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Waste Minimization through Integration of Energy-Agro-Waste Subsystems

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Abstract
The utilization of byproducts and wastes from various community subsystems (such as biosolids from wastewater treatment facilities and waste heat from electric utility power plants as feedstock for other community subsystems offers the potential of minimizing wastes and pollution, while cost effectively maximizing the use of resources. Community subsystems that offer such opportunities include the aforementioned two, as well as solid waste management, crop production, and food preparation, to name but a few. Collectively, most of these subsystems fall within the confines and definition of an energy-agro-waste system. This paper describes various types of community subsystems and the methods that can be used to effectively integrate them and to minimize wastes that commonly are discharged into the environment by the community as a whole. Effectively coupling the subsystems requires knowledge of the fundamental characteristics governing each of the subsystem processes, shared governing characteristics between or among subsystems, and appropriate mass and energy balances among the subsystems. The authors describe models that they have developed for various subsystems and potential alternatives for integrating community subsystems into an overall, larger community system. Special emphasis in the presentation is placed on the role of solid waste management in energy-agro-waste systems, including the ability of solid waste to be a source of raw materials for fuel and energy production, for food production, and for use as feedstocks for a variety of manufacturing businesses.

1 Introduction
At the present time, the basic needs from the communities typically are satisfied by individual, self-contained entities. Most of these entities use virgin materials as inputs and produce wastes and other pollutants during the course of producing their products or providing their services. Systems have been identified in which outputs from various processes, which generally are considered “wastes”, can be used to produce useful products. Furthermore, the overall efficiency of those systems can be substantially increased by using their residues.

This presentation deals with the quantification of mass and energy inputs and outputs of several agricultural and waste treatment processes. In addition, basic models are developed for use in the technical analysis of possible waste utilization schemes. The models can be combined into "energy-agro-waste complexes". In these complexes, the wastes from one process become inputs to others. Some of the processes that have been evaluated include: chicken, cattle, and swine rearing; aquaculture (fish and algae); crop production (open field and greenhouse); wastewater treatment; and anaerobic digestion. The models can be used to ascertain the size and determine the compatibility of subsystems as well as the overall feasibility of integrating more than two subsystems into complexes. In this paper, the authors present examples of some models of unit process, along with a quantitative analysis of an integrated complex.

2 Models of unit process

2.1 Procedure for the development unit process models

The model development procedure for the unit processes has been described elsewhere (Diaz, et al., 1981). Only the key aspects of the modeling procedure are reviewed in this presentation: 1) identification of inputs to and outputs from a system, and 2) quantification of the inputs and outputs relative to an appropriate process unit, e.g., per unit area or per animal. The models are developed by conducting mass and energy balances. In performing the balances, it is important to consider storage of mass and energy.

In the formulation of the models, certain assumptions must be made. Engineering models of living systems must reconcile the transient nature of such systems. In the development of the unit process models, the following assumptions were made: 1) for purposes of engineering analysis, biological processes can be adequately characterized just by their gross inputs and outputs (with the understanding that the processes are considerably more complex than as described); 2) available published data can be reasonably modified and adapted within limits of reported ranges to balance inputs and outputs without significantly affecting the validity of the model; and 3) all processes are at steady-state. Finally, for many variables. average values were used despite differences in season, geographical location, lifecycle, etc. In most cases, for animal and plant production processes. values for lifetime averages were used.

In this presentation, unit process models are built in the form of block diagrams. For each model, values for mass and energy inputs and outputs are given. Total solids (TS), N, P, and K are accounted for in all of the mass balances.

2.2 Pork production

There are many differences between values reported for specific inputs and outputs associated with pork production. In part, this is due to the fact that there is a wide variety of diets that are suitable to swine. Figure 1 shows a diagram for mass and energy balances representing an average of these reports.

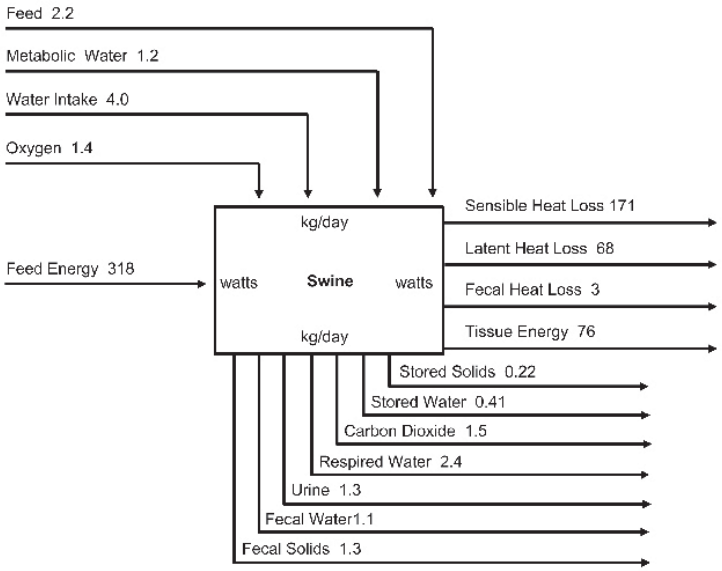


Fig. 1: Mass and energy balance diagram for pork production

Tab. 1: Growth and NPK uptake of corn

Item	Total (kg/ha-day)	Element (kg/ha-day)		
grain	23.3	0.370	0.063	0.088
stover	19.5	0.222	0.038	0.348
uptake	--	0.592	0.101	0.436

A lifetime average feed-to-weight gain ratio of 3.5:1 was used (Curry, 1960; Stapleton, 1960) with a consumption rate of 2.2 kg of feed/day (Ross, 1960; National Academy of Sciences, 1973). The energy content of the feed was assumed to be 12.6 MJ/kg (National Academy of Sciences).

2.3 Sorghum and corn production

Plant production in open fields can be used as an important element of an energy-agro-waste complex in many ways. The nutrients that are part of various waste streams can be used as fertilizers. Cooling water from condensers can provide under-soil heating or, alternatively, the cooling water can be used for spray irrigation of the fields. Grain crops can be grown for use as feed for livestock in the complex.

The growth rate and the uptake rates for N, P, and K of corn are given in Table

1. Mass balance diagrams for the production of corn and sorghum have been developed. The values in the balance are based on annual inputs and outputs per unit area (hectare) (Spector, 1956; Aldrich and Leng, 1965). In the development of the balances, it was assumed that the residues from harvesting would be equal to 0.85 of that of the grain (dry weight basis). The rest of the crop residues would be put back onto the fields for use as soil conditioning.

2.4. Production of water hyacinths

During the last few years, and especially due to some reports prepared by a group in the US National Aeronautics and Space Administration (NASA), the water hyacinth has, once again, begun to attract attention for wastewater treatment. Reported results show that the water hyacinth is effective in cleaning up waters that contain organic wastes, and to a certain extent the plants also assist in the removal of heavy metals. The role of the plant in treating wastewaters is twofold: oxygenation and assimilation of bacterial breakdown products in the wastewaters.

The use of water hyacinths for wastewater treatment has several advantages; however, the practice also is associated with some difficulties. Some of the advantages are related to the rapid growth of the plant. Rapid growth, in turn, ensures swift and effective upgrading of the wastewater. Another, but debatable, advantage is the possibility of using the water hyacinth crop as a feedstuff for livestock (Golueke and Diaz, 1981). The characteristics of water hyacinths as a feedstuff are shown in Table 2. Some of the disadvantages are: 1) being limited to tropical (or frost-free) areas; 2) the possibility of the plants "escaping" into waterways; and 3) the difficulties associated with harvesting. The major problem in terms of using water hyacinths as feedstuff is its relatively high water content. The plant typically has a water content on the order of 95%. Unfortunately, the water that would be expressed from the plant contains a relatively high proportion of the nutrient content of the plant (Gunnarsson and Mattsson Petersen, 2007).

Tab. 2: Range of values for chemical content of water hyacinth (entire plant percent dry weight). Source: Wolverton and McDonald, 1976.

Protein	9.7- 23.4
Fat	1.6- 2.2
Carbohydrate	36.9- 51.6
Fiber	17.1- 19.5
Ash	11.1- 20.4
Total Kjeldahl nitrogen	1.6- 3.7
Phosphorus	0.31- 0.89
Potassium	1.6- 3.4
Metabolic energy content	2.7- 3.1

2.5 Anaerobic digestion

The anaerobic digestion process can be used in an energy-agro-waste complex as a way of converting a fraction of the residues into energy and a fraction into fertilizing elements and soil amendments. As the result of research, these systems can be constructed in a variety of configurations for farm applications (Boersma et al., 1975).

2.6 Wastewater treatment processes

The development of a primary-secondary wastewater treatment model was made a part of the section on unit processes because sewage, whether raw or treated, can be used as an important input into an energy-agro-waste complex. Sewage can serve as a liquid medium in aquaculture, both as a suspending medium and as a source of nutrients in systems involving the production of aquatic plants or as source of nutrients to micro- and macro-fauna in the systems. With respect to land crops, wastewater also is a source of plant nutrients and of water for irrigation. Sewage can also be used as a source of heat in both land and aquaculture.

Composition and mass balances that show the combined effects of primary and secondary treatment have been developed. The values are based on one million liters of raw sewage. The values would vary depending upon the characteristics of the raw sewage and the efficiency of the primary and secondary settling chambers. The solids content of the sludge increases as the efficiency of the settling chambers increases and, conversely, the solids content of the effluents would decrease.

3. Evaluation of an integrated complex

Once the mass and energy balances for a number of likely candidate unit processes have been completed, the next logical step in the analysis was to integrate selected processes into what were deemed potentially useful and feasible complexes. Due to space limitations, the possible roles of only some unit processes in integrated complexes are shown in Table 3. The mass balances provide the information on the nature and amounts of inputs and outputs of individual processes needed in selecting and positioning those considered suitable to a given system.

Integrated mass and energy balances were carried out through an iterative process. The process consisted of combining the process models and conducting a process of iteration through the calculations between the different unit processes until acceptable balances were achieved. Iterative modifications included changing the sizing of the unit process operations (for example, reducing the operation of swine rearing from 200 to 100 swine), additions or depletions of unit processes from the complex being assembled, and the modification of parameter values (but keeping them within reported ranges).

3.1 Complex consisting of sewage-anaerobic digester-hyacinth-swine-open field

In this section, one of the integrated complexes investigated is analyzed. The complex is the "Sewage-Anaerobic Digester-Hyacinth-Swine-Open Field Complex". This complex was selected for analysis because it involves all of the unit process models described in the section "Unit Processes".

Tab. 3: Potential roles of some unit processes in integrated complexes

Unit Process	Primary Role in System	Use of Waste Heat	Possible Recycled Inputs	Possible Recycled Outputs
Cattle	Meat production	Housing	Chicken manure and bedding, water hyacinths, crop residues, algae	Manure, slaughter wastes
Swine	Meat production	Housing	Cattle manure and bedding, water hyacinths, crop residues, algae	Manure, slaughter wastes
Catfish	Fish production	Water warming	Feedlot manure, algae	Slaughter wastes, fish wastes
Greenhouses	Plant production (vegetables, flowers)	Maintenance of optimum temperature	CH_4 for heating, CO_2 enrichment, composted sludge, and crop residues	Crop residues
Water hyacinths	Water treatment	Maintenance of optimum temperature	Organic wastewater, CO_2	Feed for livestock or fish
Anaerobic digestion	Water treatment, methane production	Maintenance of optimum temperature	All types of organic wastes	CH_4, CO_2, supernatant, sludge

The relationships that comprise the Sewage-Anaerobic Digester-Hyacinth-Swine-Open Field Complex include: 1) the use of effluent from sewage treatment for field fertilization and for the production of water hyacinth; and 2) the anaerobic digestion of sewage sludge, crop wastes, and swine manure, and the feeding of field-grown grain, water hyacinths, slaughter wastes, and digested sludge to the swine. The main input to the complex is raw sewage. The main outputs are pork and methane.

Waste heat can be used to heat the area where the swine are kept and keep an optimum temperature in the sewage treatment and anaerobic digestion processes. Although under-soil heating is not included in this complex and it is not analyzed, it would provide another possibility for the use of waste heat.

Primary and secondary wastewater treatment is accomplished in the sewage treatment portion of the complex. Primary and activated sludges are loaded into the digester, as in conventional wastewater treatment practice. A portion of the

secondary effluent is discharged to a pond to support a water hyacinth crop, and another portion is discharged to open fields for irrigation. The hyacinth crop is used as a feed supplement in swine production. The effluent from the hyacinth pond is used to irrigate the open field. Solid and liquid wastes produced in rearing the swine are discharged into the digester, and the animals eventually are slaughtered. Wastes from the slaughter operation are discharged in part to the animal rearing element for use as a feed supplement, and in part to the digester. A connection could also be made between the slaughter element and the sewage treatment facility to indicate the discharge of wastewaters from the slaughterhouse to the latter for treatment. The open field receives effluents from the hyacinth pond and the digester. The grain produced in the open field is fed to the swine in the swine rearing element. Crop residue (stover) is loaded into the digester. From the preceding description, it becomes apparent that the digester plays an important role in the waste conversion function of the complex. The digester receives inputs from all of the elements, with the exception of the water hyacinth pond. The main outputs from the digester are gases and digested sludge. The gas of importance is

$$x_1 = k_1 u;\ x_2 = k_2 u;\ x_3 = k_3 u$$

$$x_7 = x_2 + x_3 + x_{13} = k_2 u + k_3 x_8 + k_{13} x_{15}$$

methane. Digester residue (settled solids and supernatant) is an important source

$$x_8 = \frac{k_7 + k_{13}(k_1 - k_{11}k_3) + \dfrac{k_{13}}{1 - k_{13}k_{14}}(k_3(k_1 + k_{11}k_7) + k_{12}k_3)}{1 - (k_{13}k_8 + \dfrac{k_{13}(k_6 \quad k_9k_5)}{1 - k_{13}k_{14}}} u$$

$$x_5 = k_5 x_4;\ x_9 = k_9 x_4;\ x_7 = k_8 x_4;\ x_9 = x_1 + x_3 + x_{13};\ x_6 = k_7 x_5$$

$$x_{10} = k_9 x_6;\ x_{11} = k_9 x_6;\ x_{12} = k_{10} x_9;\ x_{13} = k_{11} x_5;\ x_{14} = k_{12} x_5$$

$$x_{15} = x_7 + x_{11} + x_{14} + x_{15} = k_2 x_7 + k_9 x_6 + k_{12} k_3 u + k_{15} k_{14} x_{15}$$

$$x_{15} = \frac{(k_6 + k_9 k_5)x_4 - (k_9 k_1 + k_9 k_{11} k_3 - k_{12} k_3)u}{1 - k_{15} k_{14}}$$

$$x_{16} = k_{13} x_{15};\ x_{17} = k_{14} x_{15};\ x_{18} = k_{16} x_{17}$$

$$y = k_{17} x_{17}$$

$$y = k_{17} k_{16} x_{15} = (k_{14} k_{15}) \frac{(k_6 - k_9 k_5)x_4 + (k_9 k_1 - k_9 k_{11} k_3 + k_{12} k_3)u}{1 - k_{15} k_{14}}$$

of nutrients for the crops in the open field element.

3.2 Development of the sewage-digester-hyacinth-swine complex

The network analysis used in arriving at transfer functions for the model is as follows.

Substituting and solving:

Tab. 4: Transfer functions for the complex including sewage digester-hyacinth-swine

		N	**P**	**K**
Sewage effluent	k_1	0.45	0.49	0.63
Sewage sludge	k_2	0.37	0.32	0.12
Sewage effluent	k_3	0.18	0.19	0.25
Digester gas	k_4	0.00	0.00	0.00
Digester effluent	k_5	0.88	0.77	0.97
Digester sludge	k_6	0.12	0.23	0.03
Field losses (gas)	k_7	0.20	0.00	0.00
Field losses (solids)	k_8	0.20	0.56	0.49
Grain	k_9	0.34	0.26	0.09
Crop wastes	k_{10}	0.26	0.18	0.42
Pond effluent	k_{11}	0.12	0.22	0.30
Hyacinths	k_{12}	0.88	0.78	0.70
Swine manure	k_{13}	0.54	0.72	0.80
Swine body	k_{14}	0.46	0.28	0.20
Pork	k_{15}	0.69	0.69	0.69
Slaughter wastes	k_{16}	0.31	0.31	0.31

The preceding equations can be solved by multiplying the inputs to the unit processes by the corresponding transfer functions given in Table 4.

A mass balance for the entire complex has been developed. Inputs and outputs are given in units of kg per day. In constructing the diagram, not all of the inputs and outputs are included. For example, the gas exchange (CO_2, O_2) at the interface between the hyacinth pond and the atmosphere and the water losses from the open field due to evaporation and run-off are not indicated. Instead, only inputs and outputs considered to be essential to the continued functioning of the complex are presented.

The raw sewage input into the complex is 1000 m^3 per day. Crop production amounts to 1720 kg of grain per day (628 Mg per year) and 4410 kg of water hyacinths per day (1610 Mg per year), although the latter is 95% water. Slaughtered pork yield is 425 kg per day (155 Mg per year).

The daily feed ration to the 1000-swine operation is 2000 kg (dry weight) per day. The composition of the ration is 65 kg of slaughter wastes per day (3%), 210 kg of digested sludge per day (11%), 210 kg of water hyacinths per day (11%) and equal parts of corn and sorghum, each 760 kg per day (38%).

Since a substantial portion of the nutrient elements involved in the animal element of the complex is contained in the slaughter wastes, it is important that the slaughter wastes be kept within the system. This can be done efficiently by using,

as much as possible, the slaughter wastes as a feed supplement for the swine. An added advantage in so doing is that the nitrogen in the wastes is in the form of amino acids and consequently the nitrogen is more efficiently used by the animal than it would be in the form of grain.

The results of the analysis indicate that a 1000 m^3 per day sewage treatment plant could support 1000 swine, a 36-hectare corn field, a 36-hectare sorghum field, and a 0.84-hectare water hyacinth pond. An anaerobic digester of about 470 m^3 would be required in the system. The total area that would be involved in establishing this complex (excluding a power plant) would be approximately 250 hectares.

4. Conclusions

The main value of the models that were developed in the work briefly described in this paper is in their utility in the analysis of proposed energy-agro-waste complexes. The models provide a guideline for the design of such complexes by determining the sizing and the compatibility of subsystems, as well as the overall feasibility of an integrated complex. This was achieved by quantifying mass inputs and outputs of the various unit processes and the performance of mass balances on the integrated complexes.

The difficulty in developing overall mass and energy balances for biological systems can be well attested to by anyone who has worked in this field. The problems are greatest when trying to apply the balances to the total body of an animal. This consideration should be kept in mind when evaluating this and other presentations on integrated energy-agro-waste complexes. The authors' goal was to present the best possible models from information currently available, as well as to provide a useful guide rather than rigid design formulas for the analysis of energy-agro-waste complexes.

The relatively wide range of parameter values reported in the literature presented the greatest difficulty in building the models. This situation is due to a variety of reasons: 1) some of the data reported in the literature were not measured accurately and not under controlled conditions; 2) often only one parameter was measured in a study, making it difficult to relate to other parameters; and 3) most parameters involved in the analysis are functions of other parameters and not simply constants or even ratios of other parameters. A good example is feed conversion efficiency. This parameter is a function of type of feed, ambient temperatures, activity and age of the animal. The solids content of manure depends on the type of feed, amount of feed, feed conversion efficiency and water intake, and it is a weaker function than other parameters. These problems were reconciled as best as was possible by cross-calculations to verify the values used, and by the preferential use of what were considered to be the more reliable publications. In a final design project, one should refine the models to include values for the parameters actually used, e.g., breed of animals, diet, and local climatic conditions.

Many parameter values could not to be found in the open literature. Conse-

quently, in developing the models, these parameters had to be assumed, or the parameters had to be ignored. This is particularly the case when fish culture is an element of a complex. Composition of feed, tissue, and manure are parameters that frequently are not available. Additional experimental studies, especially with animals as subjects, would be useful in that existing data could be refined and additional useful data could be obtained.

The feasibility of a proposed energy-agro-waste complex is not proven by mass and energy balances alone. Other considerations must be taken into account, such as networks for the transport of materials, and operation procedures required to ensure a steady year-round distribution of inputs to the appropriate subsystems. Certain processes have a "built-in" interruption of their operation, such as slaughter or harvest. Other dependent subsystems, however, must have a continuous input. Alternatives to ensure a constant input should be investigated.

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