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Techno-economic Analysis Conversion of Empty and Partially Filled Paddy Grain Waste into Glucose through Bioconversion Route

Nurul Ain Abu Bakar[1]*, Ahmad Muhaimin Roslan[2], Mohd Ali Hassan[2], Muhammad Daaniyall Abdul Rahman[3], Rozyanti Mohamad[4]

[1] Agrobiodiversity and Environment Research Centre, Malaysia Agriculture Research and Development Institute, Malaysia

[2] Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Malaysia

[3] Department of Economics, Faculty of Economics and Management, Universiti Putra Malaysia, Malaysia

[4] Malaysian Institute of Chemical and Bioengineering Technology. Universiti Kuala Lumpur, Malaysia

***Corresponding author:** nurulain@mardi.gov.my

Waste generated from Malaysia's paddy milling factories, known as empty and partially filled paddy grain (EPFG), has been improperly managed as it can be further utilized for sustainable resources such as feedstock via biorefinery. However, the critical driver for a biorefinery is whether the proposed design is profitable. In this study, the conversion of EPFG into glucose as an alternative to sustainable management was analysed in terms of their economic performance as feedstock. The process design involved the production of non-concentrated glucose from EPFG using hydrothermal pre-treatment and enzymatic process, which led to the 76% conversion yield. The economic performance for the plant is at 1.04 million USD, 46.9%, and 34.3% for net present value (NPV), return on investment (ROI), and internal rate return (IRR), respectively. The minimum sugar selling price (MSSP), when zero NPV, is at 0.42 $/kg when the co-product revenue is considered. Sensitivity analysis results indicate that the MSSP is highly sensitive to plant size. This economic evaluation serves as an introductory guide to assess the economic performance of paddy milling waste to glucose via enzymatic hydrolysis. The results of the present study could provide insight for the Malaysian paddy industry in managing the EPFG, hence increasing their market potential.

Keywords: enzyme hydrolysis, fermentable sugars, minimum sugar selling price, paddy waste, techno-economic analysis.

Introduction

The paddy post-harvest process, which occurs along the supply chain from harvesting to packaging, is important to control the waste at a minimum level. Nevertheless, even with effective management advocacy for minimizing paddy loss during post-harvesting, various factors such as climate and pest infestation still result in grain wastage (Firdaus et al., 2020). Damaged grains with empty and partially filled paddy grain (EPFG) are considered losses since they are unqualified for further seed and rice production. Grains with abnormal colours, rotten, mouldy, and germinated need to be removed to ensure that only high-quality seeds are present for cultivation. Immature grains are unripe or unfilled paddy due to early harvesting time or infection by diseases. In an interview with one of the Malaysian milling factories, it was found that the production of EPFG generated during the milling process was at 6–25% of harvested yield (Kamaruzzaman, personal communication, Jun 2, 2017). According to Hamzah et al. (2019), the recent average damage grains in the Malaysian paddy and rice industry could reach as high as 557 000 MT in a year, resulting in losses of Malaysian Ringgit (MYR) 276 million. The high volume generation of EPFG leads to problematic disposal since it occupies large spaces and is poorly managed, posing environmental and health risks to the community. To date, landfilling remains the primary approach of EPFG management which is expensive due to transportation and unsustainable. As a result, there is an urgent need to identify and implement alternative methods for exploiting EPFG in an environment-friendly and cost-effective approach, preferably as feedstock for value-added resource recovery.

The biorefinery approach involves the development of various products derived from biomass feedstock through specific processes to facilitate the transition of a petroleum-based economy into a bioeconomy (Yuan et al., 2022). Producing hexoses (C6 sugars) from cellulose and starch is generally the first step in biomass refining for further commercial product development. Glucose, or C6 sugars, is an intermediate product in many biomass transformation routes to bioproducts such as biofuels, biochemicals, foods, and pharmaceuticals (Cheng et al., 2019). A previous study demonstrated that EPFG contains 50% of starch and cellulose, indicating a potential resource for glucose production (Abu Bakar et al., 2022b). Starch and cellulose can be converted to glucose through a biochemical process using enzymatic routes.

Nevertheless, due to the presence of lignin structure leading to EPFG recalcitrance, a pre-treatment process prior to enzymatic hydrolysis is necessary for efficient sugar recovery. Various pre-treatment technologies have been developed to accomplish this goal to reduce biomass recalcitrant (Soltanian et al., 2020). However, economical pre-treatment should require inexpensive chemicals and simple equipment and procedures (Margeot et al., 2009). In addition, the crucial driver in a commercial-scale biorefinery implementation is a profitable process design (Morone et al., 2017). Therefore, an efficient and cost-effective process must be considered for refining biomass into value-added products to transform it into a feasible bioeconomy product. Hydrothermal pre-treatment is a low-cost, simple, and environmentally friendly technology since the process only uses water as a reagent (Batalha et al., 2015). Thus, in this study, the process of converting EPFG to glucose involved a simple design process consisting of hydrothermal pre-treatment and enzyme hydrolysis.

Techno-economic assessment is an essential criterion for evaluating the quality of biorefinery systems. It helps to identify promising processes, evaluate investment projects, and secure financing (Lindorfer et al., 2019). Furthermore, the techno-economic perspective is crucial to ensure the profitability of the conversion process and the process improvement of biomass valorisation into an intermediate product. Operating parameters and cost data may affect the accuracy of techno-economic analysis (TEA). Although sugar is an intermediate product for conversion into various valuable market products, little information is available on their economic performance, mainly when different lignocellulosic biomass is used. Most studies have reported techno-economic performance on biomass conversion to bioethanol and other bio-based chemicals (Shaji et al., 2021; Pommeret et al., 2017). Few authors have reported the economic evaluation of glucose or sugar production with potential use in industrial fermentation processes. For instance, Baral and Shah (2017) have observed that sugar production from switchgrass and poplar using ionic liquid pre-treatment has the highest production cost at 3.37 and 3.31 $/kg, respectively. In addition, Cheng et al. (2019) have reported that $0.10 to $3.37 is needed to produce a kilogram of sugar from second-generation feedstock. However, a detailed TEA to assess the technical and economic feasibility of establishing a commercial scale from damaged paddy grain has yet to be conducted. Most reports have investigated glucose production mainly from wood and forest biomass (Brandt et al., 2018; Kuo and Yu, 2020). Humbird et al. (2011) have also evaluated the economic performance of fermentable sugar production from corn stover via a dilute acid pre-treatment followed by enzymatic hydrolysis with ammonia conditioning.

Paddy is one of the major crops producing abundant waste in developing countries such as Malaysia (Aditiya et al., 2016). The techno-economic aspect of paddy waste minimization through value-added products needs to be investigated. To the author's knowledge, little or no techno-economic information on glucose production from Malaysia's waste milling factory has been reported. Although several researchers have reported techno-economic study of biomass to glucose production, differences in feedstock used and processing technology create a barrier to comparative economic analysis (Cheng et al., 2019). Therefore, this study proposes to evaluate the financial feasibility of EPFG for glucose with the implementation of hydrothermal pre-treatment and enzymatic hydrolysis. An initial set of experiments was carried out to define the process variables, such as solid and enzyme loading, to obtain optimal glucose yield using statistical experimental design methodology as a tool. The outcome of this work could provide commercial benefits for paddy waste management and improve the paddy mill's sustainability.

Methods

Feedstock preparation

Empty and partially filled paddy grain (EPFG) was obtained from a paddy processing factory in Sungai Burong, Selangor, Malaysia. The biomass was ground with a laboratory grinder for size reduction to < 1 mm. The EPFG was then subjected to hydrothermal pre-treatment at 120°C for 60 min with a ratio of 1:9 w/v. The initial composition of EPFG was 32.7% of cellulose, 14.8% of starch, 18.3% of hemicellulose, and 13.3% of lignin (Ain et al., 2022b).

Enzymatic hydrolysis

The enzymatic hydrolysis process was performed sequentially after the pre-treatment process. The hydrolysis process was done in a 200 mL Erlenmeyer flask with the final 100 mL 0.05M sodium acetate buffer solution at pH 5. Two commercial enzymes were used to start the hydrolysis process: Dextrozyme (Novozyme, Bagsvaerd, Denmark; 255 amyloglucosidase unit per gram, AGU/g) and Acremonium cellulase (Meiji, Seika Co., Japan; 460 filter paper unit per gram, FPU/g). Enzyme hydrolysis was performed at 60°C, 150 rpm for 72 hours (Husin et al., 2019). Using one factor at a time, the effect of suitable solid loading (8%, 10%, 12%, 14%, and 16%) and enzyme loading (Dextrozyme at 30 units per gram (U/g), 40 U/g, 50 U/g, 60 U/g, and 70 U/g) was studied to obtain optimal glucose yield.

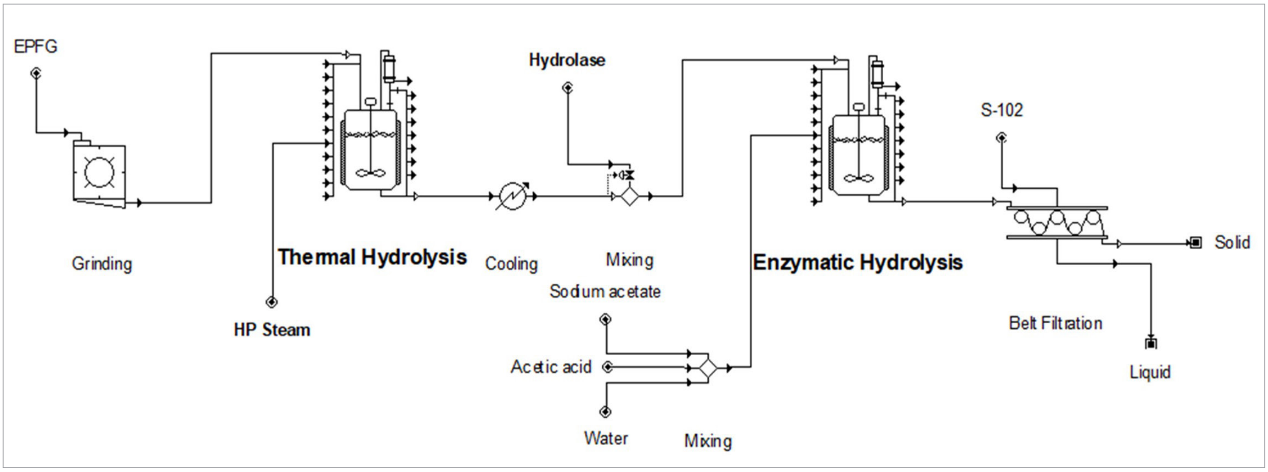
Glucose determination

Glucose was determined using high-performance liquid chromatography (HPLC) equipped with a refractive index detector (RID-10A, Shimadzu, Japan) using Rezex RPM-Monosaccharide Pb+ LC Column (300 × 7.8 mm) and a Rezex RPM-Monosaccharide Pb+ LC Guard Column (50 × 7.8 mm). The mobile phase was filtered with deionized water, and samples were eluted at a flow rate of 0.6 mL/min at 80°C. The running time of HPLC per each sample was set for 40 minutes.

Process description for techno-economic analysis

The process flow diagram of EPFG valorisation to glucose production in a proposed biorefinery is shown in *Fig. 1.* The base case for the TEA study of glucose production was conducted, relying on the biomass availability from the paddy seed milling factory in Sungai Burong, Kuala Selangor, Malaysia. The proposed biorefinery plant is assumed to be integrated within the milling factory, hence, no transportation from the milling factory to the biorefinery is necessary. About 25% (an average of 5500 tons per year) of paddy seeds were removed from the milling factory as EPFG and entered the glucose processing plant. The basis of inventory data was obtained through a laboratory study by Abu Bakar et al. (2022). The EPFG underwent size reduction to < 1 mm using a hammermill with a power demand of 30 kWh/t (Kumar and Wyman, 2009). Then, the ground EPFG was sent to a thermal reactor for the hydrothermal pre-treatment phase. The pre-treatment condition

Fig. 1. *Process flow diagram of glucose produced from empty and partially filled paddy grain; EPFG*



was set at 120°C for 60 minutes. The pre-treated EPFG was cooled down and sent to the hydrolysis process. The input of substrate and enzyme loading was based on the optimal glucose yield during the experimental investigation. Glucoamylase and cellulase enzymes were used as a cocktail formulation to enhance the release of glucose products. Around 76% of hydrolysis efficiency was obtained based on the experimental data yielding 1990 tons/year of glucose in the model plant. Afterward, the effluent of the enzymatic reactor was filtered to separate liquid and solid fractions. The liquid fraction was non-concentrated sugar for further fermentation product use, while the solid fractions were lignin residue and can be used as animal feeds or for composting. Nevertheless, in this study, the lignin residue was a co-product sold as wet lignin for 0.09 USD/kg (Ludmila et al., 2015).

Economic evaluations

Techno-economic analysis was conducted using Microsoft Excel (Cost and Evaluation Workbook) developed by Peter et al. (2003). The economic parameters and assumed values are listed in *Table 1*. Taking the case study in a paddy milling factory in Sungai Burong, Selangor, Malaysia, the proposed biorefinery operation was 6 months with 5500 t/year of EPFG processing. This is due to paddy seeds milling processing occurring for another 6 months (4 months grain processing operation and 2 months factory sterilization) to ensure adequate and quality seeds available for cultivation by the following seasons. The economic calculations were performed for the year 2020. The equipment cost was obtained from National Renewable Energy Laboratory (NREL) models, literature, and suppliers (Humbird et al., 2011; Brandt et al., 2018; Mohd Yusof, 2020). Exponential scaling was used to calculate the equipment cost for the size required, following Kumar et al. (2021), and was updated for the year 2020 using the Chemical Engineering Plant Cost (CEPCI) index. The capital cost (CAPEX) was estimated by incorporating fixed capital investment (FCI) and working capital. The FCI was estimated using the ratio factor for solid-liquid processing plants applied to total delivered equipment costs (TDEC) as described by Peters et al. (2003).

Table 1. *Techno-economic parameters and assumptions*

Economic parameter	Assumed value
Cost year	2020
Plant capacity	5500 t/year
Plant operation	6 months/year
Plant lifetime	10 years
Construction period	2 years
Distribution of capital investment	40% in the first year, 60% in the second year
Depreciation life	MARCS 7-year depreciation schedule

Operating costs (OPEX) consist of raw materials, labour, facility-related maintenance, and utilities. Since EPFG has no value and is discarded in landfills, the biomass price was assumed to carry the transportation price from the paddy field to the milling factory, which was $1.51/ton EPFG. The cost for other chemicals and materials was obtained from recent studies. The cost of electricity and water was obtained from Tenaga Nasional Berhad (TNB) and Air Selangor, Malaysia, respectively. The labour's salary was obtained from the Statistic of Labour Force, Department of Statistic Malaysia (DOSM). The annual operating labour costs accounted for two semi-skilled workers. Enzyme cost is one of the significant challenges in a biorefinery plant due to the uncertainty of the price and different estimation methods (Liu et al., 2019). In this work, the enzymes were purchased at 1.00 $/kg for cellulase and 3.50 $/kg for glucoamylase (Bulkan et al., 2021; Cheng et al., 2019).

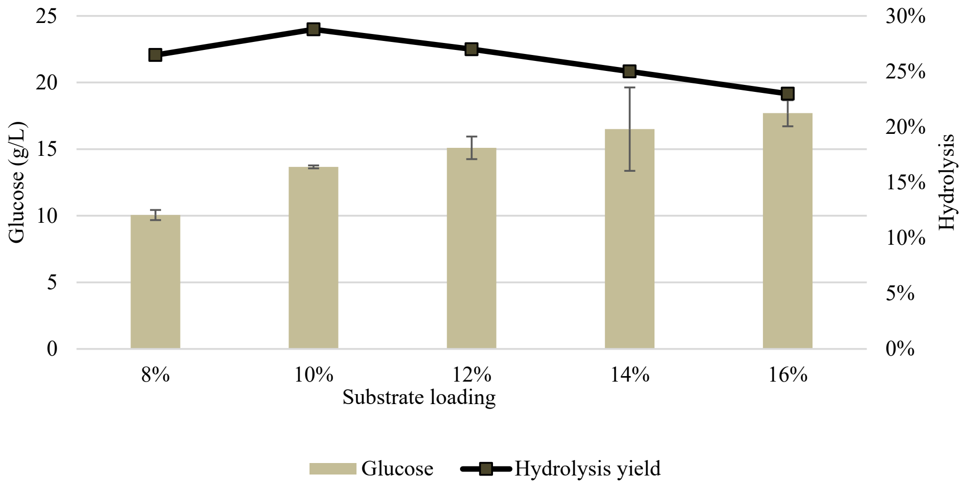
Profitability analysis of the proposed biorefinery was calculated in terms of payback period, net present value (NPV), and internal rate of return (IRR) of given initial capital cost, operating costs, and annual cash flow over expected 10-year plant life. A positive NPV indicates that the proposed project is economically feasible, while a negative NPV value suggests the project cannot provide a positive return (Kuo and Yu, 2020). The minimum sugar selling price (MSSP) considered the money's time value and was determined when the NPV was zero. In addition, the unit production cost was calculated by dividing the annual operating cost by the annual production rate (Lee et al., 2018).

Results and Discussion

Hydrolysis efficiency and glucose production

Experimental data for solid and enzyme loading parameters used in the TEA study was collected and performed to ensure optimal conditions obtained for glucose production from EPFG. The feedstock underwent hydrothermal pre-treatment at 120°C for 60 minutes. The EPFG compositions after hydrothermal pre-treatment consisted of 40.8% cellulose, 13.1% hemicellulose, 16.3% lignin, and 14.8% starch. Ideally, using high solid-loading biomass in a biorefinery would increase product concentration, thus lowering the capital and operation costs (Ramachandriya et al., 2013). However, this may be associated with problems such as increased viscosity due to difficulties in mixing, heat, and mass transfer limitations, causing inefficient hydrolysis yield (Biasi et al., 2020). Therefore, understanding the effect of solid loading on the conversion process is crucial. The effect of solid loading on pre-treated EPFG for glucose production is shown in *Fig. 2*. As shown, hydrolysis yield was increased at 8–10% solid loading, with the maximum percentage at 29% for 10% solid loading. This hydrolysis yield trend started to drop at 12% to 16% solid loading even though glucose production increased. An increase in biomass loading can negatively affect the conversion yield as it reduces the mixing efficiency. A study by Kristensen et al. (2009) has

Fig. 2. *Effect of solid loading on glucose concentration and hydrolysis yield*



observed a trend of decreasing conversion yield when solid loading of lignocellulosic biomass was increased from 5% to 30%. Nevertheless, the study observed an addition of 50 g/L of glucose with an increase in solid loading; however, the initial hydrolysis rate and the final glucan conversion were reduced. High-solid loadings can cause insufficient mixing or increase energy consumption in conventional stirred-tank reactors as the viscosity of slurries increases abruptly when over 20% solids loading is used (Modenbach and Nokes, 2013). It can be deduced that free water was available when the solid loading was at 10% and below, and suspensions were well mixed. However, increasing the solid loading at 12% and higher causes mass and heat transfer limitation due to the high viscosity of the medium (Larnaudie et al., 2019). Nevertheless, more than 15.0 g/L of glucose could be produced at above 10% solid loading. Considering the efficiency of the hydrolysis process, 10% solid loading was concluded to be used as the parameter for the TEA study.

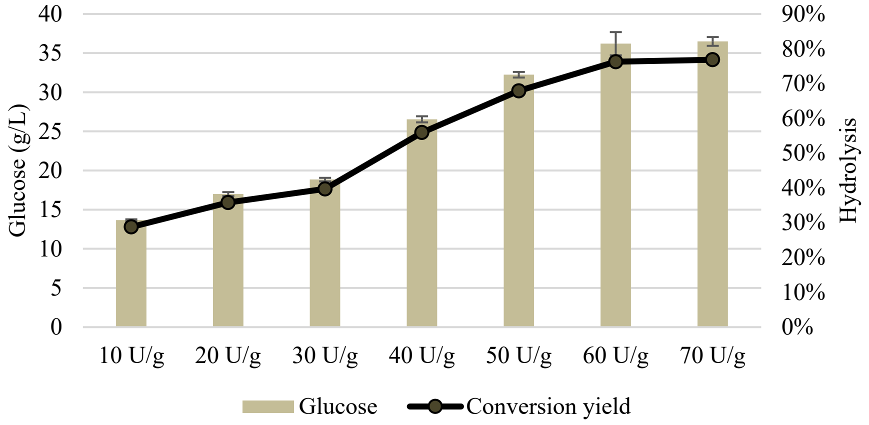
An appropriate amount of enzyme must be determined as it contributes significantly to the TEA study's operational cost (Baral et al., 2019). The effect of enzyme loading on hydrolysis yield is presented in *Fig. 3*. The enzyme loading effect variables were performed on glucoamylase enzyme only with cellulase enzyme at 10 FPU/g substrate. From the figure, it can be observed that increasing the enzyme dosage led to an increase in glucose concentration to the point where an insignificant value of glucose concentration was obtained by using 70 U/g_{EPFG} enzyme, producing 36.4 g/L glucose. Likewise, an increase in hydrolysis yield was observed, with the trend leading to a maximum hydrolysis yield of 76–78%. Generally, high enzyme loading would produce a high glucose yield. However, high enzyme consumption contributes to high input costs for hydrolysis. Furthermore, excessive enzyme loading could result in a lower enzyme utilization rate (Zhang et al., 2018).

The maximum liberated glucose concentration was 36.2 g/L, equivalent to 76% hydrolysis yield (99% starch saccharification) at 60 U/g_{EPFG}. As shown in the figure, increasing glucoamylase concentration in the reaction did not result in a significantly higher hydrolysis yield. Since increasing enzyme dosage from 60 U/g_{EPFG} did not substantially affect hydrolysis yield, this amount was chosen as the optimal condition for saccharification of hydrothermal pre-treated EPFG. An optimal hydrolysis yield of 76% was used for the economic evaluation. An increase of glucoamylase for more than 60 U/g causes wastage and affects the OPEX value, hence increasing the saccharification cost (Alias et al., 2021).

Capital and operational cost

Based on the actual case study of the Sungai Burong milling factory in Selangor, Malaysia, the glucose processing plant was assumed to be operated 180 days per year, while the rest of the year was occupied by paddy milling processes. The EPFG was collected directly from this factory, and the equipment needed was as shown in *Fig. 1*. Based on the experimental data, about 5000 t/year of EPFG will produce approximately 1.99 million kg of non-concentrated glucose.

Fig. 3. *Effect of enzyme loading on glucose concentration and hydrolysis yield*



Capital expenditure includes direct fixed capital, indirect fixed capital, and working capital. *Table 2* shows the breakdown of CAPEX for the glucose production plant from EPFG. The table shows that the proposed plant's total CAPEX and equipment costs are USD 432 000 and USD 114 000, respectively. Enzymatic hydrolysis is the main process that contributes about 72% (USD 82 000) of the purchased equipment cost, including the enzymatic hydrolysis tank, belt filter, and saccharification transfer pump. Since the end product is non-concentrated glucose, the CAPEX is relatively less than the concentrated glucose because evaporator equipment for glucose production is unnecessary (Brandt et al., 2021). According to Kwan et al. (2019), the most expensive equipment for glucose production is an evaporator that concentrates a large volume of glucose. Brandt et al. (2021) reported a 12.3% CAPEX increase for concentrated glucose production but suggested that situating the biochemical or biofuel facility adjacent to the saccharification plant could eliminate evaporation costs, thus reducing overall production expenses and enhancing efficiency. Apart from the equipment cost, delivery and installation costs were estimated following the assumption by Peters et al. (2003) and are summarised in *Table 2*. Working capital was assumed to be 5% of the FCI, which is expected to cover the expenses of the initial plant start-up (Sinnot et al., 2013).

Table 2. *Purchased equipment and other costs for estimation of capital expenditure*

Items		Cost (USD, $)
Process	Equipment	
Biomass processing	Hammermill	3000.00
Pre-treatment	Hydrothermal reactor	23 820.00
	Hydrolysate cooler	5250.00
Enzymatic hydrolysis	Mixing buffer tank	6750.00
	Enzymatic hydrolysis tank	63 760.00
	Belt pressed filter	8752.00
	Saccharification transfer pump	2820.00
Delivery		11 414.00
Installation		48 970.00
Fixed capital investment		411 821.00
Working capital		20 600.00
CAPEX		432 412.00

The OPEX obtained in this study is approximately USD 864 000 per year. The breakdown of raw materials price, labour, financing interest, and general expense are explained in *Table 3*. The significant cost of OPEX is raw materials, which are mainly contributed by the cost of enzymes. Osorio-Tobon et al. (2016) have observed a similar trend, where the main contribution to the manufacturing cost comes from raw materials. The authors reported a reduction of OPEX to 42% when the cost of raw materials decreased from 7.27 to 1.59 USD/kg. The utilities cost for glucose production was only 16.9%, which is relatively low compared to the cost of the raw materials. Electricity contributes as the major source of utilities. The hydrothermal pre-treatment required high energy consumption compared to the chemical pre-treatment type, reflecting the utility cost (Cheng et al., 2019). Overall, the enzyme hydrolysis process significantly affects the OPEX value (48%), followed by the pre-treatment process (20%), biomass processing (17%), and separation process (15%).

Table 3. *Raw materials, utilities, and other product costs used in the techno-economic analysis*

Items	Cost (USD, $)
Cellulase, USD/kg	1.00
Glucoamylase, USD/kg	3.50
Acetic acid, USD/kg	0.10
Sodium acetate, USD/kg	0.10
Utilities, USD	0.64
Labour, USD/h/2 persons	478.00
Financing, USD	22 840.00
Plant overhead, USD	19 053.00
Manufacturing cost, USD	780 164.00

Profitability analysis and MSSP

The economic performance of the proposed project was determined using profitability indicators and MSSP, as summarized in *Table 4*. The main revenue of the project was contributed by glucose products, which were approximately 1.09 million USD/year. The plant could generate total revenues of 1.39 million USD/year, with additional revenues from lignin residue as a co-product.

Table 4. *Economic performance of glucose production plant*

Items	Values
Total glucose revenues, USD/year	1 094 500.00
Total co-product revenues, USD/year	294 230.00
Total revenues	1 388 730.00
Gross margin, %	38%
Return on investment, %	46.9
Payback period, y	1.7
IRR, %	37
NPV, USD/year	1 037 000.00
MSSP, USD/kg	0.42

Based on the economic analysis, the gross margin was 38%, while the ROI was 46.9% after 10 years of operation. Practically, the minimum acceptable ROI value greater than 15% is considered financially beneficial to be accepted for implementation (Thompson et al., 2021). Higher ROI also indicates a low level of risk for new capacity investment with established corporate market positions (Peters et al., 2003).

The 1.7-year payback period for the proposed project is considered acceptable for a small-scale production plant owing to the low CAPEX. Based on the estimation by Peters et al. (2003), the maximum allowable payback period for glucose production from EPFG is 1.9 years. For this reason, the proposed project is still favourable for investment. The internal rate of return (IRR) and the net present value (NPV) measure the profitability of the proposed project investment within 10 years of the plant's lifetime. The IRR and the NPV also considered macroeconomic influences such as corporation tax, inflation, depreciation, and discount rates, as shown in *Table 1*. The IRR was estimated at 34.3%, and the NPV at 1.04 million USD indicates the economic feasibility of the proposed project.

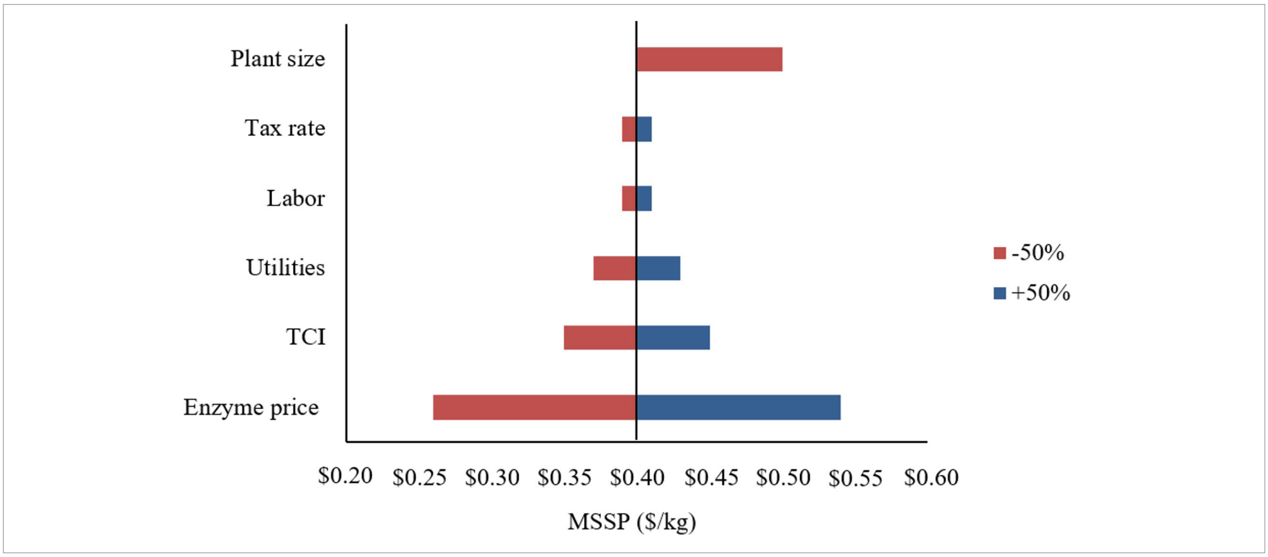
The MSSP was determined since sugar is treated as an intermediate product (Humbird et al., 2011). This study's calculated MSSP for glucose was 0.42 USD/kg. However, this value included the sales of co-products from the production plant. The MSSP was increased to 0.52 USD/kg without co-product revenues. This value is also comparable with previous studies conducted for different types of biomasses. Ou et al. (2021) have projected the MSSP for lignocellulosic biomass using autohydrolysis and mechanical refining at 0.45 USD/kg. A reduction of MSSP to 0.32 USD/kg was reported when hemicellulose and lignin fractions of the biomass were further exploited for xylitol and polyol production. Thus, the lignin residue produced in this study is sold as a co-product, while glucose is sold for feed/food, fuel, or any bioproduct plants.

Sensitivity analysis

Sensitivity analysis was conducted to evaluate the influence of several variables on the economic performance of glucose production plants, as illustrated in *Fig. 4*. The variables were independently assessed, including plant size, total capital investment (TCI), enzyme price, labour, utilities, and tax rate at ±50% variation (Kwan et al., 2019). The MSSP was evaluated concerning positive and negative changes to the input parameter (Ou et al., 2021; Sahoo et al., 2019). Based on the results, plant size and enzyme price are the most sensitive parameters toward MSSP, followed by TCI. Plant size is another factor that influences the economic performance of a biorefinery. An increase in production capacity for a plant results in an increase in production cost (Farid et al., 2020). An exponential factor is used following Hassanly et al. (2018) to adjust the equipment cost according to plant capacity. The MSSP reduced to 0.32 USD/kg when the plant capacity increased by +50%. Meanwhile, reducing the plant size would result in higher MSSP at 0.80 USD/kg, owing to low product yield, less plant revenue, and high capital and operating costs. Thus, it can be deduced that a larger facility is potentially more cost-effective. An increase in plant size would yield more profit due to higher production rates and lower unit selling prices (Farid et al., 2019). Similar findings were reported by Kuo et al. (2020), where an increase in plant capacity from 20 MT/day to 2000 MT/ day reduced the MSSP from 0.64 USD/kg to 0.29 USD/kg. According to the author, this correlation is attributed to the facility-dependent and labour costs that are not increased linearly with plant scale.

Reducing enzyme price can reduce the MSSP to 0.26 USD/kg; a variation of +50% enzyme price increases the MSSP to 0.54 USD/kg. The high cost of commercial enzymes used in the glucose production plant is the major constraint in this study. Similarly, Kuo et al. (2020) have reported that fluctuations in enzyme purchase price affect the economic performance of the sugar plant project, with a change in MSSP at ±8.5%.

Fig. 4. *Sensitivity analysis of different parameters on MSSP*



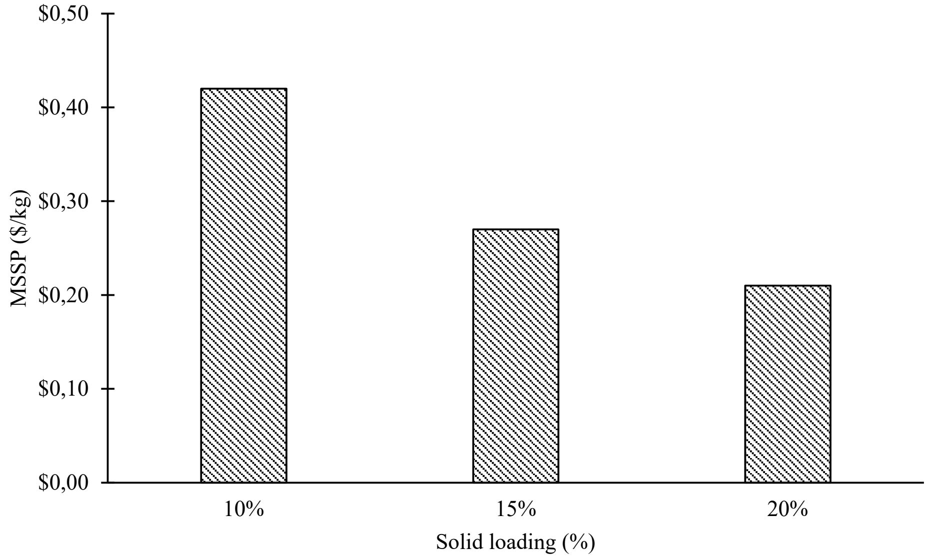
Baral et al. (2021) have suggested that improving the process and pre-treatment to enhance hydrolysis activity is an alternative solution to reduce enzyme consumption. The present study estimated that increasing the solid loading and recycling of NaOH in pre-treatment can reduce the selling product cost. Improvement of pre-treatment and enzyme activity shall result in better enzymatic digestibility of EPFG, thus producing higher sugar concentration. Consequently, higher sales are expected, contributing to revenue growth. For other parameters, the MSSP is shown to reduce by 12.5% with a reduction of TCI, while variations in utilities, labour, and tax rate are less sensitive towards the MSSP, ranging from ±2.5% to 7.5%. The MSSP is not significantly affected by TCI since less equipment is used in the plant to process 5500 tons of EPFG per year.

Impact of solid and enzyme loading of glucose production on MSSP

The impact of solid loading on MSSP of glucose production is depicted in *Fig. 5*. An increase in solid loading is shown to reduce the MSSP value. The lowest value obtained was USD 0.21/kg of glucose when solid loading increased to 20%. Higher solid loading leads to more product development that would increase the revenue of the projected plant. Moreover, as the other raw materials remained constant, higher positive cash flow could be obtained to profit the plant. Nevertheless, in this study, the increase in the solid loading did increase the glucose concentration but reduced the hydrolysis yield of EPFG. Thus, more desired products could be produced. A similar trend has been reported by Passadis et al. (2022), where 20% solid loading showed better end-product yield compared to 10% solid loading, resulting in lower production cost. The observed increase in 20% solid loading reduced the minimum product selling price due to the decrease in capital and operating costs.

In another study by Kapanji et al. (2021), an increase of 5% in the solid loading of sugarcane bagasse has been observed, significantly improving the glucose yield and reducing the process cost. Higher total solids loading in enzymatic hydrolysis could boost process efficiency by requiring fewer reactors and less energy to separate the product from background water (Humbird et al., 2010). Most studies have suggested that increasing solid loading would be cost-effective and could increase the economic viability of glucose production (Modenbach and Nokes, 2013; Ramachandriya et al., 2013). However, a few drawbacks have been discussed regarding using high solid loading in process conversion. For instance, the slurry produced would be difficult to pump to the next process tank. Additionally, enzymes would be ineffective after a certain time due to product inhibition. In a laboratory study, Pristavka et al. (2000) found that an increase in solid loading of feedstock at 25% during the bioconversion process would cause mechanical stirring of the slurry to be energy intensive and yield end-product inhibition. Despite the advantages of operating at

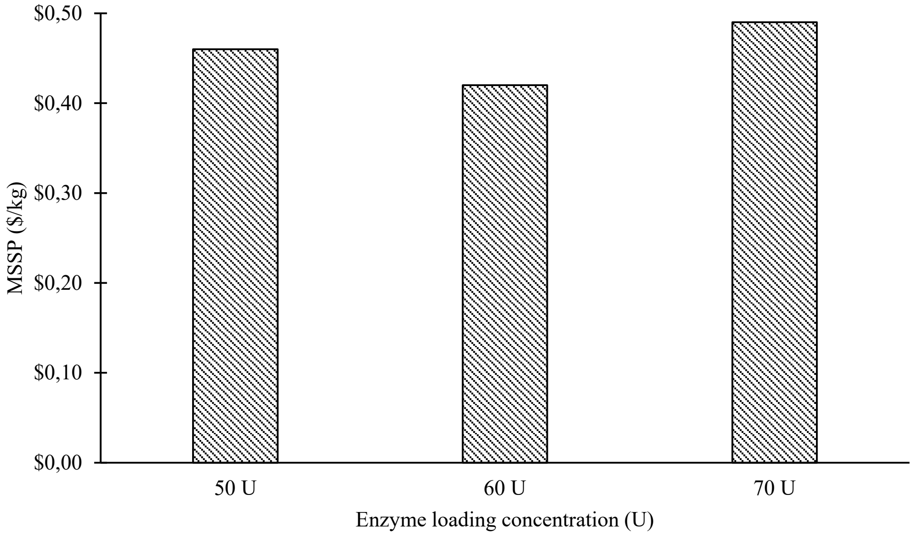
Fig. 5. *Effect of solid loading on MSSP of glucose produce*



high solids leading to low MSSP, the process is still hindered due to water availability in the mixing tank, causing difficulty in mixing and handling, increased inhibitor concentration, and ultimately increasing enzyme use (Modenbach and Nokes, 2013).

Fig. 6 shows the effect of enzyme loading on MSSP of glucose production. The changes in enzyme loading involved glucoamylase loading, and the experimental data were used to project the MSSP. The figure depicts that the optimum enzyme loading was the base case scenario at 60 U/g with the MSSP value of USD 0.42/kg. Reducing the enzyme loading to 50 U/g increased the MSSP slightly from the base case at 0.46 $/kg glucose. This is due to low hydrolysis yield, which causes inefficient glucose in obtaining optimum plant revenue. Meanwhile, an increase in the enzyme loading

Fig. 6. *Effect of enzyme loading on MSSP of glucose production*



at 70 U/g increased the MSSP to USD 0.49/kg. Even though the increase in enzyme dosage leads to an increase in hydrolysis efficiency, the higher enzyme cost is the main factor that leads to higher MSSP. Larnaudie et al. (2021) have stated that working with low hydrolysis efficiency and enzyme dosage is better in biorefinery since enzyme input is costly. Lower enzyme dosages have been suggested by Brondi et al. (2020) for the economic feasibility of a biorefinery. Due to the high cost of the enzyme cocktail used in their study, a negative NPV value was estimated. Therefore, it could be concluded that 60 U/g of enzyme loading is the optimum load that minimized the MSSP value and thus contributed to the process feasibility.

Conclusions

Sustainable and low MSSP of glucose as an intermediate product is necessary as a platform for producing a wide range of bio-based products, including ethanol, biochemicals, and other value-added products. The present study produced glucose from EPFG using hydrothermal pre-treatment and enzymatic hydrolysis. The process generated adequate glucose production at 76% conversion yield under mild conditions. Techno-economic analyses of glucose production were conducted using the experimental data generated, the actual sites, and the literature data. The profitability of the conversion plant was assessed to ensure the economic performance of the modeled investment. The MSSP obtained for glucose production using hydrothermal pre-treatment followed by enzymatic hydrolysis was 0.42 USD/kg. The co-product increases the total revenues for the glucose plant with the NPV values for 10-year projected period at 1.04 million USD. Further utilization of other EPFG fractionation, such as hemicellulose and lignin, to produce value-added products would increase the plant's profitability, thus reducing the MSSP of glucose. Nevertheless, the co-products' contribution to economic plant performance should be further studied in a commercial or large-scale biorefinery. Sensitivity analysis showed that the economic performance of glucose was sensitive to plant size and enzyme cost. Therefore, the feasibility of a project can be maximized by finding alternatives to reduce enzyme use while still being able to produce a high glucose rate. Special attention should be given to the most influential factors as indicated in the sensitivity analysis, such as enzyme cost and plant size, which may contribute to the economic benefits and influence the best options for paddy milling waste management.

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