NASA-TM-111677

Further Characterization of CELSS Wastes: A Review of Solid Wastes Present to Support Potential Secondary Biomass Production

M. S. Muller

June 1996

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M. S. Muller, The Bionetics Corporation, NASA Biomedical Operations and Research Office
John F. Kennedy Space Center, Florida

National Aeronautics and Space Administration
John F. Kennedy Space Center, Kennedy Space Center, Florida 32899-0001

June 1996

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Further Characterization of CELSS Wastes: A Review of Solid Wastes Present to Support Potential Secondary Biomass Production

Matthew S. Muller, The Bionetics Corporation
Kennedy Space Center, FL

Abstract

Controlled ecological life support systems (CELSS) may one day play an essential role in extraterrestrial colonies. Key to the success of any CELSS will be the system's ability to approach a self-supporting status through recovery and reuse of basic resources. Primary CELSS solid wastes with potential to support secondary biomass production will be inedible plant biomass and metabolic human wastes. Solid waste production is summarized and reported as 765 g DW day^{-1} $person^{-1}$, including 300 g C and 37 g N day^{-1} $person^{-1}$. One Resource Recovery configuration using the bioprocessing of solid wastes into a Tilapia feed stream is examined. Based on estimated conversion efficiencies, 12 g of protein day^{-1} $person^{-1}$ is produced as a nutrition supplement. The unique tissue composition of crops produced at the Kennedy Space Center CELSS Program highlights the need to evaluate Resource Recovery components with data generated in the CELSS environment.

Introduction

Extraterrestrial manned missions can not be undertaken with the current approach of stocking all supplies at the initiation of the journey. Future Moon and Mars colonies must approach a self-supporting status. In the absence of a breathable atmosphere, life support systems need to generate oxygen and remove carbon dioxide. To reduce resupply requirements of the colony, food must be generated from reservoirs of basic, recyclable nutrients. Thus, the use of living plants as a central component of future life support systems is currently being investigated at NASA's Kennedy Space Center. Such systems have been termed controlled ecological life support systems (CELSS) in recognition of the fundamental role of photosynthetic organisms. Key to the success of any CELSS will be the system's ability to efficiently recycle wastes into reusable resources.

Current KSC CELSS research strategies focus on the intensive culture of a group of candidate crops, specifically selected to supply the nutritional requirements of colony inhabitants. A large, atmospherically-sealed plant growing chamber has been developed to perform mass balance studies on crop productions. Through 1993, studies in the Biomass Production Chamber (BPC) have focused on four crops: wheat, potato, soybean and lettuce. It is essential to CELSS planning to recognize that the first three of these crops are only partially edible by humans. In fact, less than one-half of the current wheat and soybean yields are edible (susceptible to hydrolysis in the human digestive tract). Consequently, significant amounts of solid waste will be generated in photosynthetic-based life support systems. The investigation of the various means of processing this waste has been termed Resource Recovery, an expanding aspect of CELSS research.

Discussions surrounding Resource Recovery, and more generally CELSS, focus on the cost and reliability associated with using biological subcomponents. Costs are incurred as increased energy, mass and manpower. In Resource Recovery, one central question focuses on whether to immediately oxidize inedible biomass or to further process the waste through a combination of secondary consumers to produce additional biomass for human consumption. When incinerated, plant nutrients are promptly returned to nutrient solutions as reconstituted ash residues and carbon is released to the atmosphere to be re-fixed through plant growth. Costs incurred are not significantly increased by additional Resource Recovery components in this scenario. However, this option leaves crop production as the only source of food and ignores the potential of secondary production. Bioprocessing solid CELSS wastes into human food sources will entail additional costs, yet allow for size reduction of primary biomass production components by producing more food per crop production. There are also significant nutritional and psychological benefits associated with the diversity gained from bioprocessing that must eventually be part of the CELSS configuration selection criteria.

Reliability questions about CELSS stem mainly from the lack of historical data on biologically-based life support systems compared to their physical/chemical counterparts. To establish these data sets, CELSS research is focusing on complete mass balances, including energy inputs, element flows, biomass outputs and associated manpower requirements. The various scenarios for bioprocessing must each be investigated in this manner. However, with limited biomass currently being produced in the CELSS Program, Resource Recovery investigators have been limited to selecting one or two potential bioprocessing configurations for mass balance studies.

KSC CELSS Resource Recovery research has previously focused on components separately. This philosophy is based on the need to understand mass flows in each subcomponent before linking them into an integrated system. However, because of unique characteristics of CELSS-produced biomass and the effect each subcomponent has on its output (composition and volume), Resource Recovery studies must proceed directly toward complete configurations. As with any limited resource, the use of CELSS inedible biomass must be well-planned and appropriately scaled.

This discussion will focus on identifying potential CELSS waste streams and characterizing those which may support secondary biomass production. A Resource Recovery scenario is evaluated to assess its capacity to supplement CELSS inhabitants' energy requirements.

Primary CELSS Waste Streams

Principal CELSS waste streams will consist of inedible plant biomass, metabolic human wastes, wash waters and atmospheric humidity condensates (from crew and biomass production components). The two primary sources of fixed carbon (energy) to support secondary biomass production are the inedible plant biomass and metabolic human wastes. Wash water and condensates will contain some organics, but their production will likely be insignificant relative to the primary sources. Resource Recovery components will also generate solid waste streams, but these should be considered secondary sources and do not contribute to the overall potential increase in biomass production.

Inedible Plant Biomass

It is proposed that inhabitants of an extraterrestrial community would exist on a primarily vegetarian diet. To meet these nutritional requirements, the NASA KSC CELSS Program has selected a list of candidate crops for closed environment study (Table 1). The inedible biomass produced in a CELSS will depend on the specific crops which constitute this mix and the harvest indexes (edible/total biomass ratio) that can be obtained.

Table 1
NASA KSC CELSS Candidate Crops

Wheat	Peanuts
Soybean	Sweet potato
White Potato	Lettuce

Several studies have addressed CELSS crops and the edible and inedible biomass produced. Gustan and Vinopal (1982) proposed the diet of 2134 grams fresh weight (FW) day^{-1} shown below (Table 2). Based on conventional agriculture harvest indexes, 17,425 grams FW day^{-1} inedible biomass would be produced daily. The total harvest index for this mix (12.2%) is extremely low; not likely to be implemented into a functioning CELSS. Low harvest index crops like peanut (3%) and peas (4%) have been included for dietary benefits, and drive the total index down. A Univ. of Florida study (1990) proposed these harvest indexes could be halved with the development of new strains, and used reported dry weights to calculate a production rate of 3,043 g DW day^{-1} for Gustan and Vinopal's proposed mix. Shuler *et al.* (1981) proposed a vegetarian diet meeting 82% of human dietary requirements which produced 374 g DW day^{-1} inedible biomass. This analysis included goats to produce dairy products and utilize up to one-half of the inedible biomass produced.

Table 2
CELSS Diet Biomass Estimation
(Gustan and Vinopal, 1982)

	EDIBLE	INEDIBLE		
		current	future	future
(%total)	g FW day^{-1}	g FW day^{-1}	g FW day^{-1}	g DW day^{-1}
Wheat (6.4)	136	888	444	235
Potato (16.8)	360	136	68	14
Soybean (10.1)	216	275	138	39
Mustard green (<1)	11	3	1.5	0.2
Peanut (1.5)	32	1214	607	600
Rice (10.9)	234	1566	783	234
Pea pod (1.4)	30	61	31	5
Split pea (11.2)	240	6246	3123	937
Corn (6.4)	136	3254	1627	492
Kale (<1)	11	3	1.5	0.2
Dry bean (10.7)	228	463	232	76
Turnip green (<1)	11	3	1.5	0.2
Chickpeas (10.7)	228	463	232	76
Oats (10.1)	216	1446	723	137
Broccoli (2.1)	45	180	90	10
TOTAL	2134	17425	8713	3043

For this discussion, where the goal is to characterize the solid waste streams potential to support secondary consumers, it is meaningful to have harvest index and tissue analysis data on crops produced in a simulated CELSS environment. For that reason, four crops which have been grown in the KSC CELSS Biomass Production Chamber (BPC) will be used as a base model. A 750 g DW day^{-1} "diet" of equal parts wheat, potato, soybean and lettuce is used to evaluate the inedible biomass produced. Resulting quantities are shown below (Table 3).

Table 3

Four KSC CELSS Crops and Associated Inedible Biomass

(750 g DW day^{-1} simulated "diet", equal parts each component)

"Diet" Component (Harvest Index)	Biomass Edible	Biomass Inedible
Wheat (40% HI)	187.5	280 g DW day^{-1}
Potato (80% HI)	187.5	47
Soybean (40% HI)	187.5	280
Salad crops - Lettuce (85% HI)	187.5	33
		640 g DW day^{-1}

The resulting 640 g DW day^{-1} is slightly lower than quantities previously reported due to the relatively high total harvest index (60%). It also assumes no excess food production. However, the quantity gives a conservative base on which to evaluate the use of a secondary consumer.

Analyses performed on these tissues highlight an unexpected phenomena which seems to be related to the CELSS hydroponic crop growth methods. The nutrient and soluble organic concentrations in tissues grown at KSC is greater than previously reported concentrations in field grown crops. Garland (1992) found that a significant portion of the dry weight of the inedible biomass was soluble; 29% of soybean, 43% of wheat and 52% of potato. In fact, Garland found that the complete forms of macronutrients (NO3, PO4, K, Ca, Mg) account for 10, 17 and 25% of the dry weight of inedible residues from soybean, wheat and potato, respectively. Ultimate analyses for three tissues are shown below (Table 4).

Table 4
Ultimate Analysis of KSC CELSS Inedible Biomass
Dreschel, et al., 1991

	Wheat Residue	Soybean Residue	Lettuce Residue
%Ash	15.21	15.79	20.37
%Carbon	39.83	42.30	38.55
%Hydrogen	4.45	4.89	4.50
%NITROGEN	3.94	2.47	5.41
%Sulfur	0.10	0.05	0.14
%Oxygen	36.47	34.50	31.03
Heating Value (kJ/kg)	890	921	868

When evaluating the bioprocessing of CELSS wastes, nutrient concentrations and organic compositions of the residues are especially important. Under field grown conditions, inedible biomass often lacks the nitrogen content necessary to support active bioprocessing. However, C:N ratios reported at KSC are close to one-half those typically reported in field grown crops, with ranges for wheat, potato and lettuce crops reported between 8:1 and 12:1 (Dreschel et al. 1991). In addition, crop residues show an extremely low lignin content of approximately 3% - three to five times less than field grown crops (Strayer et al. 1989). These characteristics suggest CELSS residues are more readily adaptable to bioprocessing techniques than typical field grown material. The importance of possessing as much CELSS-derived data when evaluating potential CELSS configurations is evident.

The focus for this discussion is the quantities of carbon and nitrogen available in CELSS waste streams. Based on the harvest indexes and tissue analyses presented, the following summarizes grams of C and N produced day^{-1} $person^{-1}$ as inedible biomass from the theoretical "diet" discussed (Table 5).

Table 5

Carbon and Nitrogen Reservoirs in Inedible Biomass

(Dreschel, et al., 1991, Brannon, 1990)

	Total Biomass	g C	g N
Wheat	280	111	11
Potato	47	19	1.5
Soybean	280	118	7
Lettuce	33	13	1.5
Totals	640	261	21

Metabolic Human Waste

The second principal CELSS solid waste stream with potential to support additional biomass production is metabolic human waste. While not currently a part of KSC CELSS research, it will eventually contain a significant portion of the nitrogen present in CELSS waste streams.

Many factors affect volume and composition of human wastes, including diet, activity and body weight. It is difficult to standardize a human waste stream, especially when attempting to relate data to the CELSS environment. NASA reports a nominal crewman metabolic solids balance for

620 g food input of 59 g urine and 32 g feces solids output (Parker and West, Ed. 1973). The standardized model compiled by Spurlock et al. (1975) for evaluating spacecraft water/solid waste processing systems listed total metabolic solids as 98 g day^{-1} $person^{-1}$. Elemental composition of these waste solids reports 35 g C and 15 g N day^{-1} $person^{-1}$. Data for this summary was based on collected waste production from various NASA space flights, but does not make any adjustment for the likely difference in a CELSS diet composition. Shuler (1981) developed one of the more comprehensive estimates of CELSS human waste production using data baselined on vegetarian diet studies performed in various medical research programs. Total solids production is summarized as 124 g DW day^{-1} $person^{-1}$ for a diet with similar intake quantities discussed above. Carbon and nitrogen production is reported as 41 and 16 g DW day^{-1} $person^{-1}$, respectively. These figures are similar with an expected slight increase in total solids due to the reduction in digestibility of a vegetarian diet. Shuler's quantities are used in the following discussion.

It should be noted that inedible biomass and metabolic waste quantities are only used to approximate the potential for secondary biomass production. This potential is important to quantify and examine prior to undertaking expensive bioprocessing investigations with limited CELSS resources. However, successful bioconversion of these waste streams into secondary food production will ultimately depend on the qualitative, not quantitative nature of these streams.

Secondary Biomass Production

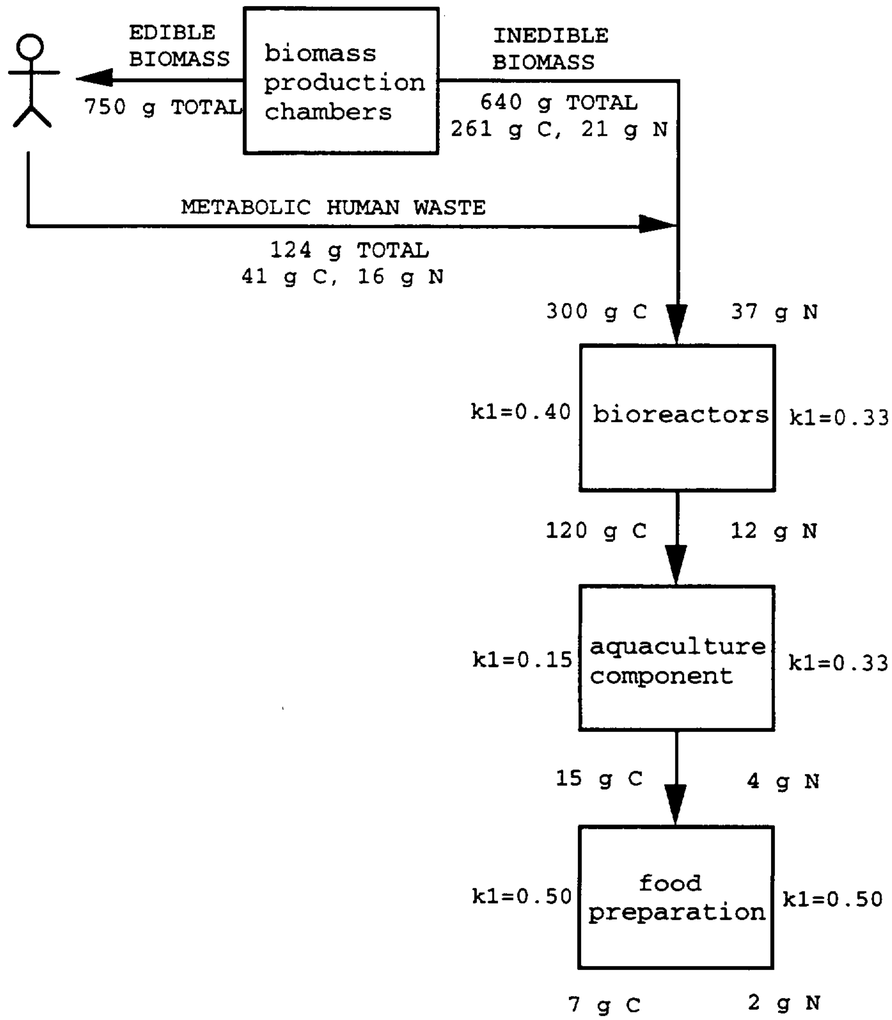
The primary CELSS solid waste streams to support secondary biomass processing are inedible plant biomass and metabolic human waste. As discussed, the total solids available are 765 g DW day^{-1} $person^{-1}$ (300 g C, 37 g N). Resource Recovery investigations should target these quantities to ascertain the potential viability of any secondary biomass production scenarios.

One proposed Resource Recovery configuration includes the aerobic and anaerobic processing of combined waste streams into a feed stream component for an aquatic-based consumer. The KSC CELSS program is currently investigating the use of the freshwater fish Tilapia in such a role. Successful growth and reproduction of Tilapia in atmospherically-closed, recirculating aquaculture systems has been demonstrated with standard fish feeds (author, in process). However, in recognition of the impracticality of transporting fish feeds to extraterrestrial colonies, it is necessary to evaluate the quantity of fish biomass that can be supported on CELSS waste streams. Eventual assessments will focus on the edible biomass produced for human consumption versus the costs associated with any increased system size incurred to support the fish population.

A flow diagram for biomass conversion is shown (Figure 1). The diagram displays conversion constants which are defined as k_1=desired output/total input for each process. Conversion constants are target values for each process and are discussed below.

The first bioprocessing goal is the conversion of inedible forms of carbon and nitrogen into single cell microbial proteins to serve as an aquaculture feed stream input. Bioreactor configuration and operational parameters will target maximum biomass production, the inverse of standard industry approach to solid waste biological

Figure 1
Secondary Biomass Production: Conversion Targets for Carbon and Nitrogen (day^{-1} $person^{-1}$)



degradation. The energy (carbon) conversion constant targeted is 0.40, which would result in 120 g C day^{-1} $person^{-1}$ as microbial biomass. Substrate carbon conversion constants for readily digestible carbon sources such as glucose are reported between 0.75 and 0.90 (Pirt, 1975; Niedhart et al. 1990). A conservative value is used for this discussion as a more realistic return from bioreactors where the substrate is relatively recalcitrant. While protein analyses are pending, carbon dioxide production and 50% dry weight losses in KSC aerobic reactors point to significant assimilation of substrate.

It is reasonable to expect that an adequate aquaculture feed stream must be at least 30% digestible protein based on previous Tilapia studies (Winfree and Stickney, 1981; Anderson et al., 1983, Jauncey, 1981). Overall macromolecular compositions of microbial cells are reported as approximately 55% amino acids and an additional 20% ribonucleic acids (Niedhart et al. 1990). If the feed stream configuration were to rely solely on bioreactor outputs (no supplements), 12 g of the 37 g N available day^{-1} $person^{-1}$ (k_1=0.33) must be incorporated into digestible proteins in the microbial biomass (assumes 50% C content). This conversion potential is especially qualitatively dependent, and will be one critical challenge in this scenario.

The second bioprocessing step is the incorporation of bioreactor outputs into fish biomass. As discussed, the conversion constants are also highly dependent on the quality of feed stream provided. However, a conservative energy conversion coefficient of 0.125 results in 15 g C fish biomass day^{-1} $person^{-1}$. Closed aquatic studies performed at KSC with Tilapia fed standard fish feeds found energy conversion coefficients of 0.21. Similar studies reported ranges of 0.15 to 0.24 for diets with varying degrees of algal, animal and plant components (Fischer, 1979). Fish biomass tissue analyses performed at KSC reported nitrogen composition over 12% DW, projecting DW protein content between 75 and 80%. Protein conversion (as nitrogen) from microbial to fish biomass is projected at 33%. Protein utilization has been reported as 36% for diets with 24% protein (digestibility = 81%) (Shiau and Huang, 1989).

The final bioprocessing step is the mechanical preparation of fish carcass into an edible portion for human consumption. Assuming a "harvest index" for fish of 50% reduces energy sources available to 7 g C day^{-1} $person^{-1}$.

Potential protein addition to the diet is approximately 12 g (6.25 x N) day^{-1} $person^{-1}$, or approximately 25% of the minimum dietary protein intake for the average human (Guyton, 1981). It should be noted that the assumed 50% inedible portion of fish biomass will return a high-quality 7 g C and 2 g N to the solid waste stream from which secondary biomass production is originating.

In summary, it appears that the quantities of solid wastes generated in CELSS warrant the investigation of secondary biomass production as a supplement to the human feed stream. Mass balances and associated conversion constants provide targets for which to evaluate potential bioprocessing steps. However, as highlighted by the unique composition of CELSS-produced biomass, it is difficult to apply previous bioprocessing conversion efficiencies to the CELSS environment. Significant research efforts need to be undertaken to overcome the challenge of meeting the nutritional needs of secondary consumers with CELSS solid wastes. Once accomplished, increased mass and energy requirements must be evaluated against the nutritional and psychological benefits associated with inclusion of the specific Resource Recovery component.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1994 June

3. REPORT TYPE AND DATES COVERED
FINAL

4. TITLE AND SUBTITLE
Further Characterization of CELSS Wastes: A Review of Solid Wastes Present to Support Potential Secondary Biomass Production

5. FUNDING NUMBERS

6. AUTHOR(S)
Matthew S. Muller

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Bionetics Corporation, Mail Code: BIO-3, Kennedy Space Center, FL 32899

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA, Biomedical Operations and Research Office
Kennedy Space Center, FL 32899

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA-TM-111677

11. SUPPLEMENTARY NOTES
Category 51

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited, publicly available

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
CELSS, solid wastes, resource recovery, inedible biomass

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

National Aeronautics and
Space Administration
John F. Kennedy Space Center
Mail Code DYN-4
Kennedy Space Center, Florida 32899