Optimization Of Pig Manure-Based Digestate Biorefinery Framework Using P-Graph

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Abstract: Hog farming is the second largest industry in the Philippines, next to rice cultivation. Waste generation is one of the main challenges of the industry with manure as its main byproduct. Philippines generates hundred million tons of pig manure being the 8th largest pork producer in the world. A manure management framework is necessary to address the problems in line with waste generation. Waste valorization of manure through anaerobic digestion and different digestate treatments to produce electricity, heat, biomethane, biofertilizer, microalgae, and compost were explored. Process graph (P-graph) was employed to determine the potential optimal pathways of processing pig manure by minimizing the production cost and greenhouse gas (GHG) emissions. Environmental impacts of the processes were expressed as global warming potential (GWP) or CO2-equivalent emissions. P-graph is a bipartite graph consisting of nodes (raw material, operating unit, and product) connected using arcs (input and output streams) capable of generating different process configurations. Six feasible solutions (S0-S5) were generated, three of which were profit-generating (S0-S2). The raw material costs were almost equivalent for every solution. S0 was the solution with the most amount of potential profit to be generated along with having the least investment cost. S1 and S2 were the net zero CO2-e processes, however, their investment costs were among the highest. Potential solutions were determined using P-graph that meets a certain criterion with its corresponding trade-off. Selection of the feasible solution would require a contextual approach. The study has shown that the application of P-graph in solving process network synthesis (PNS) problems can aid greatly in decision making process of choosing the perfectly viable solution under different contexts: environmental, social, or economic.

Key Words: Process graph; maximal structure; anaerobic digestion; pig manure; biorefinery

1. INTRODUCTION

Hog farming and production is one of the main contributors to the GDP share of agriculture. It is only second to rice in terms of agricultural farming. In 2019, 2296.7 metric tons of live-weight hogs were produced, amounting to 247.48 billion pesos (Philippine Statistics Authority, 2020). Despite the contribution to the economy of hog farming, the concern about waste generation from piggery farms is prevalent. Wastes, such as pig manure (PM) and slaughterhouse waste with the former being the main waste byproduct, pose significant threats to the environment that pollute the ground, surface water, atmosphere, soil, and vegetation, as well as being an epidemiological hazard to its nearby surroundings (Mironiuk et al., 2023). Elaborate research is required to construct an effective manure management framework for bioenergy production, nutrients recycling, and digestate utilization that minimizes the environmental risks while gaining optimal economic benefit (Awasthi et al., 2022). Anaerobic digestion (AD) is the most suitable treatment for PM in terms of energy recovery, land usage, and manure properties. Improvements have been shown when AD is coupled with subsequent digestate treatments (Kapoor et al., 2020). Duan et al. (2020) processed PM with varying end-products and treatments used. PM is valorized to biogas and digestate through AD producing electricity and bio-methane from the former while the latter is used for land application. The digestate was further processed to cultivate microalgae through integrated flocculation-biological contact oxidation and produce biofertilizer by struvite precipitation. Hollas et al. (2023) utilized the SISTRATES® Technology which uses three additive modules: Bio module for reducing the organics and biogas generation, N module for removing nitrogen, and P module for the recovery of phosphorus. The treatment methods used in these studies may be incorporated to combine into different pathways or into a bigger structure as such in a biorefinery.

It is proposed that the concept of biorefinery be entertained to address the lack of efficient manure management framework. Thus, a process network synthesis approach will be employed to account for the different pathways of processing pig manure where the objective is to minimize treatment costs or to minimize its environmental impact. The most suitable method to search for various pathways and the analysis of superstructure model is through the use of P-graph due to its ability to identify the maximal structure of the network as well as providing feasible structural solutions with efficiency.

The study aims to determine the optimal way of processing PM undergoing anaerobic digestion to value-added products. Specifically, it is desired to optimize the maximal structure for PM digestate process flows in terms of minimum production cost and greenhouse gas emissions. The digestate treatments to be employed are based on the study of Duan et al. (2020).

2. METHODOLOGY

2.1 P-Graph Algorithms

Friedler et al. (1992) established five axioms to which feasible structures should conform to. The determination of the maximal structure of a process synthesis network is first elaborated in Friedler et al. (1993). The maximal structure is the union of all the combinatorially feasible solution structures of a given PNS problem. Then, solution structure generation or accelerated branch-and-bound algorithms can be applied to find the optimal solutions to the synthesis problem. Fig. 1 relates these three algorithms in the determination of n-optimal, as well as sub-optimal solutions of a PNS.

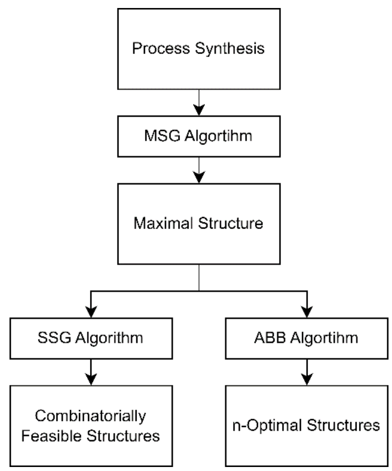


Fig. 1. Possible solution structure of the biorefinery

MSG algorithm begins by defining the input sets *M, P, R, O* where *M* represents the materials in the system and *O* as the operating units. *R* and *P* are defined as the raw material and the product, respectively. The objective is to generate a maximal structure *(m,o)* of a synthesis problem *(P, R, O).* SSG algorithm determines the combination of feasible pathways from raw materials to the products in the maximal structure. Lastly, ABB algorithm optimizes the feasible pathways by considering the capital, operating, and the capacity of the structure.

2.2 P-Graph Optimization

The material and energy flows for each manure treatment technology taken from different literature will be tabulated into a flowsheet. Forming the maximal structure, this will provide an overview of the interconnections of each unit considered for the biorefinery. Then, the selected manure digestate treatments are drawn using P-graph Studio v.5.2.4.4 published by the Department of Computer Science and Systems Technology, University of Pannónia (2021). Optimization will determine the biorefinery superstructure, optimal solutions, and near-optimal solutions based on economic (net profit) and global warming potential (GWP) constraints. The sustainability and the robustness of the feasible solutions generated will be examined by introducing different factors in the P-graph.

3. RESULTS AND DISCUSSION

3.1 Pig Manure Valorization Process

PM waste and water are fed into the anaerobic digestion (AD) unit (see Fig. 2). The product of the subsequent anaerobic digestion splits into two streams of biogas and digestate. The former is stored in the natural gas grid or partially combusted in cogeneration of heat and power (CHP) to provide heat and energy to AD, decanter centrifuge (DC), liquid fraction treatments in settling tank & centrifuge (STC) or integrated flocculation-biological contact oxidation (IFBCO), biofertilizer production through struvite precipitation (SP), and for composting in anaerobic composting site (ACS). Marginal heat and electricity are harvested as one of the final products. Then, the digestate is separated into its solid and liquid fractions. The solid fraction is employed for compost while the liquid fraction may be utilized in SP or microalgae cultivation (MC) after treatment and clarification. The microalgae culture is used as the biological agent to aid in anaerobic digestion. In summary, with manure as the raw material, the biorefinery is expected to produce biomethane, heat, electricity, and biofertilizer.

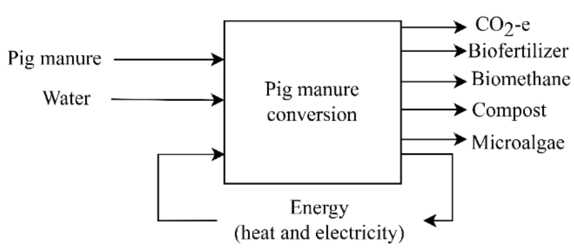


Fig. 2. Pig manure conversion block diagram

3.2 Generated Pig Manure Conversion Pathways

In the generation of solution, several assumptions were made to relieve the process from having too many constraints. For the raw materials, the input of manure was held constant at 9600 t/y (Healy et al., 2012), as well as the heat generation from the CHP unit. CO2-e production has a corresponding penalty, called carbon tax, that affects the feasibility of the solution. In this discussion, EUR 9.125/ton CO2-e was imposed on the operating units that produce it (The Organization for Economic Cooperation and Development – OECD, 2023). The IFBCO and STC units were declared to be mutually exclusive. All feasible solutions generated are ranked by their maximum profitability given that any products/byproducts (digestate, DTLF, DLF, and process water) from the process can be sold at any given context. Lastly, the operating units were assumed to be functioning for 8000 working hours per annum.

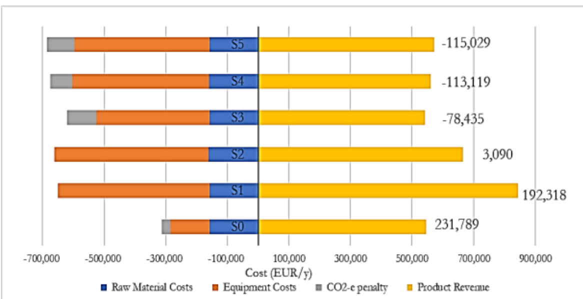
Table 1 displays the summary of the optimal and near-optimal solutions generated by profit and annual emissions. A total of six feasible solutions are described by the main operating units present. AD, CHP, and DC (except S0) are all included in the solutions by default.

Table 1. Summary of generated solutions.

No.	Component	Profit [EUR/y]	GWP [ton CO_2-e/y]
S0	AD-CHP	231,789	3,149
S1	IFBCO-MC-ACS	192,319	-
S2	STC-MC-ACS	3,091	-
S3	CHP-ACS	-78,435	10,358
S4	STC-ACS	-113,120	7,714
S5	IFBCO-ACS	-115,030	9,841

3.3 Analysis of Results

The raw material (RM) costs are almost constant for each feasible solution. The differences of the solutions lie in the products available, equipment employed, and the carbon penalty due to process emissions. Equipment costs (EC) have a considerable effect on the profitability of the generated solutions. While the carbon tax is not imposed in the Philippines, its contribution should not be neglected in the environmental aspect. The carbon tax is to demonstrate the environmental feasibility of the selected processes. Furthermore, the generation of the products is based on maximizing the raw material input that is economically and ecologically sound. The revenue from each solution reflects the volume of the products created which are assumed to be sold in any given context. These observations are as summarized in Fig. 3.



The solutions are then ranked based on different criteria as in Table 2.

Table 2. Ranking of generated solutions.

No.	EC	RM	GWP	Profit
S0	1	1	2	1
S1	5	1	1	2
S2	6	3	1	3
S3	2	1	5	4
S4	4	2	3	5
S5	3	1	4	6

The optimal solution (S0) ranks as the most desirable solution that meets the criteria of minimal production cost (equipment and raw material cost) and the most profitable out of all the solutions. A net zero carbon process can be achieved through S1 and S2. Environmentally speaking, these solutions would be the most desirable options. Despite S0 being 2nd in terms of GWP, S1 and S2 were held back by their investment costs as the least preferred choices in that aspect. Nevertheless, S1 is still the most profitable sub-optimal solution after S0. It can be observed that S3 may be a better option than S2 as the former is rated second best in investment costs. S4 and S5, however, are still performing poorly in the given criteria outside of profitability. In short, S0 is the economical choice while S1 and S2 are the least carbon-emitting structures.

4. CONCLUSIONS

As a decision mapping tool, P-graph allowed the researchers to examine the viability and feasibility of pig manure valorization processes through an economic lens and environmental perspective. The study demonstrated the application of P-graph in process synthesis which has always been a challenge for engineers to utilize its capability in this regard. It was shown that multiple potentially desirable alternatives can be selected for application or further analysis. This ability to see different options cannot be easily determined through the traditional approach in flow sheeting which requires an already defined network to derive a solution. In line with the calls for sustainability in chemical engineering process, solving PNS problems using P-graph could produce solutions which are Pareto optimal under different criteria which makes a process sustainable. In the context of this study, solutions that are advantageous economically and environmentally (through quantification of net CO2-e) were explored.

Incorporating the environmental emissions of byproducts that have negative impacts such as digestate can be further investigated to valorize it using processes not included in the study. Other applications of heat may be explored through pinch technology which was neither utilized fully nor explored in the study. In addition, microalgae produced can be employed to be co-digested with pig manure in another study and its potential for biofuel production. Moreover, the operating units employed in the study can be coupled with innovative technologies that are developing as of this writing.

Other pig manure conversion frameworks can be explored with the same purpose of minimizing production cost and GHG emissions. Relevant environmental impact aspects such as human health, ecosystem quality, resource consumption, or air quality can be considered on top of GWP. Then, a more robust ranking system such as multi-criteria decision analysis (MCDA) or analytic hierarchy process (AHP) may be employed for the selection of a Pareto-optimal solution. Future research is required to determine whether an anaerobic digestion biorefinery is the most desirable option out of all the existing manure valorization technologies.

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