PHILIPP AGRIC SCIENTIST
Vol. 107 No. 3, 253-265
September 2024

ISSN 0031-7454

A P-graph Approach for Planning Sustainable Rice Straw Management Networks

Maria Victoria Migo–Sumagang[1,*] and Michael Angelo B. Promentilla[2]

[1] Department of Chemical Engineering, College of Engineering and Agro–Industrial Technology, University of the Philippines Los Baños, College, Laguna, 4031, Philippines

[2] Chemical Engineering Department, Gokongwei College of Engineering, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines

*Author for correspondence; Email: mpmigo@up.edu.ph

Received: April 18, 2022 / Revised: April 04, 2024 / Accepted: June 30, 2024

The Philippines produces up to 15.2 Mt of rice straw waste annually. Unmanaged rice straw waste disposal can lead to pollution from open field burning. On the other hand, rice straw agricultural waste can be used sustainably to produce valuable products such as mushrooms, fodder, pellets, or bioenergy, in a rice straw management system. Such systems can be optimized using Process Integration tools so that the raw materials are used efficiently at the maximum profit and with a minimal carbon footprint. The P-graph framework is an efficient Process Integration tool that solves Process Network Synthesis problems. A P-graph finds the optimal and sub-optimal solutions for further analysis, which is useful in decision-making. This work developed a P-graph model for a rice straw management network considering the straw collection and storage steps and the production of both bioenergy and non-bioenergy products. The model can generate optimal and sub-optimal solutions (based on profit) and can simulate raw material disruption scenarios. The model is demonstrated through a case study on three rice straw fields with a maximum total rice straw yield of 96.84 t/yr. The case study considered the operating and raw material costs but did not consider the fixed and investment costs in the calculation of the profit. The results show that mushroom production using rice straw as substrate is the optimal solution with a potential profit of US$ 14 659.60/yr, followed by pellet production with a potential profit of US$ 12 627.90/yr. Disruption scenarios at reduced diesel, manual labor, and rice straw show that mushroom production is still the optimum solution, showing the robustness of the solution. This basic model shows that P-graphs can be applied to rice straw management networks to aid with decision-making for sustainability. Caution must be exercised as the results are context- and location- specific.

Keywords: sustainability, P-graph, process integration, rice straw, decision support systems

INTRODUCTION

The intensification of rice production and the use of high-yielding rice varieties have led to higher global warming potential per area in rice production (Gava et al. 2024). Intensification has also led to higher rice straw waste volume, which is commonly burned in the field. The increased adoption of combine harvesters and the narrow time window available for clearing fields after rice harvest are the primary factors compelling farmers to burn rice straw residues (Singh et al. 2023). However, open-field burning of rice straw is a serious problem as it causes air pollution and the release of potent greenhouse gases (GHG), CH_4, and N_2O (Mboyerwa et al. 2022). Aside from GHGs, the practice of burning rice straw after harvest increases the particulate matter and hydrocarbon concentration in the surrounding area by several times, threatening human health and biodiversity (Phuong et al. 2021). An alternative to open-field burning—soil incorporation, where the rice straw is left on the field to decompose—is also found to release large amounts of CH_4 and N_2O (Romasanta et al. 2017). On the other hand, the valorization of rice straw may provide economic and environmental benefits. Some examples of off-field agricultural uses of rice straw are mushroom production and livestock fodder production, while bioenergy examples are thermal production (through direct combustion, gasification, or pyrolysis), biogas production (through anaerobic digestion), and bioethanol production (through fermentation) (Gummert et al. 2020). Rice straw also has potential industrial uses such as in building materials (fiberboard or bricks) and other high-end materials such as silica and biofiber production (Van Hung et al. 2020).

The processing of rice straw from the collection, transportation, pre-treatment, and utilization composes the entire rice straw supply chain (Fig. 1). The rice straw supply chain begins after the rice harvest through mechanized straw collection since manual collection is too inefficient and costly (Balingbing et al. 2019). Next, rice straw pretreatment such as leaching, drying, storing, chopping, and densification may be done depending on the intended use (Alengebawy et al. 2023). Pre-treatments like drying and densification of rice straw (e.g., through pelletization) will improve the efficiency of combustion for bioenergy production (Migo-Sumagang, Hung et al. 2020). Rice straw pretreatment in the form of physical and chemical processing is required to improve the digestibility of fodder (Aquino et al. 2020). After pre-treatment, further processing for rice straw utilization opens opportunities for variable products. An option is to use it as a substrate for mushroom production via outdoor or indoor mushroom farming (Thuc et al. 2020). In terms of energy utilization, options include rice straw direct combustion in a furnace to generate heat in paddy drying (Migo-Sumagang, Hung et al. 2020), anaerobic digestion for biogas production (Mothe and Polisetty 2021), and fermentation into ethanol or other biorefinery products (Sreekumar et al. 2020).

To seek the best rice straw utilization alternative, decision-makers may refer to techno-economic assessments on rice straw utilization. First, it is important to look at studies that have been conducted at the early stages of the rice straw supply chain. For example, Balingbing et al. (2020) evaluated the fuel consumption, manpower requirements, and field capacity of mechanized collection in the Philippines. Quilty et al. (2014) also measured the labor energy requirements involved in operating agricultural equipment. Second, techno-economic assessments on different rice straw utilizations at the end of the supply chain are also important. Example studies include a techno-economic and environmental assessment of the production of biodiesel from rice-straw (Hu et al. 2023). Ishii et al. (2016) also examined the logistic cost analysis of rice straw pellet production. The techno-economic assessment of biogas production, briquette production, and gasification of rice straw has also been studied (Meng et al. 2020). Migo-Sumagang, Maguyon-Detras et al. (2020) assessed the energy, storage, and cost requirements of using rice straw as fuel to generate heat for paddy drying. The costs, material, and energy balances were investigated in rice straw pyrolysis to generate bio-oil and biochar (Tewfik et al. 2009). The costs of fodder (Aquino et al. 2020) and mushroom (Thuc et al. 2020) production were also evaluated. The rice straw supply chain in Fig. 1 presents a process network of different possible solutions with varying techno-economic valuations. Such systems can be integrated and optimized using Process Integration tools so that the raw materials are used efficiently to obtain the maximum profit.

Process Integration (PI) can help in optimizing resource consumption of process networks such as in rice straw supply chains. PI is a subfield of Process Systems Engineering focused on emissions reduction and the efficient use of resources (Klemeš et al. 2013). PI tools such as mathematical programming (MP) have provided clarity and insight to engineers in solving large-scale problems (Klemeš et al. 2013). The process graph or P-graph is another powerful PI tool intended to solve Process Network Synthesis problems (Friedler et al. 1979). A P-graph is composed of a bipartite graph with O-type nodes representing process or operating units and M-type nodes representing

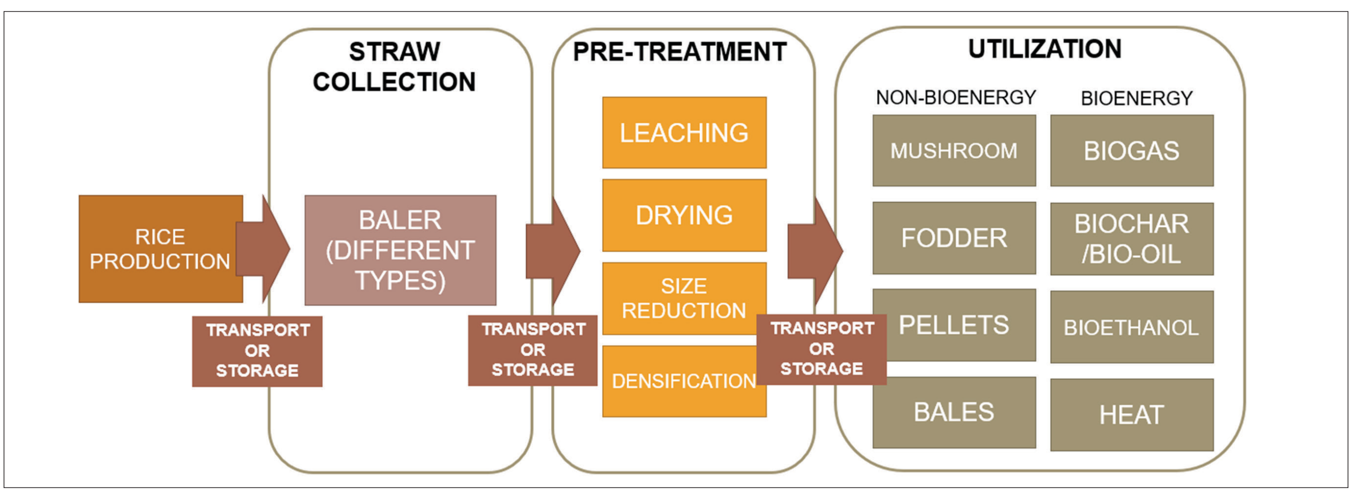

Fig. 1. The rice straw supply chain.

materials (raw, intermediate, or product). The operating units and materials are assembled in a process network following the 5 "rules" or axioms of the P-graph (Friedler et al. 1992b). The system properties such as flow streams, cost functions, input/output rates, raw material supply, and product demand can be specified. The model is solved using efficient algorithms (Friedler et al. 1992a) and the results are displayed graphically for easier visualization. Other advantages of a P-graph are the generation of the maximal structure, representing all possible connections in the system, as well as the generation of optimal and sub-optimal solutions (Aviso et al. 2019). Sub-optimal solutions may sometimes be more desirable than optimal solutions for practicality or lack of robustness of the optimal solution (Aviso et al. 2019). The P-graph optimization is analogous to the mixed integer linear programming (MILP) optimization with an assumption of a linear cost function. The free software (P-graph Studio), technical support, and tutorials are available via its official website (http://p-graph.org/) (P-Graph 2021).

A P-graph has many applications in supply chains and regional development, reaction pathways and mechanisms, chemical process synthesis, and business process management, among others (Klemeš and Varbanov 2015). One of the most impactful applications of a P-graph is in the optimization of regional energy supply chains using renewable energy (Lam et al. 2010). Studies have also been found to utilize P-graphs to optimize bioenergy supply chains utilizing agricultural wastes. The first of this kind was published by Vance et al. (2013) which optimized the design of heat and electric power supply chains using agricultural wastes as fuel. The study was further extended to consider cost constraints and sustainability indicators (Vance et al. 2014). A more recent study used a P-graph in optimizing agricultural waste-based integrated biorefinery (IBR) processes for the production of biofuels and biochemicals (Sangalang et al. 2021). The P-graph application in IBR was further extended to consider supply and demand constraints (Benjamin et al. 2021).

Given the techno-economic data and the number of possible networks, selecting the optimal rice straw utilization pathway is a challenging task. A previous study attempted to address this problem by assessing a sustainable rice straw utilization pathway using mathematical optimization (Diehlmann et al. 2019). However, a disadvantage of conventional mathematical optimization is the computational performance when handling complex problems as well as the inability to automatically show near-optimal solutions. Therefore, other approaches such as using the computationally efficient framework—P-graph—may be beneficial.

Thus, this study developed a novel P-graph model of rice straw management networks. The model considers straw collection and storage as part of the rice straw supply chain as well as the production of non-bioenergy products such as fodder and mushrooms in addition to bioenergy products. The focus of this work is technologies that do not require large capital investments and can be transferred to farmers as opposed to technologies that produce electricity, bioethanol, and other biorefinery products. The optimization used in this study is limited to a linear cost function. This work presents a decision support model in selecting optimal rice straw utilization pathways given techno-economic data. In addition, optimizing the rice straw supply chain leads to waste valorization and avoids pollution from open-field burning. Although the data used are context- and location- specific, this work can serve as the basis for modeling rice straw networks in rice-producing regions. The results of this study can guide decision- and policy-makers in addressing sustainability concerns in rice straw waste management.

MATERIALS AND METHODS

Problem Statement

Given the raw materials (rice straw, diesel, and labor energy) and various final products (pellets, mushroom, fodder, biogas, biochar, and heat) with their corresponding process streams data (unit cost/price, availability, etc.) and considering the various operating units (balers, tractor, storage, pelletizer, fodder pretreatment, anaerobic digester, pyrolizer, and furnace) and their corresponding techno-economic data and input/output rates, the problem is to find the optimal (and sub-optimal) rice straw networks in terms of maximum profit.

Data Collection

The process stream data were collected from published literature in the Philippines, Vietnam, India, and Japan. Rice straw, diesel, and labor energy were considered raw materials since they represent the main sources of energy consumption and cost. All the other materials were embedded in the operating units as part of the operating cost. Three areas (fields 1, 2, and 3) were assumed with land areas of 4, 6, and 8 ha, respectively. Sun-dried rice straw yield is at 2.69 t/ha with two cropping cycles per year (Migo-Sumagang, Maguyon-Detras et al. 2020). Hence, the maximum yields of rice straw are 21.52, 32.28, and 43.01 t/yr in fields 1, 2, and 3, respectively using Equation 1:

$$\mathbf{Y_{RS,max} = A * Y_{RS,A} * N} \qquad \textbf{(1)}$$

where $Y_{RS,max}$ is the maximum rice straw yield per year, A is the land area, $Y_{RS,A}$ is the rice straw yield per area, and N is the number of cropping cycles.

The costs of diesel and manual labor are shown in Table 1, while the cost of rice straw was embedded in the baling process. The cost of labor is US$ 0.96/man-hr, and the energy requirement in manually handling the rice straw is 0.89 MJ/man-hr (Migo-Sumagang, Maguyon-Detras et al. 2020). In the baseline scenario, it was assumed that both diesel and manual labor are unlimited. The unit prices of the various rice straw products are also presented in Table 1. Since it is also possible for baled straw and pellets to be sold as final products (e.g., for animal bedding, etc.), the prices of each were also included.

The variable costs of the operating units were obtained from the different studies as presented in Table 2. The investment and fixed costs were not included in the case study, and thus are not reported. To avoid double-counting, the diesel and labor energy costs were separated from the operating costs in Table 2 since these were accounted for under the diesel and labor energy as raw materials. Three different types of balers were considered. Baling cost includes the depreciation cost of the baler and rope for bailing. Since rice straw storage, size reduction, and densification before combustion are important to improve the efficiency of combustion (Migo-Sumagang, Hung et al. 2020), storage and pelletization operating units were included. Storage includes the depreciation cost of the storage warehouse (Migo-Sumagang, Maguyon-Detras et al. 2020). The cost of pelletization includes the depreciation cost of the equipment (Ishii et al. 2016). Fodder pretreatment considers the costs of chemicals based on 2021 prices and the amount required per tons of rice straw (Aquino et al. 2020). Mushroom production considers the cost of spawns, watering, land, etc. (Thuc et al. 2020). Anaerobic digestion considers the cost of the biogas reactor (Nguyen, Topno et al. 2016). Pyrolysis includes the depreciation cost of the equipment (Tewfik et al. 2009). Similarly, direct combustion considers the depreciation of the furnace (Migo-Sumagang, Maguyon-Detras et al. 2020).

Table 1. Raw material availabilities in the case study.

Material	Unit Cost or Price	Availability per year (Baseline Scenario)	Reference
Raw materials			
Rice straw field 1	(Embedded in the baling)	21.52 t	
Rice straw field 2	(Embedded in the baling)	32.28 t	
Rice straw field 3	(Embedded in the baling)	43.04 t	
Diesel	US$ 0.82/L	unlimited	(Migo-Sumagang, Maguyon-Detras et al. 2020)
Manual labor	US$ 0.96/man-hr	unlimited	(Migo-Sumagang, Maguyon-Detras et al. 2020)
Final products			
Baled straw	US$ 33.00/t		(Migo-Sumagang, Maguyon-Detras et al. 2020)
Rice straw pellets	US$ 290.00/t		(Ishii et al. 2016)
Mushroom	US$ 2.35/kg		(Thuc et al. 2020)
Biogas	US$ 0.41/m^3		(Nguyen, Nguyen et al. 2016)
Fodder	US$ 67.00/t		(Duncan et al. 2020)
Biochar	US$ 500.00/t		(Keske et al. 2020)
Heat	US$ 0.08/kWh		(Migo-Sumagang, Maguyon-Detras et al. 2020)

Table 2. Variable costs of the operating units excluding labor and fuel consumption.

Unit	Operating Cost US$/t straw	Reference
Baler pulled tractor	5.76	(Nguyen, Nguyen et al. 2016)
Self-propelled baler 1	7.49	(Nguyen, Nguyen et al. 2016)
Self-propelled baler 2	2.88	(Nguyen, Nguyen et al. 2016)
Storage warehouse	18.20	(Migo-Sumagang, Maguyon-Detras et al. 2020)
Pelletizer	9.20	(Ishii et al. 2016)
Fodder pretreatment	10.35	(Aquino et al. 2020)
Mushroom production	71.20	(Thuc et al. 2020)
Anaerobic digester	23.60	(Nguyen, Topno et al. 2016)
Pyrolizer	27.20	(Tewfik et al. 2009)
Furnace	23.60	(Migo-Sumagang, Maguyon-Detras et al. 2020)

The input and output rates and capacities are found in Table 3. The outputs of the balers were calculated based on the rice straw losses (Nguyen, Nguyen et al. 2016). The fuel and labor requirements and annual capacities of the baler were based on the literature data (Nguyen, Nguyen et al. 2016). Driving the tractor and balers were assumed to consume 0.97 MJ/t based on literature (Quilty et al. 2014). The storage capacities and labor requirements are also shown in Table 3. A pelletizer loss of 10% was assumed and the capacity of the pelletizer was obtained from the literature (Ishii et al. 2016). The energy requirement of a pelletizer is 230 kWh/t (Ishii et al. 2016), and this value was converted to its diesel equivalent in L using the energy value of diesel 15.6 MJ/L (Nguyen, Nguyen et al. 2016). The manual labor in pelletizing was assumed to be the same as operating a tractor. For the transportation of straw, a 4-km distance was assumed from the baled straw pickup point and the pelletizer to the biogas plant, pyrolysis plant, and furnace for direct combustion. The diesel consumption during transportation was obtained from the literature (Migo-Sumagang, Maguyon-Detras et al. 2020). No losses were assumed during transportation. The manual labor for mushroom production, fodder production, anaerobic digestion, pyrolysis, and direction combustion was assumed to be the same as manually handling of rice straw. Biochar yield was obtained from literature. The diesel requirement for the pyrolysis equipment was assumed to be the same as with the furnace operation for direct combustion from literature (Migo-Sumagang, Maguyon-Detras et al. 2020).

Table 3. Input and output rates

Unit Name	Input(s)	Rate	Output(s)	Rate	Capacity Per Year	Reference
Baler pulled tractor	Loose straw	1 t	Baled straw	0.786 t	2 590 t	(Nguyen, Nguyen et al. 2016)
	Diesel	2.61 L				(Nguyen, Nguyen et al. 2016)
	Manual labor	0.97 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Self-propelled tractor	Loose straw	1 t	Baled straw	0.823	3 090 t	(Nguyen, Nguyen et al. 2016)
	Diesel	6.57 L				(Nguyen, Nguyen et al. 2016)
	Manual labor	0.97 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Self-propelled gathering	Loose straw	1 t	Baled straw	1 t	3 705 t	(Nguyen, Nguyen et al. 2016)
	Diesel	4.18 L				(Nguyen, Nguyen et al. 2016)
	Manual labor	0.97 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Storage	Baled straw	1 t	Straw from storage	1 t	320 t	(Migo-Sumagang, Maguyon-Detras et al. 2020)
	Manual labor	4.7 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Pelletizer	Baled straw	1 t	Pelletized straw	0.9 t	1 500 t	(Ishii et al. 2016)
	Diesel	53.1 L				(Ishii et al. 2016)
	Manual labor	0.97 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Transportation (4 km distance)	Pelletized straw	1 t	Straw for biogas	1 t	960 t	(Migo-Sumagang, Maguyon-Detras et al. 2020)
	Diesel	2.18 L	Straw for biochar	1 t		(Migo-Sumagang, Maguyon-Detras et al. 2020)
	Manual labor	0.97 MJ	Straw for heat	1 t		(Migo-Sumagang, Maguyon-Detras et al. 2020)
Mushroom production	Baled straw	1 t	Mushroom	100 kg	2 000 000 kg	(Raman et al. 2018; IRRI Rice Knowledge Bank 2020)
	Manual labor	4.7 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Anaerobic digestion	Baled straw	1 t	Biogas	390 m^3		(Nguyen, Nguyen et al. 2016)
	Manual labor	4.7 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Fodder production	Baled straw	1 t	Fodder	1 t	1 000 000 t	
	Manual labor	4.7 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Pyrolysis	Pelletized straw	1 t	Biochar	0.49 t	30 000 000 t	(Tewfik et al. 2009; Wu et al. 2012)
	Manual labor	5.7 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
	Diesel	6.57 L				(Migo-Sumagang, Maguyon-Detras et al. 2020)
Direct combustion	Pelletized straw	1 t	Heat	3 058 kWh	88 682 kWh	(Migo-Sumagang, Maguyon-Detras et al. 2020)
	Manual labor	5.7 MJ				(Migo-Sumagang, Maguyon-Detras et al. 2020)
	Diesel	6.57 L				(Migo-Sumagang, Maguyon-Detras et al. 2020)

Maximal Structure Generation (MSG)

The P-graph framework, originally developed to solve Process Network Synthesis problems, includes both combinatorial and linear programming parts (Éles et al. 2021). It can effectively graph and optimize complex process networks, and therefore, combines the benefits of both combinatorial algorithms and mathematical programming (Éles et al. 2021). Since the rice straw supply chain can be represented as a process network, and the selection of the optimal utilization pathway is a combinatorial problem, the P-graph framework is adequate in addressing the problem.

The maximal structure of the P-graph model was constructed using the software P-graph Studio version 5.2.5 (**Fig. 1**). The maximal structure shows all the possible pathways that the rice straw raw material can be converted into the final products. The node representations are as follows, raw materials are represented by the circles with a white inverted triangle inside; intermediate materials by the solid circles; the final products by the circles with a smaller circle inside; and the operating units by horizontal bars. The connections between the nodes represent the input and output streams. In Fig. 2, the connections represented by the brown lines are the diesel flows, while the green lines are the labor energy flows.

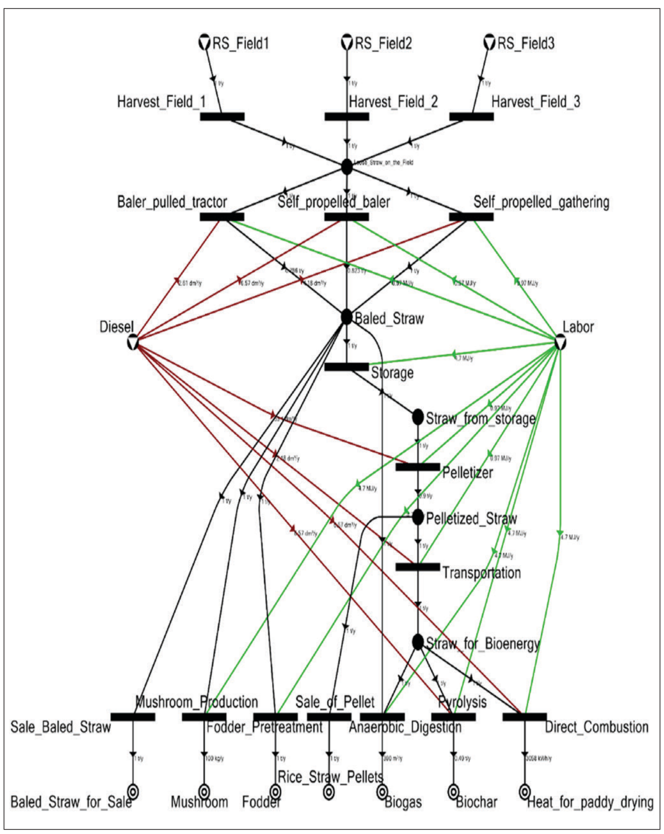

Fig. 2. Superstructure/Maximal structure of the rice straw network.

Solving the Model

A P-graph finds the optimal structure by maximizing the profit from the product less the cost of the raw materials and the operating units. The cost of the operating unit is described by a linear cost function as shown in Equation 2. The cost value C_i, is a function of x_i, which is the capacity of the operating unit. The parameters a_i and b_i correspond to annualized fixed and variable costs, respectively. Since the case study is limited to the operating costs, and the investment and fixed costs are excluded, a_i is equal to zero in the illustrative case study.

$$C_i=a_i+b_i\,x_i \qquad (2)$$

The P-graph framework uses three efficient algorithms: Maximal Structure Generation (MSG), Solution Structure Generation (SSG), and Accelerated Branch-and-Bound (ABB) (Friedler et al. 1992a). MSG generates the maximal structure based on the five axioms of a P-graph. SSG enumerates the combinatorially feasible structures based on the maximal structure. The framework includes an underlying linear programming model to be solved by the ABB algorithm (Éles et al. 2021).

The models were solved in P-graph Studio version 5.2.5, on a laptop with 8.00 GB RAM, i7–7500U CPU, and a 64–bit operating system running on Windows 10 Home Single Language. The runtimes finished in less than 1 s each.

Case Study Scenarios

Four scenarios were investigated. The baseline (Scenario 1) assumes the raw material availabilities in Table 1 where the maximum yields of rice straw are achieved, and diesel and manual labor are unlimited. This scenario is plausible when the efficiency of rice straw collection is highest and petroleum fuel is cheap. Scenarios 2 to 4 are disruption scenarios wherein the availabilities of the diesel, manual labor, and rice straw are reduced to 100 L/yr, 500 MJ/yr, and 75.32 t/yr, respectively (Table 4). Scenario 2 simulates the possible future decarbonization, thus limiting the supply of diesel. Currently, there is a move to shift to low-carbon energy sources and future policies may limit the availability of petroleum fuel. Scenario 3 simulates the possible lack of available manpower in agriculture, for example, due to the lack of interest of future generations in agriculture. The decreasing trend in the number of agricultural workers in the country is being presently observed in the country as reported by the Philippine Statistics Authority (Baclig 2022). In Scenario 4, rice straw field 1 stops producing rice, simulating the possible future land–use change. The Philippines has streamlined the conversion of agricultural land to other types (Fulgar 2021), prompting an increase in agricultural land use conversion.

Table 4. Case study scenarios.

Scenario	Type	Rice Straw Limit (t/yr)	Diesel Limit (L/yr)	Manual Labor Limit (MJ/yr)
1	Baseline	96.84	unlimited	unlimited
2	Disruption (diesel)	96.84	100	unlimited
3	Disruption (manual labor)	96.84	unlimited	500
4	Disruption (rice straw)	75.32	unlimited	unlimited

RESULTS AND DISCUSSION

Solving the model resulted in 155 feasible networks, 22 of which are presented in Table 5. The optimal solution in terms of profit is in the first row of the table, followed by the sub-optimal solutions in decreasing profits (ranks 2 to 20, 29, and 52). The required amounts of diesel, labor energy, and rice straw for each network are reported as negative values in columns 2 to 4 of Table 5. These are followed by the products wherein blank rows indicate that the specific product is not produced in the network. It is possible to have multiple types of products (such as the solutions ranked 29 and 52 shown in Figs. 3b and 3c), creating a portfolio. The values in the product columns indicate the amount of product(s) generated for that network. The last column shows the maximum potential profit generated by the network.

The optimal and two sub-optimal structures are found in Figs. 3a to 3c. The case study considered the operating and raw material costs but did not consider the fixed and investment costs in the calculation of the profit. Based on the results, the optimal solution is mushroom production with a profit of US$ 14 658.60/yr, followed by rice straw pellets production with a profit of US$ 12 626.90/yr. Among the top 18 solutions, only mushroom and rice straw pellets are selected. Fodder production only comes in 19th place, with a profit of US$ 6 993.67/yr. The other unique solutions—biochar and heat for paddy drying —are ranked 29 with a profit of US$ 5 269.13/yr, while baled straw and heat for paddy drying are ranked 52 with a profit of US$ 3 473.04/yr. Biogas production is not selected among the top 52 solutions. The difference in profit between the optimal solution and the 20th sub-optimal solution is US$ 7177.87/yr, which is almost half the optimum profit.

Table 5. Optimal and sub-optimal solutions for Scenario 1 (baseline).

Rank	Raw Materials			Products						Profit
	Diesel	Labor	Rice Straw	Baled Straw for Sale	Biochar	Fodder	Heat for Paddy Drying	Mush-room	Rice Straw Pellets	
	[dm³/yr]	[MJ/yr]	[t/yr]	[t/yr]	[t/yr]	[t/yr]	[kWh/yr]	[kg/yr]	[t/yr]	[US$/yr]
Optimum	-404.79	-549.08	-96.84					9 684.00		14 658.60
2	-5 547.00	-643.02	-96.84						87.16	12 626.90
3	-314.84	-427.06	-75.32					7 532.00		11 401.10
4	-636.24	-468.52	-96.84					7 969.93		11 301.70
5	-252.75	-451.68	-96.84					7 611.62		11 215.00
6	-4 314.33	-500.13	-75.32						67.79	9 820.91
7	-269.86	-366.06	-64.56					6 456.00		9 772.37
8	-4 868.27	-545.83	-96.84						71.73	9 629.64
9	-4 294.52	-525.51	-96.84						68.50	9 618.08
10	-494.85	-364.41	-75.32					6 198.84		8 790.21
11	-196.59	-351.31	-75.32					5 920.15		8 722.75
12	-3 698.00	-428.68	-64.56						58.10	8 417.93
13	-224.88	-305.05	-53.80					5 380.00		8 143.64
14	-424.16	-312.35	-64.56					5 313.29		7 534.47
15	-3 786.43	-424.53	-75.32						55.79	7 489.72
16	-3 340.19	-408.73	-75.32						53.28	7 480.73
17	-168.50	-301.12	-64.56					5 074.42		7 476.65
18	-3 081.66	-357.23	-53.80						48.42	7 014.94
19	-404.79	-549.08	-96.84			96.84				6 993.67
20	-179.91	-244.04	-43.04					4 304.00		6 514.91
29	-6 309.61	-1 137.19	-96.84		28.50		88 682.00			5 269.13
52	-2 369.54	-441.07	-96.84	64.62			88 682.00			3 473.04

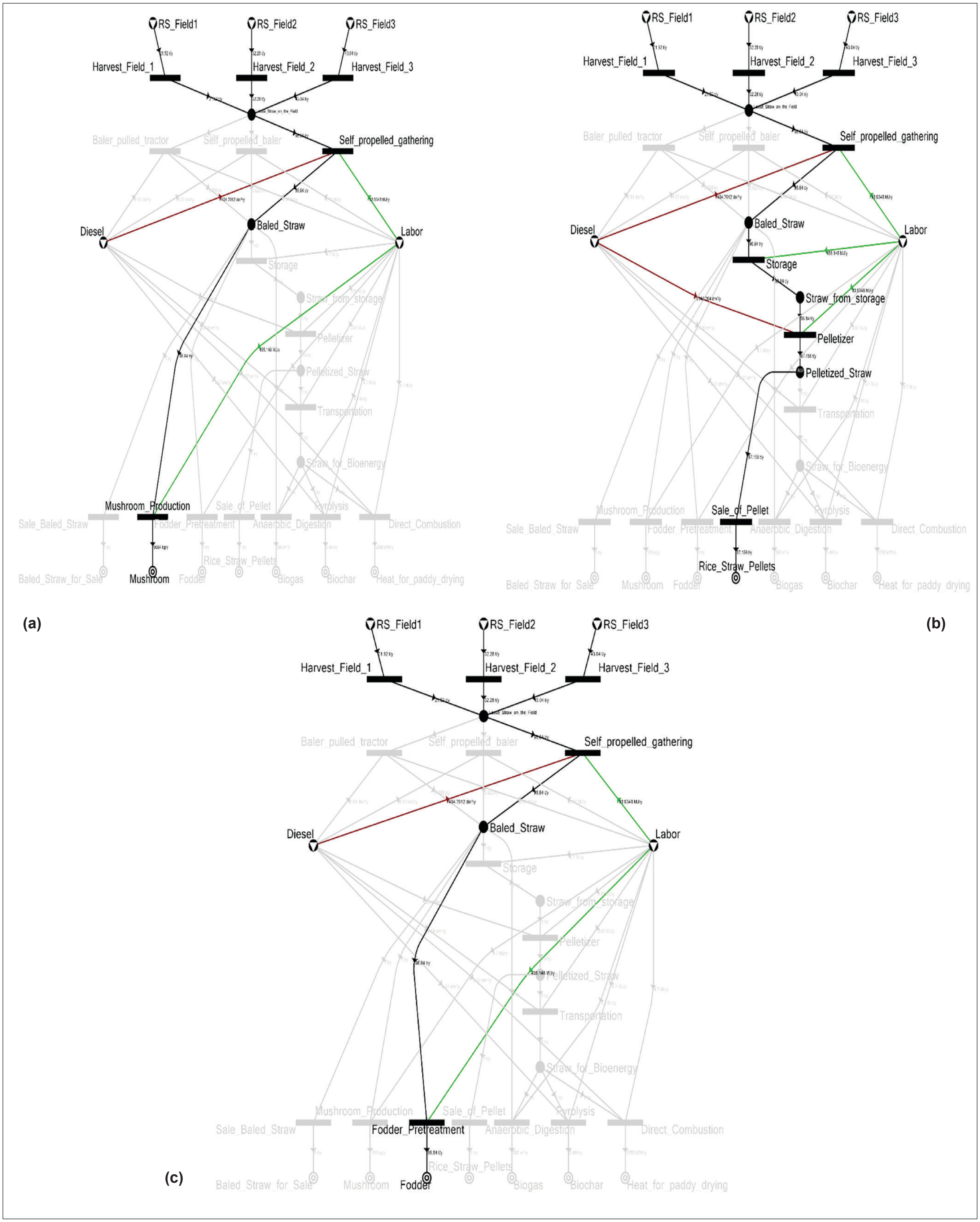

Fig. 3. The optimal solution, mushroom production (a) 2nd sub-optimal solution, rice straw pellets production (b), and 19th sub-optimal solution, fodder production (c) of Scenario 1 (baseline).

The best rice straw solution or portfolio of solutions is context- and location- specific (Van Hung et al. 2020). Hence, based only on the data used, mushroom and pellet production are the most preferable options. It is important to note, however, that the present model does not consider the demands of each product. From Table 5, networks involving mushroom production have lower diesel requirements, which may be one of the reasons for its profitability. Mushroom is known to have low production costs, growing flexibly both indoors and outdoors (Thuc et al. 2020). In addition, the native Philippine mushroom has nutraceutical and anti-inflammatory properties (Reyes et al. 2013), making it a product with great potential. Rice straw pellets (US$ 0.29/kg) also rank in the top 20 solutions. Despite the results, rice straw pellet production is affected by economies of scale and would require a capacity of 1500 t/yr to compete with wood and fossil fuels (Ishii et al. 2016). Fodder production, on the other hand, generates only half of the optimal profit. Fodder production is advantageous in other ways since it improves animal performance and increases the production efficiency of meat and milk (Aquino et al. 2020). Bioenergy products in the form of biochar and heat only come in ranks 29 and 52. The data used in the model is based on a paddy dryer simulator using an electric blower, which contributes 40% of the cost of paddy drying, which may explain the lower profitability of the product (Migo-Sumagang, Maguyon-Detras et al. 2020). The additional processing steps in bioenergy production may also explain its lower profitability compared to the non-bioenergy products.

The results of the disruption scenarios are shown in Table 6, showing the optimal solution, as well as another sub-optimal solution for each scenario. Since the optimal solution structures Scenarios 2 to 4 resemble Fig. 3a, the structures were not included in the paper. In Scenario 2, a limit of 100 L/yr in diesel was imposed, simulating the future decarbonization. The results show that the reduction in the available diesel still favors mushroom production but at almost 70% reduction in profit at US$ 4437.14/yr. Pellet production is completely removed from the top solutions, and fodder production appears in rank 14th with a profit of US$ 2053.54/yr, which is an 84% reduction in profit compared to the baseline's best pellet production. Scenario 3 reduced the available labor to 500 MJ/yr, simulating the possible lack of interest of future generations in agriculture. In this scenario, the optimal solution is still mushroom production at the same profit as the baseline scenario. Mushroom production is unaffected by the reduction in manual labor in this case since the baseline scenario only requires 549 MJ/yr of labor energy, which is close to the limit of 500 MJ/yr of Scenario 3. Pellet production ranks 5^{th} in the sub-optimal solutions in Scenario 3 but is accompanied by baled straw sales, with a total profit of US$ 9984.86/yr. Scenario 4 assumes that the rice straw in field 1 is unavailable (21.52 t/yr), simulating the possible land-use change. The top solutions in this scenario are similar in structure to that of the baseline scenario but at a 22% profit reduction (Table 6). Hence, the disruption scenarios show that mushroom production is still the optimum solution, indicating the robustness of this option using the case study data. Fig. 4 graphs the optimal and sub-optimal (rank 2) solutions of Scenario 1 with the disruption scenario solutions of Table 6. The dip in the profit of Scenario 2 shows that the profitability of the supply chain is strongly dependent on diesel as a raw material. It is beneficial to address the dependency of the rice straw supply chain on fossil fuel in future policies, for example, by looking at low-carbon alternatives.

Table 6. Disruption scenarios.

Scenario and Rank	Raw Materials			Products						Profit
	Diesel	Labor	Rice Straw	Baled Straw for Sale	Biochar	Fodder	Heat for Paddy Drying	Mush-room	Rice Straw Pellets	
	[dm^3/yr]	[MJ/yr]	[t/yr]	[t/yr]	[t/yr]	[t/yr]	[kWh/yr]	[kg/yr]	[t/yr]	[US$/yr]
Scenario 1 Rank 1	-100.00	-178.71	-38.31					3 011.49		4 437.14
Scenario 1 Rank 14	-100.00	-178.71	-21.52			30.11				2 053.54
Scenario 2 Rank 1	-368.61	-500.00	-88.18					8 818.34		14 658.60
Scenario 2 Rank 5	-4 207.62	-500.00	-96.84	25.22					64.45	9 984.86
Scenario 3 Rank 1	-314.84	-427.06	-75.32					7 532.00		11 401.10
Scenario 3 Rank 2	-4 314.33	-500.13	-75.32						67.79	9 820.91

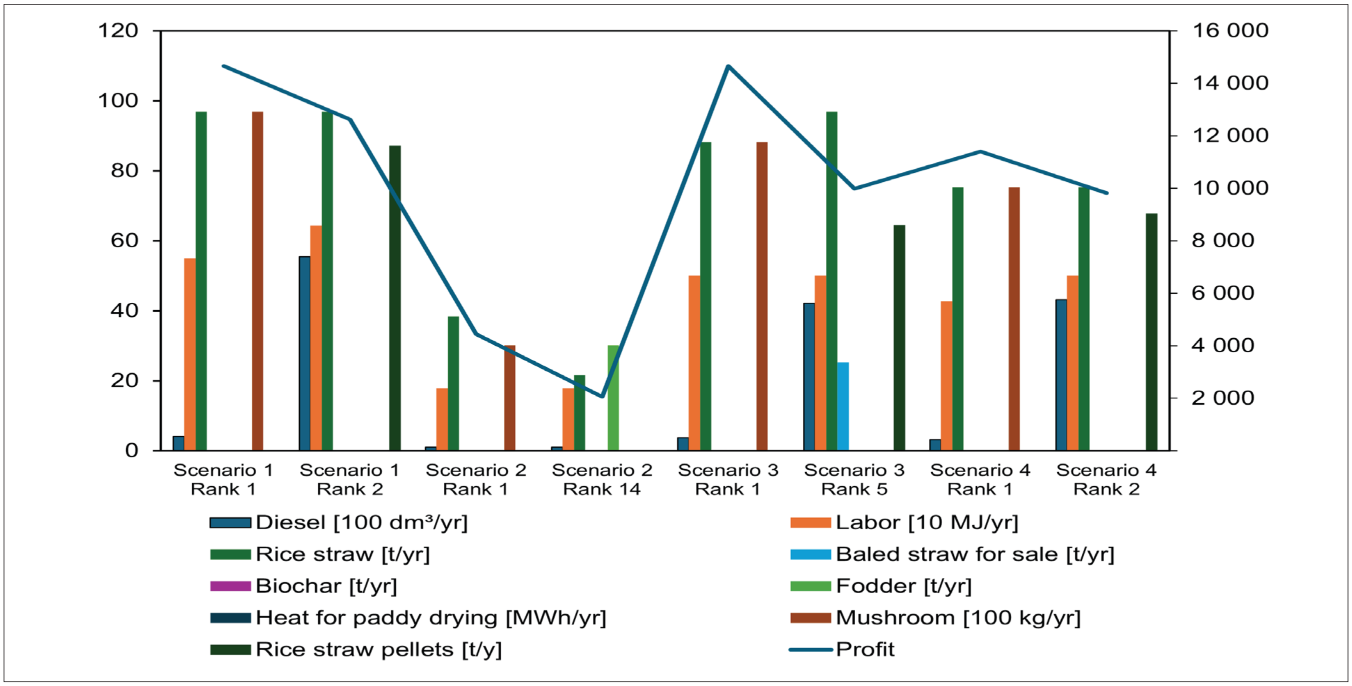

Fig. 4. Optimal and selected sub-optimal solutions for the different scenarios.

CONCLUSION

This study presents a novel P-graph model to support decision-making in optimal rice straw utilization pathways using techno-economic data. The model considers the rice straw collection and storage steps as well as the production of both bioenergy and non-bioenergy products. The model can generate optimal and sub-optimal solutions (based on profit) and can simulate diesel, labor energy, and rice straw raw material disruption scenarios. Based on the illustrative case study using 96.84 t/yr rice straw (considering the operating and raw material costs and excluding investment and fixed costs), mushroom production is the optimal solution in terms of profit (US$ 14 658.60/yr), followed by pellet production (US$ 12 626.90/yr). Disruption scenarios simulating future reductions in the available diesel, labor energy, and rice straw raw materials show that mushroom production is still the optimum solution, indicating the robustness of this option. Although the best rice straw solution or portfolio of solutions is context- and location-specific, this basic model demonstrates that the P-graph approach can be applied to rice straw management networks to aid with decision-making for sustainability. For example, in some areas, rice straw as fodder is the best solution due to the low transportation cost. In addition, the results only reflect the current scale of the study (96.84 t/yr rice straw). Mushroom production using rice straw as substrate at larger scales must be investigated. Hence, the results must be interpreted with caution and be further consulted with experts before translating into policy. Overall, this study presents a decision support model for rice straw waste valorization and avoidance of open-field burning. Future work includes carbon footprint accounting from Life Cycle Analysis (LCA) and integration with multi-criteria decision analysis (MCDA) techniques such as Analytical Hierarchy Process (AHP) to evaluate the sub-optimal solutions. It is also recommended to consider demand constraints and uncertainties in the data in future models.

REFERENCES CITED

ALENGEBAWY A, RAN Y, GHIMIRE N, OSMAN AI, AI P. 2023. Rice straw for energy and value-added products in China: A review. Environ Chem Lett. 21:2729–2760. doi:10.1007/s10311-023-01612-3.

AQUINO D, DEL BARRIO A, TRACH NX, HAI NT, KHANG DN, TOAN NT, HUNG NV. 2020. Rice straw-based fodder for ruminants. In: Gummert M, Hung N, Chivenge P, Douthwaite B, editors. Sustainable rice straw management. Springer, Cham. p. 111–129. doi:10.1007/978-3-030-32373-8_7.

AVISO KB, BELMONTE BA, BENJAMIN MFD, AROGO JIA, CORONEL ALO, JANAIRO CMJ, FOO DCY, TAN RR. 2019. Synthesis of optimal and near-optimal biochar-based Carbon Management Networks with P-graph. J Clean Prod. 214:893–901. doi:10.1016/j.jclepro.2019.01.002.

BACLIG CE. 2022. PH farms getting empty: agriculture job loss a worrying trend. Inquirer.net. https://newsinfo.inquirer.net/1703034/for-posting-edited-ph-farms-getting-empty-agriculture-job-loss-a-worrying-trend.

BALINGBING C, HUNG NV, NGHI NT, HIEU NV, ROXAS AP, TADO CJ, BAUTISTA E, GUMMERT M. 2019. Mechanized collection and densification of rice straw. In: Gummert M, Hung N, Chivenge P, Douthwaite B, Editors. Sustainable rice straw management. Springer, Cham. p. 15–32. doi:10.1007/978-3-030-32373-8_2/FIGURES/17.

BALINGBING C, HUNG NV, ROXAS AP, AQUINO D, BARBACIAS MG, GUMMERT M. 2020. An assessment on the technical and economic feasibility of mechanized rice straw collection in the Philippines. Sustainability. 12(17):7150. doi:10.3390/su12177150.

BENJAMIN MFD, VENTURA JS, SANGALANG KPH, ADORNA JA JR., BELMONTE BA, ANDIAPPAN V. 2021. Optimal synthesis of Philippine agricultural residue-based integrated biorefinery via the P-graph method under supply and demand constraints. J Clean Prod. 308:127348. doi:10.1016/j.jclepro.2021.127348.

DIEHLMANN F, ZIMMER T, GLÖSER-CHAHOUD S, WIENS M, SCHULTMANN F. 2019. Techno-economic assessment of utilization pathways for rice straw: a simulation-optimization approach. J Clean Prod. 230:1329–1343. doi:10.1016/j.jclepro.2019.04.369.

DUNCAN AJ, SAMADDAR A, BLÜMMEL M. 2020. Rice and wheat straw fodder trading in India: possible lessons for rice and wheat improvement. Field Crop Res. 246:107680. doi:10.1016/j.fcr.2019.107680.

ÉLES A, HECKL I, CABEZAS H. 2021. Modeling technique in the P-Graph framework for operating units with flexible input ratios. Cent Eur J Oper Res. 29:463–489. doi:10.1007/s10100-020-00683-9.

FRIEDLER F, BLICKET T, GYENIS J, TARJÁNS K. 1979. Computerized generation of technological structures. Comput Chem Eng. 3(1–4):241–249. doi:10.1016/0098-1354(79)80042-3.

FRIEDLER F, TARJÁN K, HUANG YW, FAN LT. 1992a. Combinatorial algorithms for process synthesis. Comput Chem Eng. 16(S1):S313–S320. doi:10.1016/S0098-1354(09)80037-9.

FRIEDLER F, TARJÁN K, HUANG YW, FAN LT. 1992b. Graph-theoretic approach to process synthesis: axioms and theorems. Chem Eng Sci. 47(8):1973–1988. doi:10.1016/0009-2509(92)80315-4.

FULGAR AJIL. 2021. Converting agricultural land for development use. Inquirer.net. https://business.inquirer.net/318173/converting-agricultural-land-for-development-use.

GAVA O, ARDAKANI Z, DELALIC A, MONACO S. 2024. Environmental impacts of rice intensification using high-yielding varieties: evidence from Mazandaran, Iran. Sustainability. 16(6):2563. doi:10.3390/su16062563.

GUMMERT M, HUNG NV, CHIVENGE P, DOUTHWAITE B. 2020. Sustainable rice straw management. Springer Cham. doi:10.1007/978-3-030-32373-8.

HU Y, CHEN J, TIAN H, HU Z. 2023. Techno-economic and environmental evaluation of the production of biodiesel from rice-straw in China. Front Energy Res. 11:1286373. doi:10.3389/fenrg.2023.1286373.

IRRI RICE KNOWLEDGE BANK. 2020. Off-field rice straw management. http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products/rice-straw/off-field-rice-straw-management.

ISHII K, FURUICHI T, FUJIYAMA A, WATANABE S. 2016. Logistics cost analysis of rice straw pellets for feasible production capacity and spatial scale in heat utilization systems: a case study in Nanporo town, Hokkaido, Japan. Biomass and Bioenerg. 94:155–166. doi:10.1016/j.biombioe.2016.08.007.

KESKE C, GODFREY T, HOAG DLK, ABEDIN J. 2020. Economic feasibility of biochar and agriculture coproduction from Canadian black spruce forest. Food Energ Secur. 9(1):e188. doi:10.1002/fes3.188.

KLEMEŠ JJ, VARBANOV PS. 2015. Spreading the message: P-Graph enhancements: implementations and applications. Chem Eng Trans. 45:1333–1338. doi:10.3303/CET1545223.

KLEMEŠ JJ, VARBANOV PS, KRAVANJA Z. 2013. Recent developments in Process Integration. Chem Eng Res Des. 91(10):2037–2053. doi:10.1016/j.cherd.2013.08.019.

LAM HL, VARBANOV PS, KLEMEŠ JJ. 2010. Optimisation of regional energy supply chains utilising renewables: P-graph approach. Comput Chem Eng. 34(5):782–792. doi:10.1016/j.compchemeng.2009.11.020.

MBOYERWA PA, KIBRET K, MTAKWA P, ASCHALEW A. 2022. Greenhouse gas emissions in irrigated paddy rice as influenced by crop management practices and nitrogen fertilization rates in eastern Tanzania. Front Sustain Food Syst. 6:868479. doi:10.3389/fsufs.2022.868479.

MENG L, ALENGEBAWY A, AI P, JIN K, CHEN M, PAN Y. 2020. Techno-economic assessment of three modes of large-scale crop residue utilization projects in China. Energies. 2020, 13(14):3729. doi:10.3390/en13143729.

MIGO-SUMAGANG MVP, HUNG NV, DETRAS MCM, ALFAFARA CG, BORINES MG, CAPUNITAN JA, GUMMERT M. 2020. Optimization of a downdraft furnace for rice straw-based heat generation. Renew Energ. 148:953–963. doi:10.1016/j.renene.2019.11.001.

MIGO-SUMAGANG MVP, MAGUYON-DETRAS MC, GUMMERT M, ALFAFARA CG, BORINES MG, CAPUNITAN JA, HUNG NV. 2020. Rice-straw-based heat generation system compared to open-field burning and soil incorporation of rice straw: an assessment of energy, GHG emissions, and economic impacts. Sustainability. 12(13):1–18. doi:10.3390/su12135327.

MOTHE S, POLISETTY VR. 2021. Review on anaerobic digestion of rice straw for biogas production. Environ Sci Pollut Res. 28:24455–24469. doi:10.1007/s11356-020-08762-9.

NGUYEN HV, NGUYEN CD, TRAN TV, HAU HD, NGUYEN NT, GUMMERT M. 2016. Energy efficiency, greenhouse gas emissions, and cost of rice straw collection in the mekong river delta of vietnam. Field Crop Res. 198:16–22. doi:10.1016/j.fcr.2016.08.024.

NGUYEN VH, TOPNO S, BALINGBING C, NGUYEN VCN, RÖDER M, QUILTY J, JAMIESON C, THORNLEY P, GUMMERT M. 2016. Generating a positive energy balance from using rice straw for anaerobic digestion. Energ Rep. 2:117–122. doi:10.1016/j.egyr.2016.05.005.

P-GRAPH. 2021. http://www.p-graph.org/.

PHUONG PTH, NGHIEM TD, THAO PTM, PHAM CT, THI TT, DIEN NT. 2021. Impact of rice straw open burning on local air quality in the Mekong Delta of Vietnam. Atmos Pollut Res. 12:101225. doi:10.1016/j.apr.2021.101225.

QUILTY JR, MCKINLEY J, PEDE VO, BURESH RJ, CORREA TQ JR., SANDRO JM. 2014. Energy efficiency of rice production in farmers' fields and intensively cropped research fields in the Philippines. Field Crop Res. 168:8–18. doi:10.1016/j.fcr.2014.08.001.

RAMAN J, LEE SK, IM JH, OH MJ, OH YL, JANG KY. 2018. Current prospects of mushroom production and industrial growth in India. J Mushrooms. 16:239–249. doi:10.14480/JM.2018.16.4.239.

REYES RG, KALAW SP, DULAY RMR, YOSHIMOTO H, MIYAZAWA N, SEYAMA T, EGUCHI F. 2013. Philippine native and exotic species of edible mushrooms grown on rice-straw-based formulation exhibit nutraceutical properties. Philipp Agric Sci. 96:198–204. https://www.researchgate.net/publication/280137047_Philippine_Native_and_Exotic_Species_of_Edible_Mushrooms_Grown_on_Rice-Straw-Based_Formulation_Exhibit_Nutraceutical_Properties.

ROMASANTA RR, SANDER BO, GAIHRE YK, ALBERTO MC, GUMMERT M, QUILTY J, NGUYEN VH, CASTALONE AG, BALINGBING C, SANDRO J, CORREA T JR., WASSMANN R. 2017. How does burning of rice straw affect CH_4 and N_2O emissions? A comparative experiment of different on-field straw management practices. Agric Ecosyst Environ. 239:143–153. doi:0.1016/j.agee.2016.12.042.

SANGALANG KPH, BELMONTE BA, VENTURA JS, ANDIAPPAN V, BENJAMIN MFD. 2021. P-graph method for optimal synthesis of Philippine agricultural waste-based integrated biorefinery. Chem Eng Trans. 83:103–108. doi:10.3303/CET2183018.

SINGH K, SINGH S, KUMAR V, KHANDAI S, KUMAR A, BHOWMICK MK, KUMAR V, SRIVASTAVA A, HELLIN J. 2023. Rice straw management. In: Rakshit A, Biswas A, Sarkar D, Meena VS, Datta R, editors. Handbook of energy management in agriculture. Springer, Singapore, p. 1–25. doi:10.1007/978-981-19-7736-7_24-1.

SREEKUMAR A, SHASTRI Y, WADEKAR P, PATIL M, LALI A. 2020. Life cycle assessment of ethanol production in a rice-straw-based biorefinery in India. Clean Technol Environ Policy. 22:409–422. doi:10.1007/s10098-019-01791-0.

TEWFIK SR, SOROUR MH, ABULNOUR AMG, TALAAT HA, EL DEFRAWY NM, FARAH JY, ABDOU IK. 2009. Bio-oil from rice straw by pyrolysis: experimental and techno-economic investigations. J Am Sci. 7(2):59–67. https://www.researchgate.net/publication/288516201_Bio_oil_from_rice_straw_by_pyrolysisexperimental_and_techno-economic_investigations.

THUC LV, CORALES RG, SAJOR JT, TRUC NTT, HIEN PH, RAMOS RE, BAUTISTA E, TADO CJM, OMPAD V, SON DT, VAN HUNG N. 2020. Rice-straw mushroom production. In: Gummert M, Hung N, Chivenge P, Douthwaite B, editors. Sustainable rice straw management. Springer, Cham, p. 93–109. doi:10.1007/978-3-030-32373-8_6.

VAN HUNG N, MAGUYON-DETRAS MC, MIGO MV, QUILLOY R, BALINGBING C, CHIVENGE P, GUMMERT M. 2020. Rice straw overview: availability, properties, and management practices. In: Gummert M, Hung N, Chivenge P, Douthwaite B, editors. Sustainable rice straw management. Springer, Cham. doi:10.1007/978-3-030-32373-8_1.

VANCE L, CABEZAS H, HECKL I, BERTOK B, FRIEDLER F. 2013. Synthesis of sustainable energy supply chain by the P-graph framework. Ind Eng Chem Res. 52(1):266–274. doi:10.1021/ie3013264.

VANCE L, HECKL I, BERTOK B, CABEZAS H, FRIEDLER F. 2014. Designing energy supply chains with the P-graph framework under cost constraints and sustainability considerations. Comput-Aided Chem En. 33:1009–1114. doi:10.1016/B978-0-444-63455-9.50003-9.

WU W, YANG M, FENG Q, MCGROUTHER K, WANG H, LU H, CHEN Y. 2012. Chemical characterization of rice straw-derived biochar for soil amendment. Biomass Bioenerg. 47:268–276. doi:10.1016/j.biombioe.2012.09.034.