Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-024-05904-8

ORIGINAL ARTICLE

Process variable optimization on hydrogen production from sawdust mill of *Paraserianthes falcataria* wood with one stage gasification process using promoted calcium hydroxide absorption

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Received: 17 March 2024 / Revised: 12 June 2024 / Accepted: 29 June 2024

Abstract

Production of hydrogen from biomass waste using single-stage gasification is an innovative method, in which gasification, water gas shift conversion and CO_2 separation processes are carried out in one reactor so that the product gas leaving the reactor has a partially large composition is hydrogen gas. This process presents several advantages when compared to the conventional method, where hydrogen formation is carried out through several stages that occur in more than one reactor, making it more complicated and economically unprofitable. In addition an innovative method on how to make the absorption of CO_2 gas more effective by adding PEG surfactant to the absorbent solution as a promoter is presented. The biomass used in this research is sawdust wood. The composition of H_2 as well the corresponding yield were optimized under constant operating conditions, namely gasification temperature 400°C and holding time 15 min for surfactant concentration (800–1500 ppm) and the ratio of absorbent solution/biomass weight (1.5–2.0 ml/g). A central composite design (CCD) model utilizing Statistica 6 software was applied. The optimization results show the optimum ratio of absorbent solution/biomass is 1.786 ± 0.004 while for the surfactant concentration, the results were obtained for 1200 ppm (for H_2 composition) and 1250 ppm (for yield). At the optimum conditions H_2 content was 30.82% and the yield was 2.937 mmol H_2/g of biomass. The surfactant concentration variable has a greater effect than the ratio variable from the % H_2 side, while from the yield side the effect is not significantly different.

Keywords Carbon capture · Central composite design · Gasification · Hydrogen production · Optimization · Surfactant

Nomenclature

CaO	Calcium oxide
$Ca(OH)_2$	Calsium hydroxide
$CaCO_3$	Calcium carbonate
CH_4	Methane
C_3H_8	Propane
CO_2	Carbon dioxide
CCD	Central composite design
CO	Carbon monoxide
GC	Gas chromatography
N_2	Nitrogen
PEG	Polyethylene glycol
H_2	Hydrogen
H_2O	Water
SESR	Sorption-enhanced steam reformation
SMR	Steam methane reforming
X_1	Surfactant concentration (ppm)
X_2	Ratio of absorbent solution/biomass (ml/g)

Highlight 1. Hydrogen production through single stage gasification – absorbtion process of saw dust wood.
2. Utilizing surfactant to maximized Carbon dioxide absorbtion from gasification process.

1 Introduction

The global increase in energy consumption was a direct consequence of the simultaneous rise in population growth and industrial development. At present, fossil fuels such as

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coal, natural gas, gasoline, and solar power fulfill around 80–81.4% of the world's energy requirements [1, 2]. The utilization of fossil fuels, including coal, crude oil, and natural gas, for energy resources has disadvantage in social, political, and economic consequences. Fossil fuels have detrimental effects on the environment and ecosystems in the long term, such as contributing to global warming, escalating greenhouse gas emissions, causing acid rains, and altering weather patterns [3–6]. To overcome this difficulty, it is crucial that we strive to discover alternative and renewable energy sources, such as biomass. Biomass encompasses any organic matter that is not generated from fossil fuels and contains inherent chemical energy. This encompasses a wide range of vegetation, including plants and trees in their natural state (referred to as virgin biomass), as well as other forms of biomass waste such as municipal solid waste, agricultural waste, plant waste, forest waste, farm waste, some types of industrial waste, and waste mud [7–9].

Biomass technology has the capability to convert biomass into a diverse range of renewable energy. Given various factors such as the depletion of fossil energy reserves, the abundance of biomass resources, energy diversification initiatives, and the importance of environmentally-friendly energy sources, it is necessary to investigate the production of renewable energy from biomass materials. Indonesia has a plentiful supply of biomass, which serves as a viable alternative energy source. The conversion of biomass into liquid fuels by pyrolysis encounters challenges stemming from the instability of the resulting liquid compounds. Nevertheless, biomass may undergo gasification to produce gas that can be used as fuel for transportation, such as H_2, or further processed into hydrocarbons (by the Fischer Tropsch synthesis route) or methanol [10].

Hydrogen is a promising alternative energy source for the future due to its numerous benefits, particularly its high energy density in comparison to conventional fuels such as gasoline, biodiesel, LPG, LNG, coal, and others [11]. Hydrogen possesses significant promise as an alternative to fossil fuels due to its high heat energy (122 kJ g – 1), little pollution, and abundant power sources [12, 13]. Hydrogen is an eco-friendly energy source that acts as a sustainable energy carrier, generating zero CO_2 emissions upon combustion. Hydrogen gas serves as a primary component in several chemical industries, including water filling, ammonia synthesis, methanol production, and chloric acid manufacture. Additionally, it functions as a reduction agent in steel and plant sectors [14–17].

Hydrogen may be utilized as a power generator through the technique of Solid Oxide Fuel Cells (SOFCs). Hydrogen is injected into the anode of the solid oxide fuel cell (SOFC), where it undergoes an oxidation process, resulting in the production of hydrogen ions (protons) and electrons. Furthermore, this process produces thermal energy due to the fact that solid oxide fuel cells (SOFCs) function at elevated temperatures ranging from 600 to 1000 ^{o} C. The cathode is supplied with oxygen from the air. In this process, the oxygen undergoes reduction to produce oxygen ions. Subsequently, these ions migrate through the solid electrolyte in the direction of the anode. At the anode, the oxygen ions combine with hydrogen ions and electrons to produce water (H_2O) and create electrical energy. The liberated electrons in this chemical process traverse an external circuit, generating electrical energy that may be harnessed for many purposes. Furthermore, apart from producing electricity, the process also provides thermal energy that may be used in cogeneration systems to enhance the total efficiency [18].

Hydrogen could be produce from organic waste using gasification technology, which resulting a synthetic gas composed by carbon monoxide (CO) and hydrogen (H_2) [19]. There are several methods of producing hydrogen including natural gas reforming, electrolysis, gasification, and thermochemical water separation [20]. The study conducted by Kazmi et al. [21] utilized anaerobic digestion to create biogas, which was then purified and converted into hydrogen. The process of extracting hydrogen from biomass involves several steps. First, biogas is created. Then, the biogas is purified using solvents to obtain high concentrations of methane. Finally, the methane reacts with water vapor at high temperatures (600–700 ^{O}C) to produce biohydrogen. While Kazmi views this technique as cost-effective, it does need a significant amount of time. Mehdi et al. [22] research on the gasification of municipal solid waste (MSW), it was shown that increasing the temperature from 700 ^{O}C to 1300 ^{O}C resulted in a rise in H_2 content from 37 to 51 mol%. The concentration of H_2 increased from 34 to 44 mol% when the mass proportion of steam to MSW increased from 0.05 to 0.8. The H_2 concentration decreased from 47 to 39 mol% as the air to MSW mass fraction increased from 0.01 to 0.5. The concentration of H_2 reached its highest point at 0.05, with a composition of 48 mol% H_2. The gasification process necessitates a significantly elevated operating temperature.

Currently 96% of H_2 production technology depend on non-renewable resources, specifically steam methane reforming (SMR) from natural gas/oil-based or coal gasification. The process of H_2 synthesis coupled with carbon dioxide (CO_2) capture is a promising solution for mitigating carbon emissions. However, its practical use is still in the first phases of development [23].

Studies have been conducted to investigate the production of H_2 from different biomass sources and processes. These include: the use of bio-oil and steam reforming with CaO as absorbent [24]; the gasification of cane powder using a fluidized poultry reactor [25]; the utilization of cattle manure through microbial activity of microflora [26]; the anaerobic bacterial activity in household waste [27, 28]; and the steam gasification of wood biomass with CaO as absorbent on a single-stage process [29].

The challenge comes from the fact that despite several studies on the utilization of biomass waste as a raw material for producing H_2, there is currently no economically feasible result for large-scale production. Therefore, the objective of this work is to transform non-productive biomass waste into hydrogen (H_2) using a gasification process that incorporates novel and improved methods. Gasification is a thermal conversion process that involves using steam gasification and/or hydrogasification to create a gas mixture by partial oxidation at high temperatures. The gasification process produces a gas mostly composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), nitrogen (N_2), water vapor (H_2O), and hydrocarbon molecules spans from methane (CH_4) to propane (C_3H_8). The gases produced through this gasification process can be further processed to produce purified gas, which can be used as a basis for the production of chemical compounds like methanol or gasoline. Alternatively, it has the potential to be converted into thermal energy or electrical [30].

In general, the production of H_2 through gasification involves multiple phases. These include the gasification phase, which produces a mixture of H_2, gas, and other substances, and the separation phase, which separates the H_2 from the other substances to obtain relatively pure H_2 [31]. Recent research have explored the use of a one-stage procedure in a gasification reactor [32] to produce H_2 by removing CO_2 on-site. The thermodynamics of equilibrium processes that facilitate the formation of H_2 flows with higher purity can be disrupted by the loss of CO_2 [33]. Sorption-enhanced steam reformation (SESR) is a thermochemical process that efficiently generates high-purity H_2 by removing CO_2 in the presence of absorbers.

The conventional method for hydrogen production consists of three sequential steps (as shown in reaction (a) to (c), while in the new method presented in this study, hydrogen will be obtained directly through reaction (d) or (e) that occurs in a single reactor [34]. The process as describe by reactions (a) and (b) is known as the TEXACO process [35]. The HyPr-Ring process is the hydrogen production process in one step using calcium oxide (CaO) and/or calcium hydroxide $Ca(OH)_2$ as CO_2 absorber [36]. In the HyPr-Ring process, $Ca(OH)_2$ is converted to calcium carbonate ($CaCO_3$) and simultaneously absorbs the resulting CO_2, as shown by reaction (e).

Gasification : $C(\text{biomass}) + H_2O \rightarrow CO + H_2$ (a)
Water gas shift reaction : $CO + H_2O \rightarrow CO_2 + H_2$ (b)
Separation (absorption) CO_2 : $\text{Absorbent solution (CaO)} + CO_2 \rightarrow CaCO_3$ (c)
Integrated steam : $C\ (\text{biomass}) + CaO + 2H_2O \rightarrow CaCO_3 + 2H_2$ (d)
: $C\ (\text{biomass}) + Ca(OH)_2 + 2H_2O \rightarrow CaCO_3 + 2H_2$ (e)

The composition of the end gas and the production of H2 are influenced by several factors, such as temperature, operating pressure, absorber-to-biomass ratio, feed biomass composition, holding time [37], absorbent solution concentration [38] and steam carbon ratio [39].

Surfactants are used to improve the absorption of CO_2, as previous research has confirmed the effectiveness of surfactant solutions as CO_2 absorbers [40]. By introducing surfactants into the absorbent solution, it is expected that both the contact surface area and the residence time of the gas in the liquid will be enhanced, leading to a more efficient CO_2 absorption process.

This investigation is a continuation of the initial phase of research that focused on hydrogen production. The research involves a novel technique that converts biomass (such as straw, rice husk, and sawdust wood) into hydrogen within an integrated system. This system includes gasification, water gas shift reaction, and CO_2 separation, all taking place in a single reactor. The CO_2 separation process is simplified by the addition of polyethylene glycol (PEG) as a surfactant. The initial stage of the study focused on investigating the effect of the gasification process variables. This analysis revealed the significance of two factors: the ratio between the absorbent solution and the raw material, and the quantity of surfactant introduced. Thus, in this later investigation, the influential factors are optimized. This study aims to investigate the application of surfactant as a catalyst to improve the efficiency of CO_2 absortion in the one-phase biomass gasification process. Surfactants are chemical substances that, when dissolved in a system with two phases, have a tendency to adsorb at the interface between the phases, resulting in a reduction of the interfacial tension. A surfactant molecule is composed of two components: a hydrophilic head, which is a polar compound made up of carboxylate, sulfate, or sulfonate groups, and a hydrophobic tail, which is a non-polar compound composed of long-chain alkyl groups. Surfactants serve the purpose of stabilizing dispersion systems, such as emulsions of liquids or foams of liquids and gases. Surfactants in an absorbent solution enhance the dispersion of CO_2 gas in the liquid, leading to increased contact area and longer gas retention duration. As a result, this is anticipated to improve the efficiency of the CO_2 absorption process. The main goal of the developed work is to develop a single stage processs that allows for a high concentration of H_2 in the end gas by otimizing the effect of biosurfactant concentration and ratio of absorbent solution/biomass weight. None of these studies investigated the addition of surfactants to the absorbent solutions as a method for improving H_2 transfer.

Various statistical methods such as design experiment method and response surface methodology (RSM) have been used to determine the effective parameters in several engineering applications. Central Composite Design (CCD) and Box-Behnken Design (BBD) are both successful methods for optimization in RSM. Nevertheless, they saw distinct benefits and constraints for each. CCD often offers more comprehensive insights because it incorporates a greater number of design points, enabling more accurate modeling of the response surfaces and interactions among components. On the contrary, BBD demonstrated more efficiency in terms of the number of tests needed, making it a cost-effective choice with minimal compromise on accuracy. The selection between CCD and BBD hinges on the particular demands of the experiment, including the intricacy of the response surface and the resources at hand. According to the authors, CCD is more suitable for in-depth and intricate research, whereas BBD is more useful for initial screenings and circumstances with limited resources [41]. Zalazar-Garcia's [42] research on pumpkin seed drying using the experimental design RSM found that both CCD and BBD offer distinct benefits in improving the drying process of pumpkin seeds. CCD is more suited for extensive exploration and detecting non-linear relationships, but BBD is more efficient in terms of the number of tests and cost. The selection between CCD and BBD relies on the specific requirements of the research or industrial application, with BBD potentially offering cost and time advantages, while CCD offers wider coverage and more detail. Research on ammonia-water absorption in a refrigerant system demonstrates that employing CCD yields a more accurate prediction of the real value compared to BBD. The CCD more flexibility and the ability to estimate the response surface more accurately, especially when curvature is present [43].

2 Materials and methods

2.1 Materials

Sawdust of *Paraserianthes falcataria* wood was receive from wood sawmill. Afterwards, it was open air dried using sunlight and then screened through 10 mesh and 40 mesh sieves. In addition, we conducted a proximate analysis to determine the amount of moisture and ash contained in the sawdust. Poly Ethylene Glycol (PEG) 600 and calcium Oxide (CaO) were purchased from Sigma Aldrich,

2.2 Gasification equipment

The gasification device (Fig. 1) is a cylindrical steel pipe with a diameter of 2 inches (5.08 cm) and a height of 10 cm. It is equipped with an electric heater. Gasification devices are fitted with temperature sensors to as certain the temperature within the reactor, venturi meters to quantify the flow rate of gas exiting the reactor, gas meters to measure the volume of gas generated from the reactors, and syngas were collected on a special tube. Composition of gas that produce from the process was analyzed using Shimadzu GC – 8 A with setup includes a gas flow rate of 1 mL/min, a helium carrier gas, a column pressure of 110 kPa, a split injection mode with a ratio of 1:50, an injector temperature of 100 °C, a detector temperature of 250 °C, and a column temperature of 100 °C.

2.3 Methods

Saturated $Ca(OH)_2$ was prepare by diluting Calcium Oxide (CaO) in an aqueous solution. Liquid adsorbent was prepare by introducing a certain amount of Poly Ethylene Glycol (PEG) 600 into $Ca(OH)_2$ solution. Gasification reactor was prepared by removing the gases inside of the reactor by flushing it with nitrogen gas. Then a mixture of 25 g of biomass material (sawdust) was mixed with liquid adsorbent in a certain ratio, and feed into reactor. The reactor is then heated by an electric furnace. The reactor temperature is measured with a thermocouple. After the temperature on the thermostat reaches 400 ^{O}C the needle valve is opened slowly, so that the gas product will flow into the gas collector, where the volume is measured with a flow meter that previously calibrated. The overall gas flow time is recorded and then the resulting gas is analyzed using GC (gas chromatography) to determine the H_2 content. By knowing the volume of the resulting gas, the yield of H_2 can be calculated.

2.3.1 Experimental design

Variable optimization is carried out by statistical methods, namely RSM, utilizing Statistica 6 software. With this method, the correct response value will be obtained,

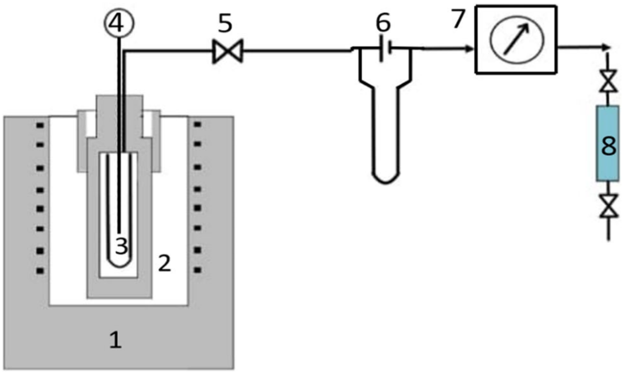


Fig. 1 Experimental set-up: (1) electric furnace; (2) reactor; (3) sawdust + $Ca(OH)_2$ + PEG600; (4) temperature control; (5) valve; (6) venturi meter; (7) gas meter; (8) gas collector

the mathematical model equation that matches the data obtained from the experiment, and the optimal values for the independent variables. In this optimization, used the CCD method. As stated by Kazemian [43] that CCD can provide a better response and close to the actual value and more flexibility and more accurately, for that in this study the authors used RSM with CCD.

For a 2 factorials designs, the design is shown in Table 1. In general, the CCD mathematical model is:

$$Y_u = \sum \beta_L X_{uL} + \sum \beta_Q X_{uL}^2 + \sum \sum \beta_{Lj} X_{uL} X_{uj} + \varepsilon \tag{1}$$

$$X_i = \frac{[X_i - (x_{it} + x_{ib})/2]}{[(x_{it} - x_{ib})/2]} \tag{2}$$

where:

Yu	predicted response to u
u	1, 2,3, …, n
β_0	0th term (mean)
β_L	linear term
β_Q	quadratic term
β_{Lj}	interaction terms
x_{it}, x_{ib}	unidimensional number of an upper or lower bound variable
X_i	the real value of an independent variable

Table 1 Experimental design 2**(2) central composite, nc = 4, ns = 4, n0 = 2, runs = 10

Standard run	Factorial	
	X_1	X_2
1	-1	-1
2	-1	1
3	1	-1
4	1	1
5	-1.414	0
6	1.414	0
7	0	-1.414
8	0	1.414
9 (C)	0	0
10 (C)	0	0

Description: X_1 = (surfactant concentration-1500)/350; X_2 = (ratio-1.75)0.25

Lower level (-1) = 800 ppm; 1.5. Upper level (+ 1) = 1500 ppm; 2. Center point (0) = 1150 ppm; 1.75

Experimental response: composition (% H_2) and hydrogen gas yield (mmol H_2 / g biomass)

$$X_1 = \frac{ppm-1150}{350};\ X_2 = \frac{ratio-1.75}{025} \tag{3}$$

3 Results and discussion

The results of the biomass gasification analysis show that the inclusion of $Ca(OH)_2$ absorbent with PEG600 surfactant promoter reduces the quantity of CO_2 in the produced gas, as seen in Table 2.

According to the data shown in Table 2, the addition of a surfactant to $Ca(OH)_2$ during the absorption process results in a reduction in the CO_2 content in the final gas product, as compared to using $Ca(OH)_2$ alone. The results indicate that the utilization of surfactant, namely PEG 600, can improve the absorption of CO_2 gas by $Ca(OH)_2$. The increased CO_2 absorption efficiency observed when a surfactant is included in the $Ca(OH)_2$ absorber suggests that the surfactant acts as a catalyst. Based on the results, it is evident that when PEG 600 (1200 ppm) is added to $Ca(OH)_2$ and held for 10 min, the resulting gas shows a CO_2 content of 46.35%.

3.1 Optimization using response surface methodology

The experimental results for each run according to Table 1 with responses % H_2 in gas and yield are presented in Table 3. The values of X_1 and X_2 in Table 1 are each transformed into the actual size of the corresponding variable using Eq. (1), X_1 corresponds to surfactant (ppm), while X_2 to the ratio of absorbent solution/biomass (ml/g). The % composition of H_2 was obtained from GC analysis, while yield was obtained from GC analysis and gas flow rate data. The results of variable optimization using the Statistica 6 program are presented in Figs. 2, 3 and Eq. (4) for the % H_2 response, and in Figs. 4, 5 and Eq. (5) for yield response.

Table 3 indicates that the concentration of H_2 might potentially reach a maximum value of 30.41% under the conditions of surfactant concentrations at 1150 ppm and an absorbent ratio to biomass of 1.75 ml/g. The current study demonstrates a greater concentration of H_2 compared to a previous inquiry conducted by researchers on biomass waste gasification without the use of surfactants [39]. Al Nashrey [31] investigated the gasification employed pine wood dust and utilized a three-stage top reactor using a high concentration of nickel and calcium oxide 10, the highest concentration of H_2 attained was

Table 2 CO_2 concentration in yield gas from gasification biomass single-stage using absorbent ca$(OH)_2$ and surfactant

Gasification process	Holding time (minutes)	Surfactant concentration (ppm)	ratio absorbent solution/biomass (ml/g)	$CaCO_3$ (mmol)	CO_2 concentration (mmol/100 g)
Absorbent $Ca(OH)_2$ (A)	1	0	1.80	2.06	11.04
	5			5.41	10.79
	8			6.87	10.09
	10			8.18	9.60
Absorbent $Ca(OH)_2$ + surfactant (B)	1	1200	1.80	2.37	9.80
	5			6.42	6.74
	8			7.99	5.61
	10			9.29	5.15

Table 3 Experimental results on each run in actual conditions

RUN	VARIABLE		RESPONSE	
	Surfactant concentration (ppm)	ratio of absorbent solution/biomass (ml/g)	% H_2	Yield (mmol H_2/g biomass)
1	800	1.50	4.78	0.35
2	800	2.00	12.90	0.89
3	1500	1.50	9.84	1.04
4	1500	2.00	10.46	1.13
5	655	1.75	6.54	0.38
6	1645	1.75	22.25	2.63
7	1150	1.40	17.02	1.44
8	1150	2.10	24.74	2.20
9	1150	1.75	30.41	2.85
10	1150	1.75	30.41	2.85

19.32%. The research conducted by Prasertcharoensuk et al. [9] discovered that when wood wastes are exposed to gasification in a two-stage reactor at a temperature of 900 ^{O}C, it results in the production of 24.4% mol of H_2. This study was conducted using a batch reactor. Upon comparing the research findings, it is evident that doing the research using a batch reactor leads to higher quantities of H_2 products.

3.2 Variable optimization for response %H_2

The mathematical equation model describing % H_2 as a function of the main variables of concentration, ratio, and their interactions is expressed by Eq. (4).

$$\begin{aligned} Y_{(\%H2)} =& 30.410 + 6.209X_1 - 20.086X_1^2 \\ &+ 4.914X_2 - 13.601X_2^2 - 3.750X_1X_2 \end{aligned} \tag{4}$$

Fig. 2 Pareto diagram for the effect of the main variables and their interactions for % H_2

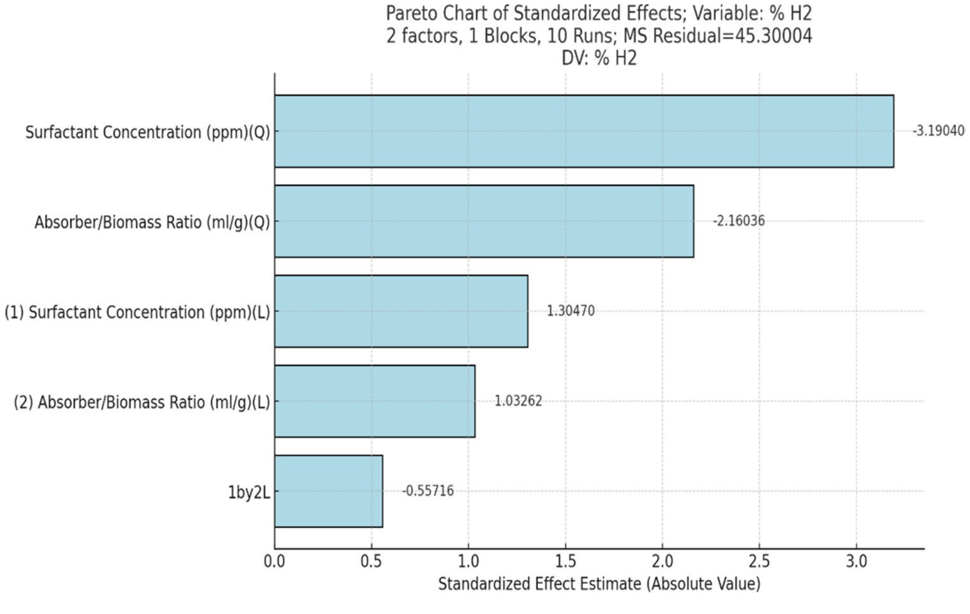
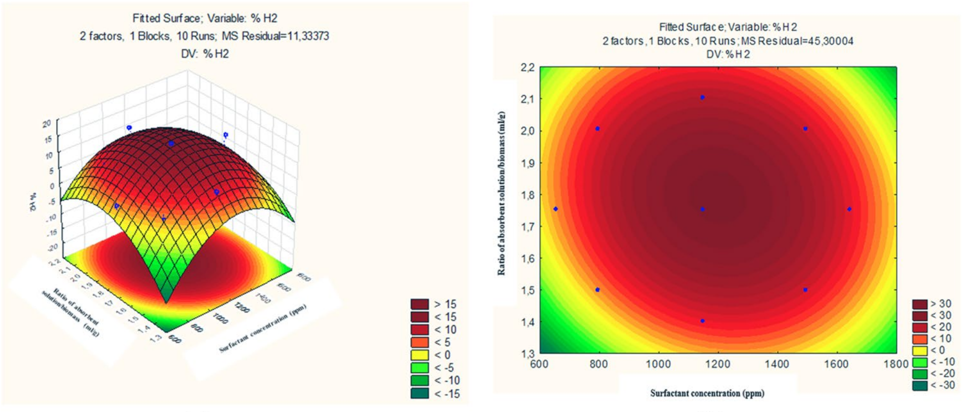


Fig. 3 Response surface concentration and the ratio of absorbent solution/biomass to % H_2. **a** Three-dimensional drawings; **b** contour plot



(a) (b)

Fig. 4 Pareto diagram for the effect of the main variables and their interactions for Yield

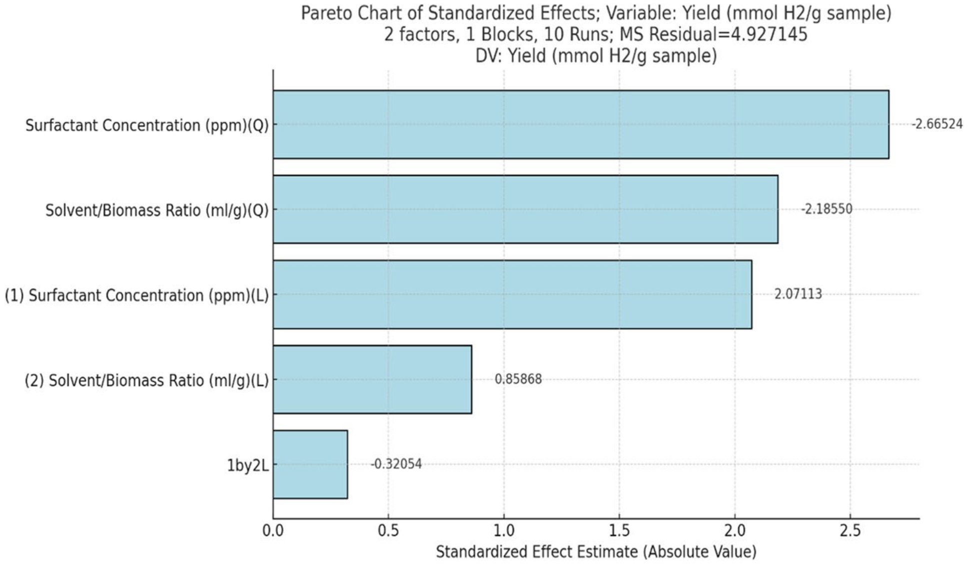
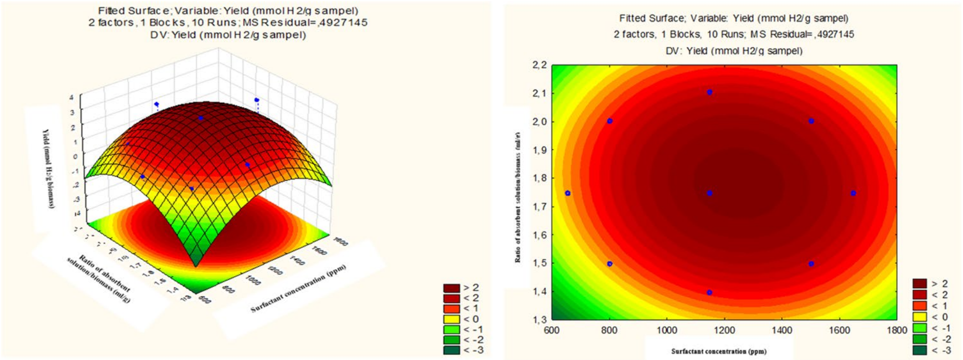


Fig. 5 Response surface concentration and the ratio of absorbent solution/biomass to yield. **a** Three-dimensional drawings; **b** contour plot



(a) (b)

From the Eq. (4) it is clearly shown that both the surfactant concentration variable (X_1) and ratio of absorbent solution/biomass variable (X_2) have a positive effect, where the surfactant concentration effect is greater than the ratio of absorbent solution/biomass effect, while the interaction between variables shows a negative and quite large effect. To obtain a higher % H_2, the values of X_1 and X_2 must be positive, i.e. the operating conditions of each variable must be greater than the median value, namely, surfactant concentration: $1150 < C_S \leq 1500$ and solvent ratio (R): $1.5 < R \leq 2.0$

The main effects and interaction of variables can also be seen from the Pareto diagram in Fig. 2. In line with Eq. (4), from the diagram, it can be seen that the concentration (L) and ratio (L) variables show a positive effect where the effect of concentration (L) is slightly larger than the ratio (L). The effect of concentration (Q) and Ratio (Q) is quite large and has a negative effect, while the interaction effect of the two variables is very small. Optimum operating conditions can also be evaluated from Fig. 3a (3 dimensions surface response) and Fig. 3b (2 dimensions contour plot). Figure 3a consists of the Z axis (dependent variable) is % H_2, and the X and Y axes (independent variable) are concentration and ratio, respectively. From the observations of Fig. 3a and b, it can be seen that the maximum % H_2 obtained from the interaction of 2 variables X and Y in the form of a maximum point in the darkest red area, which is > 30%, at a concentration value of about 1200 and a ratio of 1.8. From the statistical processing, these critical conditions are presented in Table 4, where the predicted maximum % H_2 was 30.825%, at a surfactant concentration of 1200 ppm and a solvent ratio of 1.790.

3.3 Variable optimization for yield response

The mathematical equation model for yield as a function of the main variables of the surfactant concentration, ratio of absorbent solution/biomass, and their interactions is expressed by Eq. (5) following.

$$
\begin{aligned}
Y_{(Yield)} = & 2.850 + 1.028X_1 - 1.750X_1^2 \\
& + 0.426X_2 - 1.435X_2^2 - 0.225X_1X_2
\end{aligned} \tag{5}
$$

Like Eq. (4), the model Eq. (5) also shows that the surfactant concentration variable (X_1) and ratio of absorbent solution/biomass (X_2) both have a positive effect, where the surfactant concentration effect is slightly larger than the ratio of absorbent solution/biomass effect and the difference is not significant. While the interaction of the variables gives a small negative effect so that it can be ignored. This is further clarified by the Pareto diagram of Fig. 4. which shows that the effect of surfactant concentration and the ratio of absorbent solution/biomass variables are not significantly different, while the interaction effect of the variables is very small. To obtain a higher yield, the values of X_1 and X_2 must be positive, i.e. the operating conditions of each variable must be greater than the median value, namely, surfactant concentration: $1150 < C_S \leq 1500$ and the ratio of absorbent solution/biomass (R): $1.5 < R \leq 2.0$.

Table 4 Optimal condition for % composition of H_2 and Yield

FACTOR	Observed minimum	Observed maximum	Critical value	
			Yield	% H_2
Surfactant concentration (ppm)	655	1645	1250	1200
Ratio of absorbing solution / biomass (ml/g)	1.3964	2.104	1.782	1.790
Predictive response value			2.937	30.825

The optimum operating conditions for yield can be seen in Fig. 5 where the maximum yield is obtained in the darkest red area, namely > 2, at a concentration value of about 1300 and a ratio of 1.8. Statistical processing of critical conditions in Table 4 shows the predicted maximum yield was achieved at a value of 2.937, at a surfactant concentration of 1250 ppm and the ratio of absorbent solution/biomass of 1.782.

The method of optimization produced data indicating that the best ratio absorbent solution/biomass is 1.786 ± 0.004, representing the standard deviation. Furthermore, the ideal concentration of surfactant is 1200 parts per million (expressed as the percentage of hydrogen they contain) and 1250 ppm (expressed as the yield). Under ideal conditions, the biomass achieved a yield of 2.937 mmol H_2 per gram, with a hydrogen production rate of 30.82%. Although the ratio of absorbent solution/biomass was shown to have a significant effect on the percentage of hydrogen, it was determined that the concentration of the surfactant has a greater impact on the percentage of hydrogen. However, the impact on crop production does not indicate a significant variation. The findings offer more proof that a single-step process has the potential to be used as an environmentally benign and efficient technique for producing hydrogen from biomass. However, more study is necessary to confirm the feasibility of using this technique on a large-scale industrial level.

4 Conclusion

The results of the optimization process indicate that the optimal ratio of solvent to biomass is 1.786 ± 0.004, while the optimal concentration of surfactant is 1200 ppm (relating to the percentage of hydrogen) and 1250 ppm (relating to the yield). At the optimal circumstances, a yield of 2.937 mmol H_2/g of biomass was reached, and the percentage of hydrogen produced was 30.82%. It was further shown that the concentration of the surfactant has a more substantial impact than the ratio of the biomass to the solvent variable from the point of view of the percentage of hydrogen, although the effect does not differ considerably from the point of view of yield. The findings obtained further demonstrate that a single-stage process has the potential to be utilized as a method that is both environmentally friendly and effective for the production of hydrogen from biomass. However, additional research is required to verify this technique on an industrial scale.

Acknowledgements The authors would like to thank the University of 17 Agustus 1945 Semarang Indonesia for funding this work, through the Internal Grants scheme.

Author contributions Retno Ambarwati Sigit Lestari: conceptualization, experimental procedure, interpretation of the results, writing original draft of manuscript. Mega Kasmiyatun: conceptualization, experimental procedure and methodology, interpretation of the results. Ery Fatarina Purwaningtyas: experimental procedure, collection of data. Ahmad Shobib: experimental procedure, collection of data. Teodora Da Silva: collection of data, Software-programming. Supriyono Suwito: writing original draft of manuscript, review, and editing. Jose Antonio Texeira: supervision, writing review and editing draft of manuscript. All authors read and approved the final manuscript.

Declarations

Conflict of interest There is no conflict of interest.

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