methane and carbon dioxide. The operating strategy can change the product-mix to include acetic acid and hydrogen, since methane production is a stepwise process with different intermediates. Different microorganisms act on the waste material at different stages of the digestion process[7]. Hydrolytic bacteria (such as *Bacillus*) hydrolyze the waste. Acidogenic bacteria like *Clostridium* produce volatile fatty acids from hydrolyzed solution. Many of the acidogens also act as acetogens, thereby producing the intermediate acetate and the byproduct hydrogen. Methanogenic bacteria take up the acetate and produce methane. The liquid digestate after biogas recovery is a potential source of nitrogen for plant growth[20-24].

Research on Earth-based anaerobic digestion of agricultural and municipal waste is also quite extensive[21-24], owing to useful end-products and mild operating conditions. The ADM1 model (ref. 21) reflects the performance of the major steps of the anaerobic digestion process in terms of the input sludge properties and operating conditions. For a space mission, differences in waste characteristics as well as in operating environment affect anaerobic digestion prospects. Literature studies[14,15,25] have optimized design strategies for application during surface missions. ESA's Micro Ecological Life Support System Alternative (MELiSSA)[26] focused on digester design and operating conditions to improve biogas yield.

The infrastructure and logistics of a digester system that produces polymer with methanotrophic bacteria[27] can be accounted for by ESM. ESM evaluates the relative performance of processes with different sets of operating parameters[10],

$$ESM = M + V_{eq} \times V + P_{eq} \times P + C_{eq} \times C + CT_{eq} \times D \times CT, \tag{1}$$

where pressurized volume (V), power (P), thermal control (C) by utilities, and crew time (at a daily rate of CT) over a mission horizon (D) augment physical shipped mass (M). Shipped infrastructure here involves an anaerobic digester, a polymer bioreactor, and a compactor only for high waste loading. The equivalence factors V_{eq}, P_{eq}, C_{eq}, and CT_{eq} in

(1) that convert inputs of V, P, C, and $D \times CT$ to mass units are not generic. Their values are functions of deployed technologies such as solar or nuclear power, and the specifications for a lunar or Martian, transit or surface mission. We consider nuclear power generation and thermal control by vertical flow-through radiators with silver Teflon coating, having equivalence factors P_{eq} and C_{eq} of 54 kg/kW and 145 kg/kW, respectively for a Mars surface mission[28]. We also add the impact of technology change in power generation and thermal control on ESM in a sensitivity analysis.

B. Reaction Stoichiometry

We consider inedible plant matter and human excreta as waste streams. To determine the quantity of available plant matter on a given day, we need the crop cultivation rate. To obtain this rate, we use the food demand for a six-member crew[28], with the assumption that 25% of the crew's food demand is met by rice to determine the cultivation rate of edible rice. We choose rice because the amount of rice straw and husk easily follow from their typical ratio, and because the fractions of cellulose, hemicellulose and lignin in the rice straw and husk are readily available[29]. The reaction stoichiometry for the conversion of cellulose and hemicellulose of inedible plant matter, represented generically as $C_nH_aO_b$, is[7]:

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4\ . \tag{2}$$

Lignin is not anaerobically digestible at nominal operating conditions[30].

We represent human waste, urine, and feces as $C_nH_aO_bN_c$, per ref. 31. The reaction stoichiometry is[32]:

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{7c}{4}\right) H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} - \frac{5c}{8}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) CH_4 + cNH_4{}^{+} + cHCO_3{}^{-}. \tag{3}$$

C. Scenario Descriptions

Our analysis optimizes four different operating parameters by studying the impact of their variations on anaerobic digestion process efficiency. Temperature, loading rate, digestion duration, and pretreatment chemical loading amount all affect methane yield[14,15,25]. Among the possible pretreatments, this paper considers NaOH alkaline pretreatment[32] for inedible plant biomass. For human waste, we do not include any pretreatment, and consider natural loading rates for feces alone, and feces with urine.

The literature does not include a complete response surface for methane yield for all four parameters, and so we consider only discrete parameter values instead of a continuous parametric range in our analysis. Table 1 presents the impact of these different operating parameters on anaerobic digestion, the level of their values in this paper, and their corresponding impact on methane yield, measured as a fraction of theoretical methane yield (TMY) from stoichiometry. Consequently, we can obtain methane yield quantity by multiplying the fractions in Table 1 with TMY. We choose different levels of these parameters to study trade-offs. For instance, yield is higher with higher temperature, which requires more input energy. We obtain changes in more than one parameter by multiplying their methane yield fractions to acquire the total impact on the methane yield.

We acknowledge that the methane fractions in Table 1 do not account for operational effects such as batch or continuous, single- or multi-stage, etc. For this paper, we assume a constant additional fractional effect of 0.855 scaling across all scenarios to account for these factors. We will explore scenario-specific operational effects in future work.

In addition to the four parameters of temperature, loading rate, digestion duration, and pretreatment chemical loading amount, a ratio called the carbon to nitrogen ratio (C/N) plays a critical role in determining the fraction of TMY that is attainable[8]. A high value of C/N leads to lower productivity owing to rapid consumption of nitrogen by bacteria, while a low value of C/N leads to ammonia accumulation that is toxic to methanogens[8]. Unlike the parameters in Table 1, we cannot control the C/N ratio because it is a function of waste or waste combination. Operating conditions also affect the level of C/N for a given waste stream. We use published ranges of C/N values and their effects on methane yield from plant and animal waste[24] to estimate C/N impact on TMY.

We consider a two-stage continuous digester. We assume that the volume of both stages is 20 L. We assume that the residence time in the first stage is three days. We take a six-member crew mission that lasts for 300 days, and we start waste collection after 100 days to account for rice that was cultivated and has matured since mission start. In our study, we assume that demand of polymer is 200 g/day for the last 200 days of the mission. We also assume that all methane from anaerobic digestion goes to meet this daily demand. Additionally, we assume that no methane is lost between digester collection and the feeding of the methanotrophic bacteria. We further assume that 20% of lignin content is accessible for anaerobic digestion at a higher loading of 300 g/L, which is achievable with the help of a compactor. We justify exploring such compactor usage despite knowing the optimal water content for anaerobic digestion on Earth because it may not be possible to attain this optimal water content level in space when water is siphoned off to provide crew oxygen. Finally, we assume that for the cases involving alkaline pretreatment, we recycle 50% of this pretreatment.

Table 1

Impact of Different Operating Parameters on Anaerobic Digestion

Parameter [units]*	**Effect on AD**	**Possible Values***	**Methane Yield* (Fraction of TMY)**
Temperature[24] [°C]	Changes the efficiency of the bacteria in the digester	25, 35, 45, 55	0.41, 0.60, 0.79, 0.84
Loading Rate[22] [g/L]	Changes how much waste material can be in the digester at a time	50, 300	0.85, 0.48
Duration[25] [days]	Changes how much time the microbes have to digest the waste material, varying the percent of theoretical yield	22, 26, 30	0.67, 0.79, 0.86
Pretreatment chemical amount[33] [% dry wt]	Breaks down waste material *a priori*, allows for a greater percent of theoretical yield to be collected	0, 4	0.57, 0.84

* References listed as superscript

We use these assumptions to study the digestion of different combination of wastes. We consider cases with uniform (or homogeneous) and non-uniform (or heterogeneous) loads. The two homogenous waste cases that we consider are rice straw and human feces. The two heterogeneous cases that we consider are rice straw combined with rice husk, and human feces combined with human urine.

For our food demand assumptions, we can compute the total available amount[28,29] of cellulose and hemicellulose in rice straw to be 356.5 g/day; for the rice straw and husk mixture, the corresponding amount is 426.4 g/day. With a 300 g/L loading achieved via a compactor, the digested amount of lignin is 35.7 g/day and 43.2 g/day for the homogenous and heterogenous rice waste, respectively.

The total amount of solids in feces is 192 g/day, and that in the urine-feces mixture is 612 g/day for six crew members[28]. Loading either waste combination into a digester not only increases the total amount of waste that is present in the digester, but also changes the C/N ratio, which then affects the methane yield.

Methanotrophs use this methane for their growth to produce PHB. The PHB production flux is half of the methane flux over a batch time of four days[27]. Since we consider continuously operating anaerobic digesters, we assume staggered operation of the polymer bioreactor. This helps to ensure a seamless and direct integration of the two key process steps, thereby eliminating extra waste storage.

We omit crew time ESM costs owing to a lack of such estimates for bioprocesses on a space mission, amending (1) accordingly. Instead, we replace these costs with that of startup energy. We take alkaline fuel cells to provide our initial startup energy (S) in a way that is similar to the literature[27], so that we attain operational temperature from an initial, assumed, starting temperature of 15°C. Hence, (4) now computes the ESM:

$$ESM = M + V_{eq} \times V + P_{eq} \times P + C_{eq} \times C + S_{eq} \times S, \tag{4}$$

where S_{eq} is the corresponding equivalence cost for startup energy. We assume that this startup energy is provided only once over a mission, because operation is continuous. We further assume that our downstream bioreactor with biopolymer-producing methanotrophs operates in batch mode, with every batch requiring some startup energy.

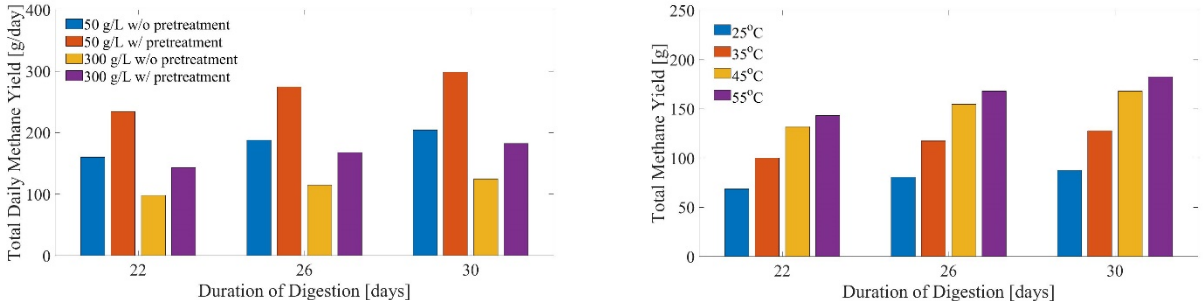
III. Results

On computing the polymer yield and ESM for the anaerobic digester and polymer-producing bioreactor, we compare the ESM cost per unit of polymer produced to determine the best scenario. Below, we compare scenarios with the cost of shipping the amount of polymer that the crew will need over the course of the mission, to determine the viability of using waste recycling in a space biomanufacturing plant.

A. Optimization of Operating Parameters

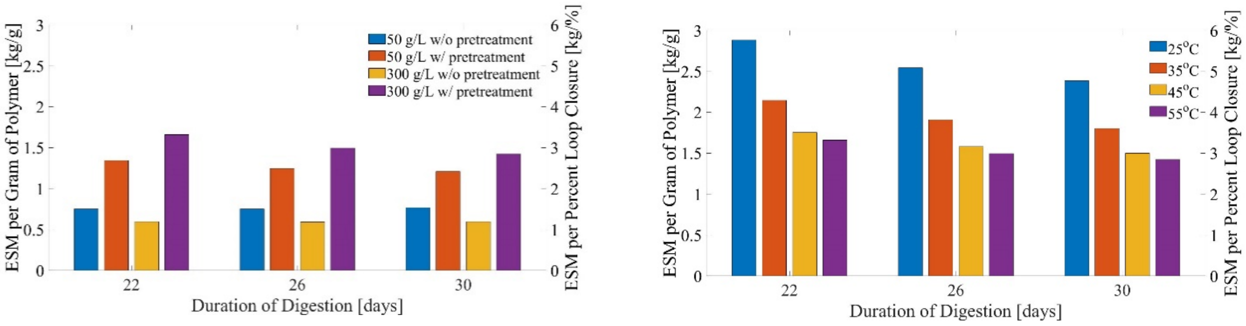
Figure 2 shows 24 cases of methane yield for a homogeneous load of rice straw. Figure 2(a) shows variations in the loading and pretreatment amount while the temperature is constant. Here, 300 g/L loading always yields less methane than 50 g/L loading. We see that 50 g/L loading with pretreatment and 30 digester days has the highest methane yield. Figure 2(b) shows temperature variation effect while the loading and pretreatment amount are constant. Here, operating at higher temperatures gives a higher methane yield, with 55°C giving the highest methane yield.

Figures 2(a) and 2(b) both show that performing anaerobic digestion for a full 30 days yields the maximum amount of methane. The maximum amount of methane in this case is 300 g/day of methane, which yields 150 g/day of polymer. If the mission requires 200 g/day of polymer, we are finding 75% loop closure for the case of maximum methane yield. However, we have not yet seen the cost of obtaining this extent of loop closure, as the cost to ship the amount of pretreatment and maintain that temperature and loading may be high. Next, we will look at the cost/polymer ratio, Figure 3, to determine which case is best.



(a) **(b)**

Figure 2: Methane yield of anaerobically digested rice straw over varying durations under different operating parameters. (a) Digestion fixed at 55°C. (b) Digestion fixed at 300 g/L loading with 4% NaOH pretreatment.



(a) **(b)**

Figure 3: ESM-polymer yield and ESM-percent loop closure ratios of anaerobically digested rice straw over varying durations under different operating parameters assuming 200 g/day polymer demand. (a) Digestion fixed at 55°C. (b) Digestion fixed at 300 g/L loading with 4% NaOH pretreatment.

Figure 3 shows the ESM-polymer yield and ESM-percent loop closure ratios of the same 24 cases from Figure 2. Figure 3(a) shows that the ESM-polymer disparity with and without pretreatment at 300 g/L loading is greater than the ESM-polymer disparity with and without pretreatment at 50 g/L loading. At 300 g/L, anaerobic digestion uses much more alkali solution, and the added cost of shipping the required amount of NaOH far outweighs the added methane from its presence. The ratio with NaOH pretreatment is 1.42, while without, the ratio is 0.59, a 42% decrease.

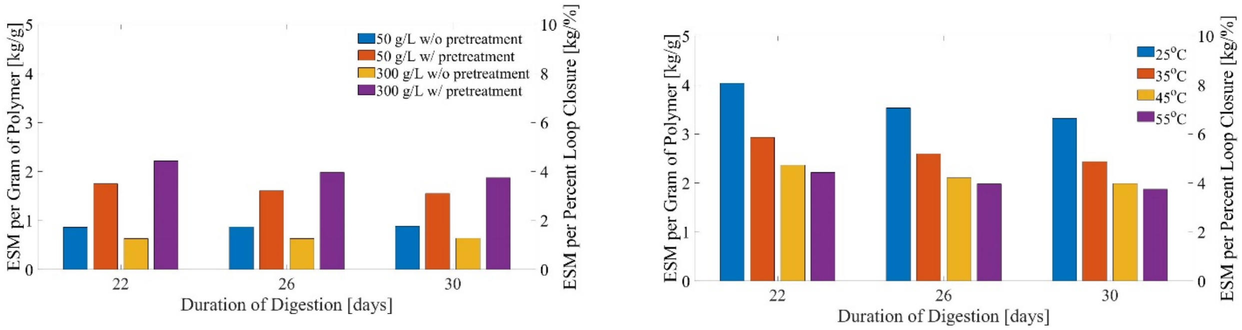
Figure 3(b) shows that the increased cost in thermal energy from maintaining 55°C is worth the expense, as the ratio for operating at that temperature is the lowest for any duration. Although the thermal cost to maintain 25°C is lower, the ESM-polymer yield ratio still remains high, since the reduced amount of methane yield is not worth the benefit of a lower ESM. So, among all the cases with rice straw as waste, the one with 300 g/L loading over 26 days of operation at 55°C without any pretreatment corresponds to the least ESM per unit of polymer produced, 0.59 kg/g of PHB, or equivalently, 1.18 kg/% loop closure in Figure 3(a).

Table 2 presents the configuration of the process steps and the contribution of individual contributing factors to the ESM. The polymer-producing bioreactor contributes most (around 89%) of the ESM. The methane yield for this lowest ratio case is 115 g/day, yielding 57.5 g/day of polymer, and if we assume the same daily need as before, 200 g/day, then we are finding 29% loop closure. Though the extent of closure is much less, the lower cost/polymer ratio assures us that this is the best case for those studied.

Table 2

Distribution of ESM across the process-steps for the case of rice straw digestion at 300 g/L loading over 26 days of operation at 55°C with no pretreatment, leading to the most economical processing at 0.59 kg ESM/g PHB

	Mass [kg]	Volume [m^3]	Power [kW]	Thermal Control [kW]	Startup Energy [kJ]	Total ESM [kg]
Anaerobic Digester 1	64.76	0.02	0.05	0.04	3,330.55	80
Anaerobic Digester 2	518.08	0.16	0.40	0.35	25,534.20	649
Polymer Bioreactor	1,878.04	0.58	1.45	0.47	36,093.39 [per batch]	6,040

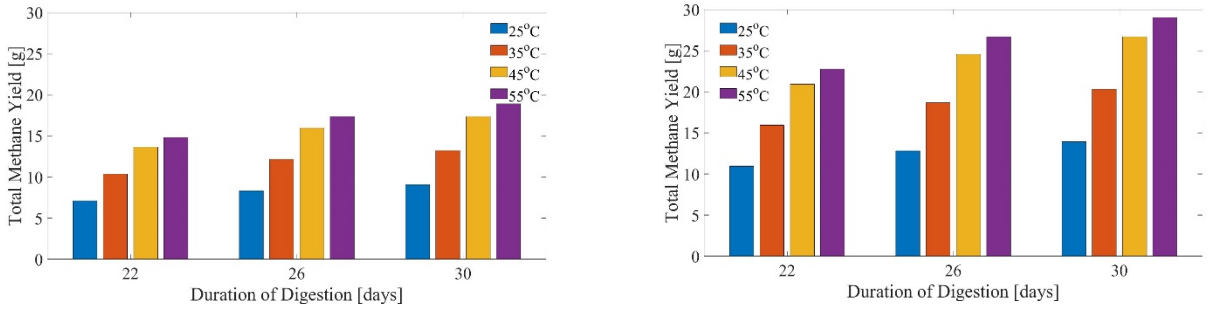


(a) **(b)**

Figure 4: ESM-polymer yield and ESM-percent loop closure ratios of anaerobically digested rice straw and rice husk over varying durations under different operating parameters assuming 200 g/day polymer demand. (a) Digestion fixed at 55°C. (b) Digestion fixed at 300 g/L loading with 4% NaOH pretreatment.

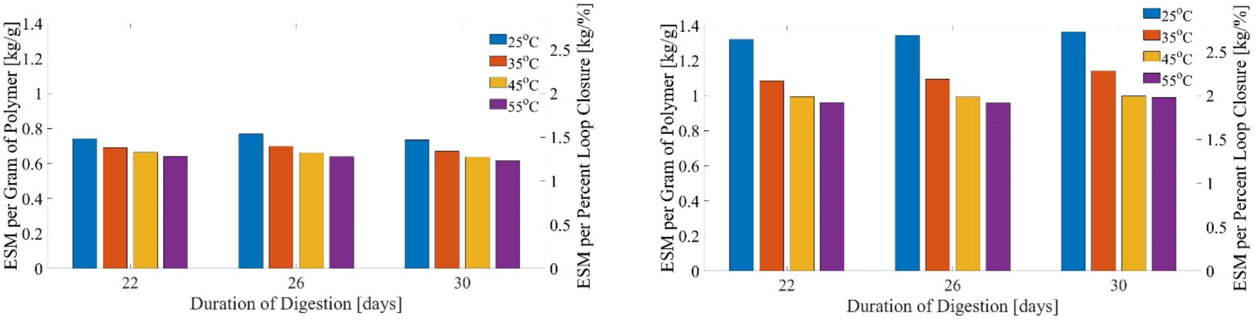
Figure 4 presents a heterogenous waste case, rice straw digested at the same time as rice husk. Here, the C/N ratio plays a role in determining the ESM-polymer yield ratio. The C/N ratio for this waste combination is effectively 40/1 (this ratio for rice straw alone is 31/1, while for husk alone, is 80/1)[34]. This 40/1 ratio is not in an ideal range of conditions[24] and thus, the actual methane yield is 70% of prior yield values. Though we now have a larger total amount of waste input into the digester, at 426.4 g/day compared to 356.5 g/day from the rice straw only case, the C/N ratio greatly inhibits the digestion of the waste. The best ESM-polymer yield ratio of 0.632 kg/g in this heterogeneous waste case is higher than the corresponding case in the homogeneous rice straw waste case, which was 0.59 kg/g. Although the total amount of waste is higher, we are collecting less methane daily, 96.25 g for the heterogeneous waste case compared to 114.9 g for the homogenous waste case. This highlights the trade-off between total waste amount and C/N ratio. As we notice in Figures 3 and 4, rice straw, despite its lower available waste amount, guarantees a smaller ESM per unit polymer than rice straw and husk, which, despite its higher waste amount, has a lower methane yield due to unfavorable C/N ratio. However, this is specific to the type of waste. Given a different waste combination that still allows for a viable C/N ratio, this result may not hold.

Figures 5(a) and 5(b) show the total methane yield from only human feces and feces-urine mixture, respectively. As mentioned in the previous section, for human waste, we do not analyze the impact in variations in loading. Rather, we follow the natural loading, which, for feces without urine, is 350 g/L (similar to the 300 g/L case of rice waste), and for feces with urine, is 60 g/L (similar to the 50 g/L case). Thus, the impact on TMY is similar to the one in prior cases. Additionally, the effect of the C/N ratio is again relevant: while feces and urine together provide more waste to be digested, it also produces a C/N ratio that is less conducive for methane production. Moreover, feces also has a poor C/N ratio[35] of 6/1 to 10/1. Figures 5(a) and 5(b) show the same trend of increasing yield with temperature from Figure 2(b). The case resulting in the highest methane yield gives 29 g/day of methane, which results in 14.5 g/day of polymer. With the same assumption of 200 g/day of biopolymer needed, we find that the resulting loop closure is 7.25%. While this might seem to be a much lower closure than the rice husk cases, this is also a consequence of having much less human waste than inedible biomass.



(a) **(b)**

Figure 5: Methane yield of anaerobically digested human waste over varying durations under different operating parameters. Anaerobic digestion only using human feces (a) yields the same methane production pattern seen in Figure 2, but produces less total methane than anaerobic digestion with human feces and urine together (b).



(a) **(b)**

Figure 6: ESM-polymer yield and ESM-percent loop closure ratios of anaerobically digested human waste over varying durations under different operating parameters assuming 200 g/day polymer demand. Anaerobic digestion using only human feces (a), and with human feces and urine together (b), both follow the same pattern established in Figures 3 and 4.

Figure 6 presents the cost-yield ratio for the cases shown in Figure 5. In Figure 6(a), the case with the lowest ratio is the 30-day duration of homogeneous human feces at 350 g/L loading (the natural loading rate of human feces). We find a different “best duration for ESM-polymer yield ratio” in the human waste case compared to the rice straw case. This is because the amount of human waste divides more evenly into an integer number of digesters than does the amount of rice straw. Figure 6(b) shows that the same pattern from previous cases still holds true, as operating at 55°C still yields the best ratio. Table 3 presents the contribution of individual process steps towards the ESM for the most economical scenario, amounting to 0.62 kg ESM/g PHB, equivalently, 1.24kg ESM/% loop closure. Similarly, in the case of rice straw (Table 2), the polymer-producing bioreactor is the single-largest contributor (86%) to the ESM. The ESM per unit of polymer for the most economical cases of rice straw and human feces are very similar in their values. For the case of rice straw, the yield of polymer is higher owing to a higher methane yield, while the number of digesters and reactors needed are also higher. The methane amount in the case with the lowest ratio is 19 g/day of methane. It follows that we recover 9.5 g/day of polymer, and with 200 g/day being the necessary amount of polymer, we find 4.75% loop closure. Again, the extent of closure is much less than seen in the other parts of this study, but this is because we are choosing to discount the amount of waste that we are digesting in favor of a lower ESM/polymer ratio.

Table 3

Distribution of ESM across the process-steps for the case of human feces over 30 days of operation at 55°C, leading to the most economical processing at 0.62 kg ESM/g PHB

	Mass [kg]	Volume [m^3]	Power [kW]	Thermal Control [kW]	Startup Energy [kJ]	Total ESM [kg]
Anaerobic Digester 1	64.76	0.02	0.05	0.04	274.53	74
Anaerobic Digester 2	64.76	0.02	0.05	0.04	2,104.73	78
Polymer Bioreactor	323.8	0.1	0.25	0.08	5,465.46 [per batch]	957

B. Sensitivity Analysis

We study the impact of technology choice for power generation and thermal control on ESM. To determine ESM sensitivity, we consider photovoltaic (PV) power generation for an updated P_{eq} of 178 kg/kW, along with a fuel cell storage with equivalency factor of 10 kg/kWh. For the thermal control equipment, we choose the one with a light-weight radiator made of composite materials, with a C_{eq} of 121 kg/kW. These values come from Ref. 30. We report the results for the cases of 26 days of operation for rice straw and 30 days for human feces as per the most economic scenarios for polymer production.

For power generation with solar PV for anaerobic digestion of rice straw, we study the impact on the change in ESM. This change is least for the cases with alkaline pretreatment: around 2% for 300 g/L loading and around 4% for 50 g/L loading, Figure 7(a). However, the corresponding values for the cases with no pretreatment are around 7% and 8.5%, respectively. This is evident from the fact that shipment of alkali has a major share in the ESM (60-75% for 300 g/L and 45-60% for 50 g/L). Thus, the impact of change in energy resource is higher for a smaller loading value.

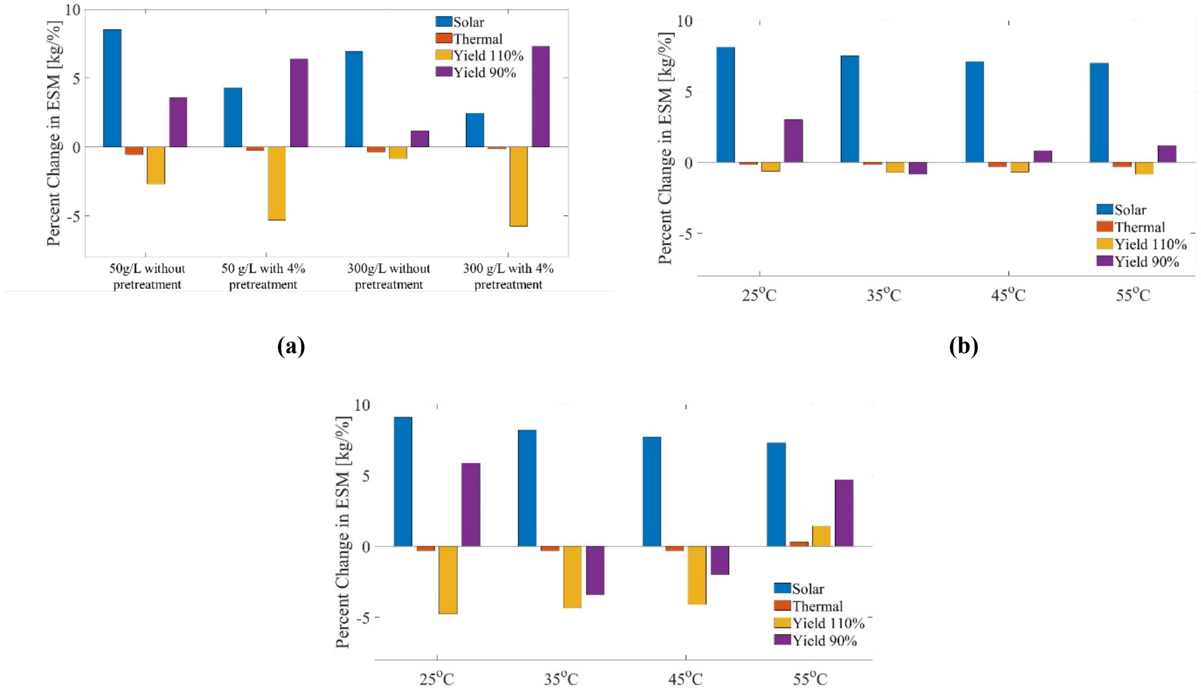
In terms of operating temperature, we notice two separate trends. For the cases without pretreatment, the solar PV impact is inversely proportional to temperature, Figure 7(b), because the startup energy increases with temperature and is a major ESM contributor. Hence, the relative impact of a change in energy source is less at higher operating temperature. This understanding on variation in startup energy with temperature is also true for the pretreatment cases. However, the pretreatment process, while having an even higher share on ESM than the startup energy, has a smaller contribution as temperature increases. Consequently, there is a higher impact of change in P_{eq} at higher temperatures for cases with alkaline pretreatment. Such a detailed understanding of the associated trade-off helps in a better-informed design and operation of the system.

The above impact trend for rice straw without any pretreatment is similar to that with human feces, Figure 7(c). The impact is higher at lower temperature and ranges from around 7% to 9% as temperature drops.

For a change in C_{eq}, there is no noticeable impact in the ESM for any of the cases with rice straw or human feces since the change is too small relative to the other contributors in ESM.

Next, we change the methane yield by 10% in either direction, one at a time, from their base level values for all the scenarios. This highlights the discrete design decisions involved, and also quantifies the possible change in ESM and parameter relationship. Here, we summarize the impact of this change for rice straw digestion for 26 days and human feces digestion for 30 days, as above. The cases with alkaline pretreatment experience a higher change in ESM per unit of PHB, Figure 7(a). Since pretreatment enhances methane yield, the impact of a 10% change in yield is more drastic (5-6% change in ESM per unit of PHB), thereby necessitating a major change in the amount of infrastructure in the polymer production stage too, which itself can have parametric sensitivity. The impact for scenarios with no pretreatment is around 1-3%. Although a higher yield typically ensures a lower ESM per unit of PHB and a lower yield has the opposite effect, irrespective of the waste, there may be a few exceptions due to discrete design decisions, such as the number of digesters or reactors in the ESM calculations. Thus, while entities such as polymer yield and energy demand change linearly, the change in capital infrastructure is always step-like. Hence, there are instances when we encounter a directly proportional impact in ESM per unit of PHB, as in Figure 7(c).

We also note the impact of mission horizon. For the most economical cases with both the rice straw and human feces, as above, for 1,000 days of time horizon as against 200 days in this study, the ESM per unit of PHB production is 0.4 kg/g compared to 0.59 kg/g for the case of digesting rice straw over 26 days at 55°C at 300 g/L loading without any pretreatment, and 0.62 kg/g for the case of digestion of feces over 30 days at 55°C. This points to the greater benefit of this process for longer-term missions, ignoring any resupply for repairs or replacement bioreactor parts.



(a)

(b)

(c)

Figure 7: ESM sensitivity to changes in power generation and yield for rice straw and human feces as loading for rice straw (a), temperature for rice straw (b), and temperature for human feces (c) vary.

IV. Discussion

Space biomanufacturing is a promising alternative to traditional physicochemical *in situ* resource utilization processes. Owing to their relatively mild requirements, biomanufacturing has great potential to reduce payload by obviating the infrastructure that is necessary for intensive process reactions. Thus, readily-available mission waste presents itself as a potential resource. Accordingly, it is important to study the conversion of mission waste to some useful intermediate that is easily usable as feedstock for a downstream biomanufacturing process.

In this work, we analyzed anaerobic digestion of wastes in conjunction with a downstream polymer bioproduction process. We investigated waste materials like rice straw, straw-husk mixture, human feces, and feces-urine mixture. We considered numerous process conditions to minimize the total ESM of the two-step process relative to the amount of polymer bioproduction. ESM accounts for the necessary demands for power generation, thermal control, and start up energy, on top of shipped mass and equipment pressurized volume.

Our approach gives simultaneous insight into the extent of loop closure that may be possible for a chosen space biomanufacturing process, and its trade-off with ESM cost. For the cases that we investigated, we found that it is possible to achieve substantial loop closure (roughly a third) for low ESM outlay with certain waste streams.

The downstream space biomanufacturing polymer-producing bioreactor functions as a bottleneck in our setup because it contributes to more than 80% of total ESM in most cases that we studied. This suggests a clear direction for future research. Next steps also include analyzing more waste streams and waste stream combinations, determining loop closure for alternate space biomanufacturing processes, and investigating different waste treatment technologies.

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