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Life-cycle assessment of hydrogen production via catalytic gasification of wheat straw in the presence of straw derived biochar catalyst

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Professor Ashok Pandey (Editor-in-chief) and Guest Editors
ELSEVIER Special Issue of Bioresource Technology,

Subject: Submission of research article for the VSI: RABRA-2021 in ELSEVIER Bioresource Technology "Recent Advances in Biochar Research and Applications"

Dear Guest Editor,

On behalf of my co-authors, I am submitting the revised article entitled 'Life cycle assessment of hydrogen production via catalytic gasification of wheat straw in the presence of straw derived biochar catalyst'. I am the corresponding author of this study and would be held responsible for all aspects of this paper during and after the publication process. The manuscript has not been submitted for publication nor has it been published before in whole or in part elsewhere. The other co-authors and I had agreed to submit this article to this journal. This work reported represents the results and findings from joint efforts with researchers from several institutions

The authors are in the opinion that the enclosed article fits well within the scope of ELSEVIER Bioresource Technology "**30,080 Life cycle analysis of biofuel and 70,030 Gasification**" that demonstrates the sustainable and renewable approach of thermo catalytic approach using biochar as catalyst. Most importantly, this manuscript is well fitted the theme of the special issue "**Environmental benefits/impacts of emerging applications of biochar**".

We thank the reviewers for the valuable comments that enabled us to enhance the quality of the manuscript. The manuscript has been revised to a great extent by incorporating all the comments/ suggestions from the reviewers. We believe our work is of broad interest and reference to researchers and engineers especially from the biomass industry and biochar utilization. Thus, we consider our work is of sufficient originality, applicability, and impact to appeal to the readership of this journal.

Thank you for considering the manuscript for publication in your prestigious journal.

The declaration and ethical statement are as follows:
- Screening of similarity index by Turnitin to 13% similarity in total which excludes the references, acknowledgement and author affiliation.
- Word count: Abstract (130), and Full article (8114 words, 32 pages)
- Number of Figures – 4, and Number of Tables - 2

Sincerely,

Adrian Loy

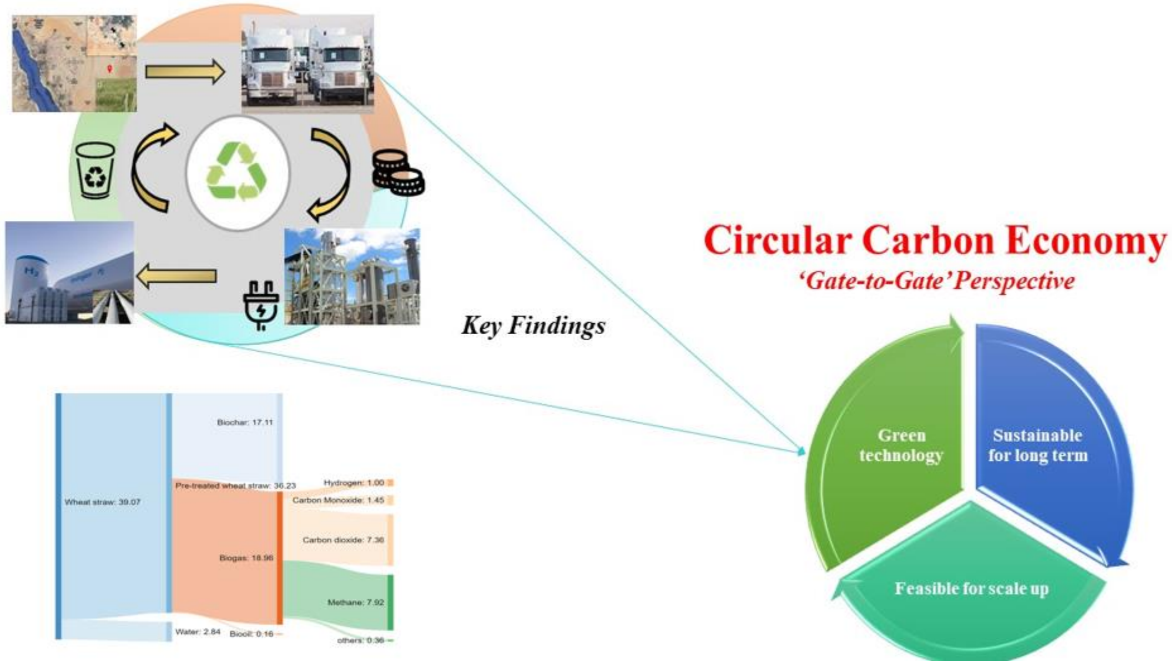
Manuscript Number: BITE-D-21-04350R2

Title: Life cycle assessment of hydrogen production via catalytic gasification of wheat straw in the presence of straw derived biochar catalyst.

We thank the editors and reviewers for the valuable comments that enabled us to enhance the quality of the manuscript. The following sections summarize our responses to all comments from the reviewers. The changes in revised manuscript were shown in RED font.

Editor

No.	Comment	Action/Response
1.	E-supplementary figures and tables cannot be quoted in text as Fig S1..Table S1.., etc. These should be mentioned as (see supplementary material) in the text at relevant places and after the conclusion in a sentence as "E-supplementary data for this work can be found in e-version of this paper online".	• Thank you for the comment. We have amended the changes accordingly. - Line 178-179 (see supplementary material) - Line 531, after the conclusion- We have added the sentence "E-supplementary data for this work can be found in e-version of this paper online"


Circular Carbon Economy
'Gate-to-Gate' Perspective
Key Findings
Green technology
Sustainable for long term
Feasible for scale up
Wheat straw: 39.07
Biochar: 17.11
Pre-treated wheat straw: 36.23
Biogas: 18.96
Water: 2.84
Biooil: 0.16
Hydrogen: 1.00
Carbon Monoxide: 1.45
Carbon dioxide: 7.36
Methane: 7.92
others: 0.36

Highlights

1) The environmental impacts based on P5 unit are found to be negligible.

2) P4 unit poses the highest environmental impact, especially on human health category.

3) The whole process environmental impact is found to be 93.4017 mPt.

4) “Wheat straw loading” parameter contributes the most to global warming potential.

5) Straw biochar catalysts offer competitive H_2 yield and lower environmental impact.

Life-cycle assessment of hydrogen production *via* catalytic gasification of wheat straw in the presence of straw derived biochar catalyst

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Abstract (130 words)

The environmental footprints of H_2 production *via* catalytic gasification of wheat straw using straw-derived biochar catalysts were examined. The functional unit of 1 kg of H_2 was adopted in the system boundaries, which includes 5 processes namely biomass collection and pre-treatment units (P1), biochar catalyst preparation using fast pyrolysis unit (P2), two-stage pyrolysis-gasification unit (P3), products separation unit (P4), and H_2 distribution to downstream plants (P5). Based on the life-cycle assessment, the hot spots in this process were identified, the sequence was as follows: P4 > P2> P1 > P3 > P5. The end-point impacts score for the process was found to be 93.4017 mPt. From benchmarking analysis, the proposed straw-derived biochar catalyst was capable of offering almost similar catalytic performance with other metal-based catalysts with a lower environmental impact.

Keywords: Life-cycle analysis; Biochar; Gasification; Hydrogen; Biomass

1. Introduction

With the alarming demand of global energy and rapid growth of the world population across the globe, the necessity in searching for alternative renewable and carbon-neutral energy sources is vital to meet the soaring global energy needs. From both economic and environmental standpoints, valorization of agricultural crop residues to platform chemicals is deemed as a feasible and attractive approach to achieve a circular carbon economy (Alhazmi & Loy, 2021). Owing to the infinite, cheap, and environmentally friendly properties of agricultural crops, its extensive utilization as renewable energy resources can be observed lately with the emerging closed-loop economy and the on-going transition towards post-fossil-carbon societies (Giuntoli et al., 2013). According to the UN Food and Agriculture Organization (FAO) 2018, the global production of agricultural crops is growing exponentially due to the drastic demand from human mankind, specifically the agricultural crops of wheat, maize, and rice (Roser, 2020). Among the agricultural crop residues reported in the literature, wheat straw is one of the most widespread residues readily available in Europe, America, and Western Asia continents with an annual global production of 132.59 million tonnes per year (Ingrao et al., 2021).

Instead of landfilling or direct combustion of wheat straw (after harvesting), such abundant lignocellulosic wastes can be transformed into sustainable renewable bio-based products *via* thermochemical methods. Among all the thermochemical pathways, gasification is one of the key technologies that has been extensively investigated. Over the years, many experimental studies have successfully demonstrated a high production of H_2 from biomass gasification process, including wheat straws as feedstock. In 2017, Cao and co-authors have investigated supercritical water gasification of wheat straw soda black liquor in a batch reactor system (Cao et al., 2017). Notably, high yield of H_2 (62.38 mol/kg) with carbon content

(98.17%) was attained at 1023 K with a diluted black liquor of 2.5 wt% as reactant. Another similar finding reported by Hu and co-authors, showing that 36 vol% of H_2 was attained with the aid of 60% Fe_2O_3/Al_2O_3 at 5g of wheat straw, reaction time of 10 min, and temperature of 1123 K (Hu et al., 2018).

Over the decades, non-noble metal-based catalysts (e.g. Ni, Cu, Co) have been reported as the best reforming catalysts for industrial applications in biomass gasification (Cao et al., 2020). They have shown great potential as reforming catalysts given its high selectivity, cheap cost, and high availability. Nevertheless, some drawbacks (e.g. large amount of loading, short lifespan, and easy scaling) are inevitable. Whereas, noble metals (e.g. Pt, Ru, and Rh) have both high catalytic activity and long lifespan, but they cannot be applied on a large scale due to economic consideration (Cheah et al., 2021). In this sense, the search for an affordable and highly active reforming catalyst is essential to support the realization of the circular gasification economy.

Lately, biochar has emerged as a new class of biomass-derived functional materials that can be applied as a catalyst in various energy recovery applications (Do Minh et al., 2020; Waqas et al., 2018). The rise of the application of biochar as a support material for the preparation of tar cracking/reforming catalysts, particularly, for the synthesis of char-supported metal nanoparticles has attracted large interest from both industrial and academic communities (You et al.,2018; Guo et al., 2020). For instance, Yao and co-authors have investigated the effect of Ni-based biochar catalysts for H_2 production *via* gasification process (Yao et al., 2016). Notably, cotton-char supported Ni catalyst demonstrated the highest catalytic activity of H_2 production (64.02 vol.%) as compared to its counterparts (rice husk char, activated carbon char, and wheat straw char). In 2021, Farooq et al. reported that the presence of silica in the rice husk chars can reduce coke formation in Ni- char supported catalysts (Farooq et al., 2021). Most importantly, the metal oxides in the rice husk char induced a positive synergistic effect to pure Ni catalyst and thus, a higher tar conversion and H_2 yield were obtained in contrast to the bi-functional Ni/α-Al_2O_3. Emerging knowledge and evidence on the applications of biochar as a reforming catalyst with high effectiveness in tar cracking, and low cost, suggesting that the valorization of biochar can be a feasible alternative that can improve the overall economic and environmental values of a gasification system.

To the best of the authors' knowledge, the analysis of environmental impacts of H_2 production from gasification of wheat straw using straw-derived biochar catalyst is still yet to be reported in the literature. The environmental aspect of a wheat straw-based gasification plant is important to be examined since it is one of the key considerations for future technology investment. Thereby, the whole gasification process starting from the raw materials to the end product should be analyzed and optimized from the perspective of the life-cycle of resource and environment performance. Hence, this work aims to assess and identify the possible environmental impacts of carbon chain of wheat straw gasification from the beginning (biomass collection and pre-treatment of wheat straw) until the end process (H_2 distribution to petrochemical plant). Based on this framework, the hypothesis of " the monetary value of the environmental impact of biochar production and the application as as biochar catalyst" can be elucidated. Moreover, the comprehensive performance of each process unit on the environmental impact can be evaluated without value-choices based weighting factor (Li et al. (2020).

The case study was modeled based on a gate-to-gate view, taking consideration from biomass collection and pre-treatment units (P1), biochar catalysts production in fast pyrolysis unit (P2), two-step pyrolysis -gasification units (P3), products separation unit (P4), and lastly H_2 product distribution to downstream plants (P5). Furthermore, a sensitivity analysis was also performed to identify and ascertain the most significant input parameters in affecting the environmental impacts based on the gate-to-gate LCA boundaries. This study provides a postulated assessment of the environmental impacts with regards to catalytic gasification process of wheat straws using straw-derived biochar catalyst and knowledge to support future decision-making in moving towards higher TRL based on the LCA with the selected boundaries.

2. Methodology

2.1 Method

According to the ISO 14040 (Principle and framework) and 14044 standards (Requirement and guidelines), the LCA method comprises of four independent phases: (1) goal and scope definition; (2) life-cycle inventory analysis; (3) impact assessment; and (4) interpretation (Alhazmi & Loy, 2021). This LCA case study was carried out based on the IMPACT 2002+, where the environmental impact categories include but not limited to global warming potential, ozone depletion potential, aquatic acidification potential, aquatic eutrophication, aquatic ecotoxicity, terrestrial ecotoxicity, ionizing radiation, mineral extraction, non-renewable, land occupation, and respiratory inorganics were analyzed. The damage categories such as human health, ecosystem quality, climate changes, and resources were also being investigated. Most researchers have applied IMPACT 2002+ in their study because this method considers the environmental impacts on both a midpoint and endpoint level (Hong, Li, & Zhaojie, 2010; Jolliet et al., 2003).

2.2 Goal and Scope Definition

The goal of the present LCA study was to evaluate the environmental assessment of H_2 production in catalytic wheat straw gasification using straw-derived biochar catalysts. The environmental footprints of all input processes of the defined life-cycle from raw material pre-treatment to the final product (H_2) were included in this study (Fig. 1). The system boundary of this case study was adopting a 'gate-to-gate' approach. It includes biomass collection and pre-treatment units (P1), biochar catalyst production using fast pyrolysis unit (P2), two-stage pyrolysis- gasification unit (P3), products separation units (P4), and H_2 distribution to downstream plants (P5).

2.3 Life-cycle inventory (LCI)

Wheat is one of the most important staple grains in the Kingdom of Saudi Arabia where most of it is consumed in the form of pita or bread. According to the U.S. Department of Agricultures' Foreign Agricultural Service (FAS), wheat production in Saudi Arabia is expected to escalate in the next two market years due to intensive government policy to reduce irrigation. The production is forecasted to increase by 40 % in the year 2019-2020 relative to production capacity of 500,000 tonnes in 2018-2019 (World Grain, 2021). The pilot-scale catalytic gasification plant was proposed to be located at Al-Hasa Oasis, Saudi Arabia, which has about 30,000 acres of agricultural land that are irrigated by the flow of more than 60 artesian springs. More importantly, there are a few downstream plants located nearby.

Meanwhile, the data of biochar catalyst production was adopted based on authors' previous works (Loy, et al.(a), 2018; Loy, et al.(b), 2018) and the remaining units was retrieved from literature (Kalinci, Hepbasli, & Dincer, 2012; Wang, You, Lu, Chen, & Xu, 2020; Yao et al., 2016) and Ecoinvent database v3.6. All the data used were based on the optimum conditions of the bench to pilot scale experimental work. The environmental performance of H_2 production from the catalytic gasification was evaluated following the LCA approach. Note that the functional unit was fixed at 1 kg of H_2, while the project lifespan is assumed to be 15 years with an annual operating day of 300 days. The plant capacity is assumed to be 200,000 tonnes of wheat straw per year. Full details on input and output of the whole process (see supplementary material), and the explanation of each process are shown in the following section.

2.3.1 Biomass collection and pre-treatment units (P1)

Pre-treatment process is an important stage in upgrading biomass to reduce its size; thus increaseing the accessible surface area (Chiaramonti et al., 2012). The wheat straw was sieved to approximately 50 mm^2 using a vibration ball milling machine; to increase the reaction surface area (Kumar et al., 2020). After milling, the wheat straw was fed into the mixing tank to wash out the unwanted alkali and alkaline earth metals using a diluted acid mixture of hydrochloric acid solution (30 vol.%), which can lower the reagent cost without affecting its effectiveness (Solarte-Toro et al., 2019). Then, the wheat straw and the acid mixture were then transferred into an ultrafilter (50 m^2 of active surface per module) to remove the impurities (Waste 1). "Waste 1" mainly includes chlorides, water, alkali, and alkaline metals. Whereas the drying process was modeled to produce wheat straw (dry basis) at less than 2% w.c. In order to produce 36.23 kg of wheat straw at 2% w.c. (Base = wheat straw at 5 % w.c), 3.46 kg of water (unremoved waste) was assumed to be evaporated.

2.3.2 Biochar catalyst production using fast pyrolysis unit (P2)

Fast pyrolysis is reported to be a suitable technology to produce microporous and fragmented chars that are potentially favorable for biochar catalyst usage (Brewer et al. 2009). Thus, the biochar catalyst in this work was produced *via* fast pyrolysis of wheat straw in a semi pilot-scale tube furnace at 773 K (Yao et al., 2016). In order to gasify 36.23 kg of wheat straw, a 30.81 kg biochar catalyst (i.e., biochar catalyst-to-feedstock ratio= 1:0.85) was required (Yao et al., 2016). Meanwhile, the wheat straw loading (205.4 kg) was calculated based on Pfitzer's study (Pfitzer et al., 2016), where approximately 15 wt% of biochar can be obtained *via* fast pyrolysis of wheat straw. The electricity consumption of the semi-pilot pyrolysis unit was assumed to be 0.0281 kWh per kg biomass as reported (Brassard, Godbout, & Hamelin, 2021). The carbon emissions attributed to catalyst loading was assumed to be negligible since it will only be conducted manually once after every few years (Montoya et al., 2020; Gholizadeh et al., 2021).

2.3.3 Two-stage pyrolysis-gasification unit (P3)

The catalytic gasification process of wheat straw was operated in a two-stage fixed bed; thereby it has the advantage of producing gaseous products with higher calorific value as compared to conventional gasifiers (Kosov and Zaichenko, 2016). During the first stage, the feedstock was pyrolyzed under inert condition. Then, the pyrolysis volatiles were catalytic steam reformed in the presence of biochar catalyst to enhance the yield of H_2. Nitrogen flow (99.99%) was supplied as carrier gas to prevent any unwanted oxidation in the pyrolysis zone (773 K). Whereas, the gasification temperature was set to be 1173 K, while steam was introduced into the system to aid the water gas shift, catalytic reforming, and boudouard's reactions (Loy, et al., 2018 (a)). The H_2 yield attained was reported to be 27.61 g/kg biomass or 52.35 wt.%, respectively.

2.3.4 Product separation units (P4)

This process can be divided into 3 sub-processes, namely 1) cyclone separation unit (biochar), 2) condensation unit (biooil) and, 3) gas separation unit (biogas). The full explanation of each unit operation is discussed in the section below:

2.3.5.1 Cyclone separation unit

Among all the industrial cyclone separators, square cyclone separators have vast advantages that include simplicity, lower cost, small volume, shorter start time, and shorter separation time compared to the single stage and two stages cyclones (Zhang et al., 2021). Thus, a square cyclone separation unit was selected in this study to remove the biochar produced from the catalytic two-stage pyrolysis-gasification process. Three-square aluminum steel cyclone was modeled with a thickness of 0.002 m based on the functional units. The energy consumption of the side channel cyclone blower was 1.5 kW/hr and single phase (220-240 V) (Venkatesh et al., 2021).

2.3.5.2 Condensation unit

The condensation process was proposed for the condensable vapors produced from the catalytic gasification of wheat straw using biochar catalyst (Brassard et al., 2021). In order to calculate the energy consumption of water pumping, a submersible pump of 1 HP with a capacity of 10 L/min at 20 PSI was modeled (a typical submersible pump of 1 HP with a capacity of 43.2 L/min at 20 PSI and 20-foot depth was selected (Monarch Industries, Model MST5-100). Based on the catalytic gasification experiments of 1 kg of wheat straw per hour using a water flow of 180 Lwater/h, it was estimated that 6521 L of water was pumped and recirculated for the gasification of 36.23 kg of wheat straw (Brassard et al., 2021). The electricity consumption of the pumps (in MJ) was calculated by the total energy consumption of the pump (0.7 kW) with the time needed to pump 6521 L of water (~12 hr) and divided by a factor of 3.6. Also, it was assumed that 5000 L of water per year was used in each condenser (1st condenser: 100 % water and 2nd condenser: 50/50 ratio water to ethylene glycol to prevent boiling issue). The specific volume of each liquid annually was attained using Eq. (1) as shown:

$$Unit\ volume\ (L\ Mg^{-1}) = \frac{Total\ volume\ \left(L\ year^{-1}\right)}{200000\ Mg_{biomss}\ year^{-1}} \quad (1)$$

The water circulating in the two condensers was maintained at 393 K and 278 K, respectively. In the 1st condenser, the temperature was set to beat 333 K and 393 K each day, considering that the heat losses were compensated by hot gases heating during pyrolysis. For the 2nd condenser, the temperature has to be in the range of 294 K to 278 K each day. The energy consumption was calculated based on Eq. (2) as shown:

$$Q = mCp\Delta T \quad (2)$$

where m is the mass of water circulated in the condenser for 36.23 kg of biomass, Δt is the difference of temperature for heating or cooling (in K) and Cp = 4.185 kJ kg $^{-1}$ K^{-1}.

2.3.5.3 Gas separation unit

In this gas separation phase, the dry syngas (16.12 kg) was fed to a pressure swing adsorption (PSA) unit where H_2 was fully adsorbed on the adsorbent (e.g. zeolite and silica) of the unit, before being transferred to the petrochemical plants (Kohlheb et al., 2020). The electricity of the PSA was found to be around 1.26-1.52 kWh/Nm^3-CO_2 depending on the capacity of H_2 production. The unadsorbed flue gases (e.g 9.07 CH_4 vol%, 26.31 CO vol%, 18.01 CO_2 vol%) can be incinerated in a flame oxidation burner which can be utilized as an energy source. However, in this study, we did not consider the fraction gaseous mixture as a source of energy.

2.3.5 H_2 distribution to downstream plants (P5)

There are a few downstream petrochemical plants located at or near to Al-Hasa Oasis region such as Saudi Aramco and SATORP. As such, the average pipeline distance was calculated based on Eq. (3). The calculated pipeline distance from the gasification site to the downstream plant in terms of -kilometers was around 2-km, and the pipeline was assumed to be made of chromium steel 18/8 – GLO steel 9.

$$r = \frac{1}{6}\tau\sqrt{\frac{F}{yf}(\sqrt{2} + \ln(1 + \sqrt{2}} \quad (3)$$

where r = average pipeline distance, F is the H_2 delivered annually to the plant (t/year); y is the annual yield of feedstock (t/year); f is the fraction of acreage around the plant devoted to feedstock production; τ is the ratio of the actual distance to the straight-line distance from the plant.

2.4 Sensitivity analysis

Sensitivity analysis was carried out to examine the effects of individual input parameters on the environmental impacts based on the gasification process. A ± 20 % variation of the input parameters, including the feedstock transportation distance, biochar loading, syngas yield, and wheat straw loading was studied. With the sensitivity analysis, process engineers and academicians will have a better overview of the evaluation by minimizing the uncertainty attributed to the empirical data.

3. Results and discussion

3.1 Interpretation of LCIA results

3.1.1 Impact 2002+ Midpoint Categories

The results of LCIA of the 5 different processes involved in catalytic biomass gasification for H_2 production using biochar-derived catalyst are reported in Table 1 in terms of Impact 2002+ midpoint categories. Significant midpoints that contributed to the damage categories in section 3.1.2 have been elucidated in the following:

With respect to aquatic ecotoxicity, the environmental impact was found to be the most significant among all categories, whereby the major contributions were dominated by P2 unit (4443 kg TEG water), followed by biomass collection and pre-treatment unit (4138 kg TEG water), products separation unit (3800 kg TEG water) and two-stage pyrolysis-gasification unit (403 kg TEG water). Although the Environment Protection Agency (EPA) has not published any water quality guidelines for TEG, there are still several aspects with relation to the environmental readiness level of the whole process from the point of view of legislation should be incorporated (EPA, 2006). Since the outputs from P2, P3, and P4 units include biooil, which contains organic aromatic compounds that were acidic in nature, whereby the low pH of biooil obtained was expected to produce significant ecotoxicity upon exposure to aquatic organisms and systems (Oasmaa, Elliott, & Korhonen, 2010). On the other hand, the toxic effect of biomass pre-treatment was due to the washing out of alkali and alkaline earth metals from the biomass. A substantial quantity of alkali and alkaline metals, such as Si (31.86 wt%), K (19 wt%), Ca (4.14 wt%), Cl (2.67 wt%), and Mn (1.10 wt%), was being removed into Waste 1. It has been reported that the Si component, which can be easily oxidized into silica, contributes to total suspended solid (TSS) in water. Thus, it should be carefully practiced to meet the 10 mg/L as regulated by "2003-Ministry of Municipal and Rural Affairs (MMRA)" and '2006-Ministry of Water and Electricity (MWE) of Saudi Arabia" (MMRA, 2003; MWE, 2006). In addition, the washed ions in the wastewater, typically, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and chlorides (Cl^-), that are released into aquatic ecosystems have been reported to be responsible for physiological irregularities of aquatic lives while distracting ion regulatory mechanism in the living organisms (Hansen, Olsen, & Rosenkilde, 1996).

Another environmental impact that demonstrates a significant point was terrestrial ecotoxicity. Although it was consistently less severe as compared to aquatic ecotoxicity from all processes, the impact on terrestrial ecosystems was considered high and should never be neglected. The environmental impact towards terrestrial ecotoxicity was found to be mostly contributed by P1 (2892.09 kg TEG soil) and P2 (1482.92 kg TEG soil). The terrestrial ecotoxicity potential value from P1 was about 10-fold that of P3, due to the attribution of the presence of alkaline earth metals in wheat straw that may potentially affect soil ecosystems. Previous study has reported that poor quality irrigation water that contains certain ions at concentrations above the threshold values (>3.00 dS/m) can cause plant toxicity problems by impairing growth, reducing yield, changing morphology of agriculture plants (Memon, Kuboi, Fuji, Ito, & Yatazawa, 1983).

Viewing from the aspect of terrestrial acid and aquatic acidification, the midpoint impact point was found to be smaller than the ecotoxicity potential. The processes that contribute the most to acidification were product separation, and catalyst preparation. These processes produce biooil and biogas that contain mainly acid components and gases, such as SO_X and NO_X. These gas components were accumulated in the atmosphere to be captured by the moisture to form acid rain that contributed to terrestrial and aquatic acidification ultimately (Plens, Monaro, & Coutinho, 2015). This shall be given utmost consideration since EPA has regulated Primary National Ambient Air Quality Standard (NAAQS) for SO_X and NO_X to be at a maximum concentration of 75 ppm and 100 ppm for 1 hr, respectively (EPA, 2010, 2018). It was seen that the midpoint score that originates from carcinogens (<0.5 kg C_2H_3Cl eq.) was smaller in impact points as compared to non-carcinogens (<1.4 kg C_2H_3Cl eq.) consistently. The EPA has regulated the toxicity threshold of C_2H_3Cl to 1×10^{-4} mg/L since it has been demonstrated to be highly potential to induce cancer (EPA, 2000) and therefore, exhibiting detrimental health effects. The impact of carcinogens was mostly from P1 process since it involves washing out of alkali and alkaline earth metals that are toxic to the environment (Ge & Li, 2018). In addition, it was found that the presence of chloride in the wastewater may lead to the generation of toxic and carcinogenic by-products (Prasse, von Gunten, & Sedlak, 2020). In a similar manner, the contribution from ionizing radiation was found to be from P1, followed by P3 that exhibited a very similar impact point. The apparent impact from P1 was due to the diesel fuel used in wheat straw transportation, while P3 produce aromatic hydrocarbons biooil that have ionizing radiation potential. On the other hand, impact of non-carcinogens was found to be consistently higher than the carcinogenic counterparts and were mainly contributed by P2, followed by P1 and P4, respectively. This has been attributed to usage of electricity that consumes sources of energy in these processes, such as 577.17 and 342.51 kWh, for catalyst preparation and product separation, respectively. The electricity consumption and reactions involved in the processes emit substances, such as PM_{10}, SO_X and NO_X, that are not categorized as carcinogens but detrimental to human health with prolonged and high dosage exposure (Lock et al., 2019).

On the other hand, ozone layer depletion demonstrated a negligible effect with minimum gaseous emission from fossil fuels and chlorofluorocarbons (CFCs) from the utilization of renewable biomass resources, which aligns with the initiative of Montreal Protocol to alleviate ozone depletion issue (OEQ, 1988). By evaluating the effect of global warming, it was found that the processes contributed to moderate consequences with the dominant phase originating from P4, while P1, P2, and P3 demonstrated a similar impact. P5 acts as an indirect GHG through its effect on hydroxyl radicals (Derwent et al., 2006). As a whole, the results from the environmental indicators show that both aquatic acidification depletion and global warming potential have remarkably influenced the life-cycle environmental performance of the gasification system. Thus, both parameters were selected for the sensitivity analysis to provide an in-depth understanding of the relationship between the input variables with both individual environmental impacts.

3.1.2 Impact 2002+ Damage Categories

All midpoint scores as discussed in section 3.1 were related to the four damage categories, which are human health, ecosystem quality, climate change, and resources, respectively. The percentage contribution of each mid-point impact to the four end-point impacts for H_2 production *via* catalytic gasification of wheat straw using biochar as catalyst is shown in Fig. 2. The "human health" damage category is the sum of the midpoint categories "carcinogenic and non-carcinogenic toxicity", "organic and inorganic respiratory effects", "ionizing radiation", and "ozone layer depletion". The "ecosystem quality" damage category is the sum of the midpoint categories from "aquatic ecotoxicity", "terrestrial ecotoxicity", "terrestrial and aquatic acidification", "land occupation", and "aquatic eutrophication". On the other hand, the damage category "climate change" is the same category as the midpoint category "global warming". Finally, the damage category "resources" is the summation of the midpoint categories from "non-renewable energy consumption" and "mineral extraction".

The damage assessment based on the 5 different processes involved in catalytic biomass gasification for H_2 production using straw-derived biochar catalyst is summarized in Table 2. In this context, the value was calculated as the average person's annual share of the environmental impacts of the entire population in Europe. The scale was chosen in such a manner that the value of milli-point (mPt) represents one thousandth of the annual load from one average European inhabitant. The purpose of normalization was to facilitate interpretation and comparison between respective shares of each impact to the overall damage.

From Fig. 3, it was found that the impact of the different processes was in the order of P4> P2> P1> P3> P5. Based on the findings, the most detrimental contributing criterion that exemplifies impact of the different processes arises, particularly from the human health, resources, and climate change damage categories. The damage impact of P5 was considered minor and negligible as compared to the other units Since the human health category was dominated by respiratory effects caused by substances emitted into air, the product separation phase that has the highest middle point category exhibited the greatest damage potential. In a similar manner, P4 yielded the highest point due to the generation of GHG radicals and components from the process that can be potentially inhaled. Resource depletion impact was also the highest from the P4 since it utilizes several equipment, such as cyclones, pumps, condensers, and PSA, that requires energy consumption from combustion of non-renewable fuels. In addition, it also involves the usage of water with high capacity for the condensation process to convert condensable vapours into biooil. The findings pinpoint that the feasibility and sustainable circular carbon benefits of catalytic biomass gasification for H_2 production using biochar catalysts can be enhanced by improving the separation efficiency of the process.

Subsequently, P2 has the second highest damage potential from the Impact 2002+ assessment, with the greatest point contributed by human health, climate change, and ecosystem quality, respectively. Human health was significant due to similar reasoning attributed to respiratory effects due to the emission of organic and inorganic substances, such as PM_{10} and VOCs. Energy consumption was also necessary for the catalyst preparation phase, which produces potential GHG components, typically CO_2 and CH_4. The ecosystem quality carries the third-highest contribution in the damage assessment since it produces several air emissions and organic compounds that can potentially affect the aquatic and terrestrial balance.

P1 was the third-highest contributor to the damage assessment with the most detrimental impact originating from the resources, human health, and climate change. The highest contributor from resource utilization inherited similar points to product separation and two-stage pyrolysis-gasification units. This has been attributed to the similar usage of energy, water, and feedstocks from wheat in these processes. Viewing from the impact of human health, the biomass pre-treatment was found to be much lower as compared to the product separation and catalyst preparation phases. This demonstrates that although the biomass pretreatment involves the production of wastewater with alkali and alkaline earth metals, the ultimate impact was not dominant since it has a lower score point for respiratory substances.

Fourthly, P3 exhibited the damage impact in the order of human health > climate change > resources. In fact, the score points between two-stage pyrolysis-gasification and biomass pre-treatment were quite similar when comparing the contribution by these two categories. The difference lies in lower contribution in the two-stage pyrolysis- gasification *via* the ecosystem quality since it has a smaller impact that originates from lower aquatic and terrestrial ecotoxicity as well as acidification properties. The reasoning has been attributed to lower concentrations of emissions and organic outputs from the process. In addition, on the contrary, climate change contributes to a higher score in the impact assessment since the process still emits greenhouse pollutants albeit at lower concentrations. Based on the findings, the main trade-off concerning environmental impacts was not found to be associated with the initial upstream nor end-user distribution units but with the downstream separation unit (P4). This suggests that more emphasis on the strategic tactical and operational planning on this unit is required to produce a more environmentally friendly catalytic gasification system.

3.2 Sensitivity Analysis

Sensitivity analysis of significant parameters in the input for aquatic acidification depletion and global warming potential of H_2 production *via* catalytic gasification of wheat straw is depicted in Fig. 4. From Fig. 4 (a), it can be seen that a 20 % reduction in the feedstock transportation distance has the highest decrease of aquatic acidification. The findings suggest that the soot emissions from vehicles during transportation, which contain NOx, $SO_{X,}$ and CO_2, contribute to acid gas formation. Such environmental impact can be reduced by strategically locating the plant site (i.e., locate at a closer vicinity). It is then followed by the syngas yield, where its reduction will result in a significant drop in the acidification potential. This is due to the presence of acidic NOx, $SO_{X,}$ and CO_2 gases in the compositions. On the contrary, the reduction of the biochar and feedstock loading by 20 % increased the aquatic acidification with the biochar loading showed a more significant impact. The analysis highlights the importance of having sufficient biochar and feedstock to facilitate efficient conversion performance as well as minimize the production and emission of acidic NOx and SOx. On the other hand, a 20 % increment in the syngas yield and distance of feedstock transportation could lead to an approximately similar increment in the aquatic acidification potential. The increment in aquatic acidification potential with increasing feedstock transportation distance by 20 % was found to be not that significant as compared to its counterpart when the distance was decreased. In a similar manner, the 20 % increment in biochar and feedstock loading leads to the opposite impact in the reduction of aquatic acidification, whereby the decrement was exceptionally observed with the alteration in feedstock loading, due to the enhancement in reaction efficiency of catalytic biomass gasification.

From Fig. 4(b), it was found that the decrement in the input parameters by 20 % caused a reduction in global warming potential consistently with the descending order of feedstock transportation distance > syngas yield > biochar loading > wheat straw loading. The decrement in the transportation distance and syngas yield demonstrated a higher reduction due to a reduction in CO_2 produced during the process. On the other hand, CO_2 emission was less affected by the reduction of biochar and wheat straw loading, mainly attributed to the nature of the reactions involved in the biomass gasification that produce GHG. The increment in 20 % of the input parameters was depicted to be increasing persistently in the order of wheat straw loading > feedstock transportation distance > biochar loading > syngas yield. The wheat straw loading was found to be much higher in increment as compared to the other input parameters. The findings suggest that a high loading necessitates a bigger capacity and consumption of resources that release an exemplified amount of GHG to the atmosphere.

As a whole, the most significant input parameter that contributes to a reduction of aquatic acidification depletion and global warming potential with a 20 % decrease was the feedstock transportation distance. Whereas, with an increment in the inputs by 20 %, the most significant parameters were found to be biogas yield and wheat straw loading to aquatic acidification depletion and global warming gas potential, respectively. From the sensitivity analysis, different uncertainty factors in the system with respect to environmental burdens have been determined. The integration of the sensitivity analysis with energy and exergy assessment should be carried out to provide a bigger picture of the biomass sustainability frontier.

3.3 Benchmarking study

This subsection aims to benchmark the proposed biochar-based catalytic gasification of wheat straw to other existing relevant works. Based on the findings, although the studies are not conducted under the same conditions, it can still be seen that the straw-derived biochar catalysts proposed in this work, are capable of offering a decent H_2 yield as compared to other studied catalysts for wheat straw gasification. It is interesting to note that H_2 yielded through straw-derived biochar gasification (25.59 g H_2/kg wheat straw) is comparable to other metal oxide catalysts such as Ni-based catalysts (5.6~ 25.3 g H_2/kg wheat straw), Rh-based catalyst (8.4 g H_2/kg wheat straw), and Fe-based catalyst (16.02-23.93 g H_2/kg wheat straw). Moreover, biochar catalysts are known as a promising substitute for traditional metal-based catalysts, given their cost effectiveness and environmentally friendly-nature (Lee, Kim, & Kwon, 2017). Given that there is only a scarce amount of literature that has performed LCA study for a wheat straw catalytic gasification process, benchmarking analysis on the environmental performance is difficult to be performed. Nevertheless, one can still qualitatively justify the environmental benefit of using char-based catalysts as compared to other metal-based catalysts in two ways. Firstly, its relatively high H_2 yield simply indicates a more efficient use of resources (e.g. lower amount of feedstock required, and lower energy consumed), which further results in lower environmental impacts. Secondly, the catalysts are derived purely from biogenic resources which do not add significant burden to the carbon cycle. This, therefore, leads to a lower environmental impact as compared to metal-based catalysts. Using Ni catalyst as an example, every kg of Ni contributes 13 kg CO_2-eq (LCA, 2020)), which is about 7.7 times higher than that of the proposed straw-derived char catalysts (equivalent to 1.69 kg CO_2-eq/kg catalyst). This is in agreement with the comparative study made by Frazier et al. (Frazier RS, 2015)), where the GWP of metal-based catalysts is significantly higher (>10 folds) than that of the char-based catalysts. As the world is marching towards sustainable development, the use of catalysts that were derived from natural renewable resources are deemed favourable. Policymakers can put efforts in encouraging such applications to promote green economy development in the industry sector including the hydrogen production industry.

4. Conclusions

The LCA results showed that environmental impact of the different processes was in the descending order of P4 > P2 > P1 > P3 > P5. The P4 was found to be the targeted hotspot in this study, which yields the highest greenhouse gas and resource depletion impacts. Thus, it is recommended to take into consideration the "separation unit, P4" thoughtfully in any decision making of scaling up this process. Also, future research direction should be pivoted towards metal-based supported biochar catalysts to provide a more in-depth understanding of the feasibility of biochar catalyst application.

*E-supplementary data for this work can be found in e-version of this paper online

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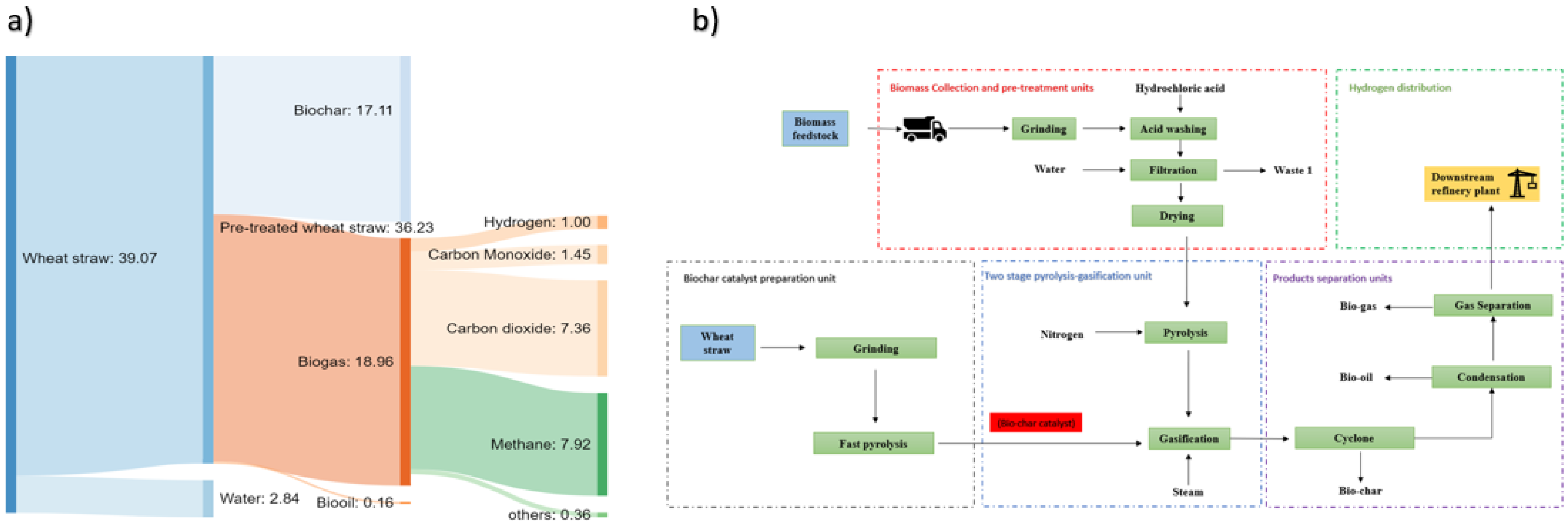

Fig. 1. a) Sankey diagram of the product distribution of catalytic gasification of wheat straw. b) System boundaries of catalytic gasification of wheat straw using straw derived biochar catalyst, which includes biomass collection and pre-treatment units (P1), catalyst preparation using fast pyrolysis unit (P2), two-stage pyrolysis and gasification unit (P3), and products separation units (P4) as well as hydrogen distribution to downstream plant (P5)

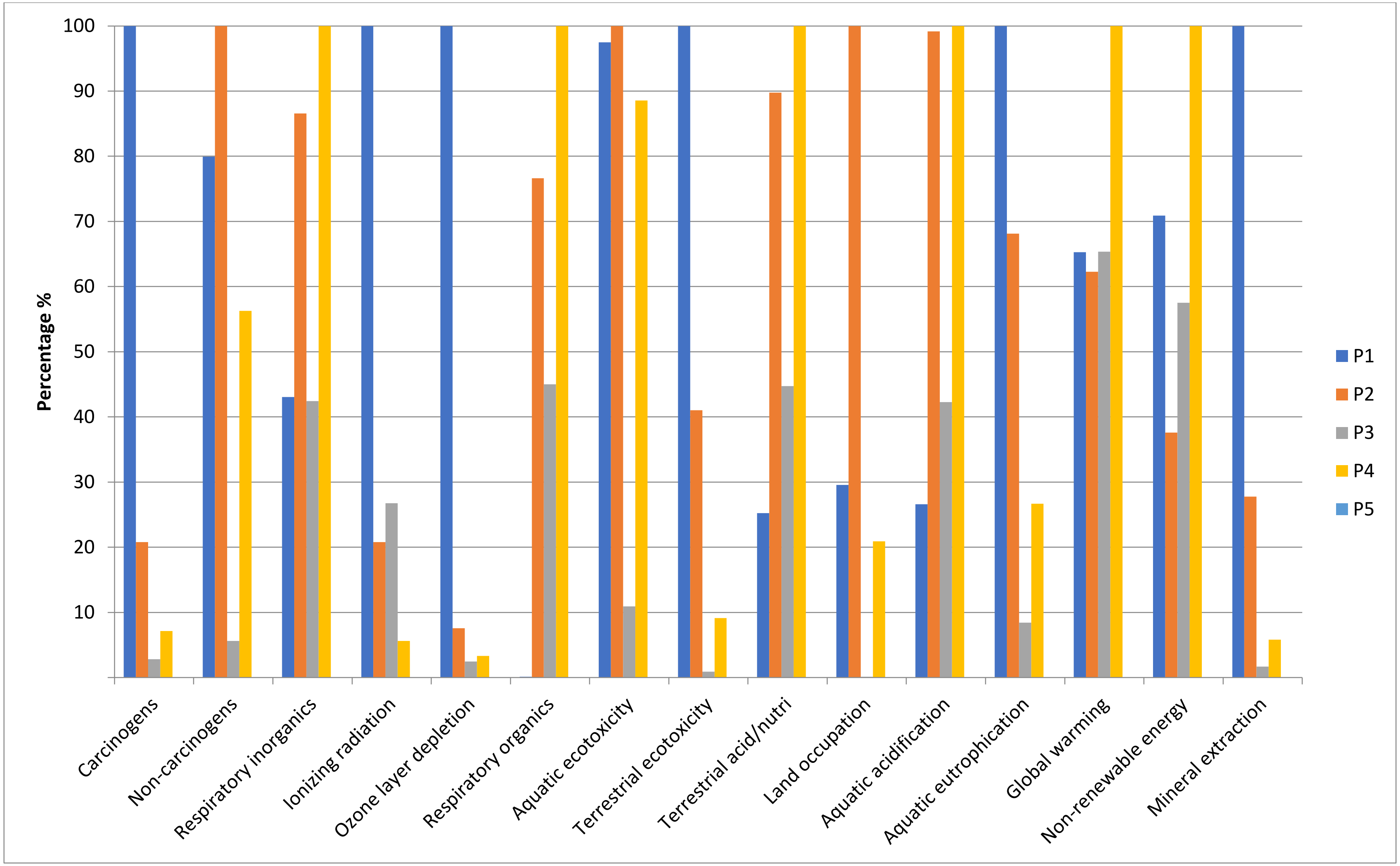

Fig 2: Comparison of the life-cycle environmental impacts of P1, P2, P3, P4 and P5 processes.

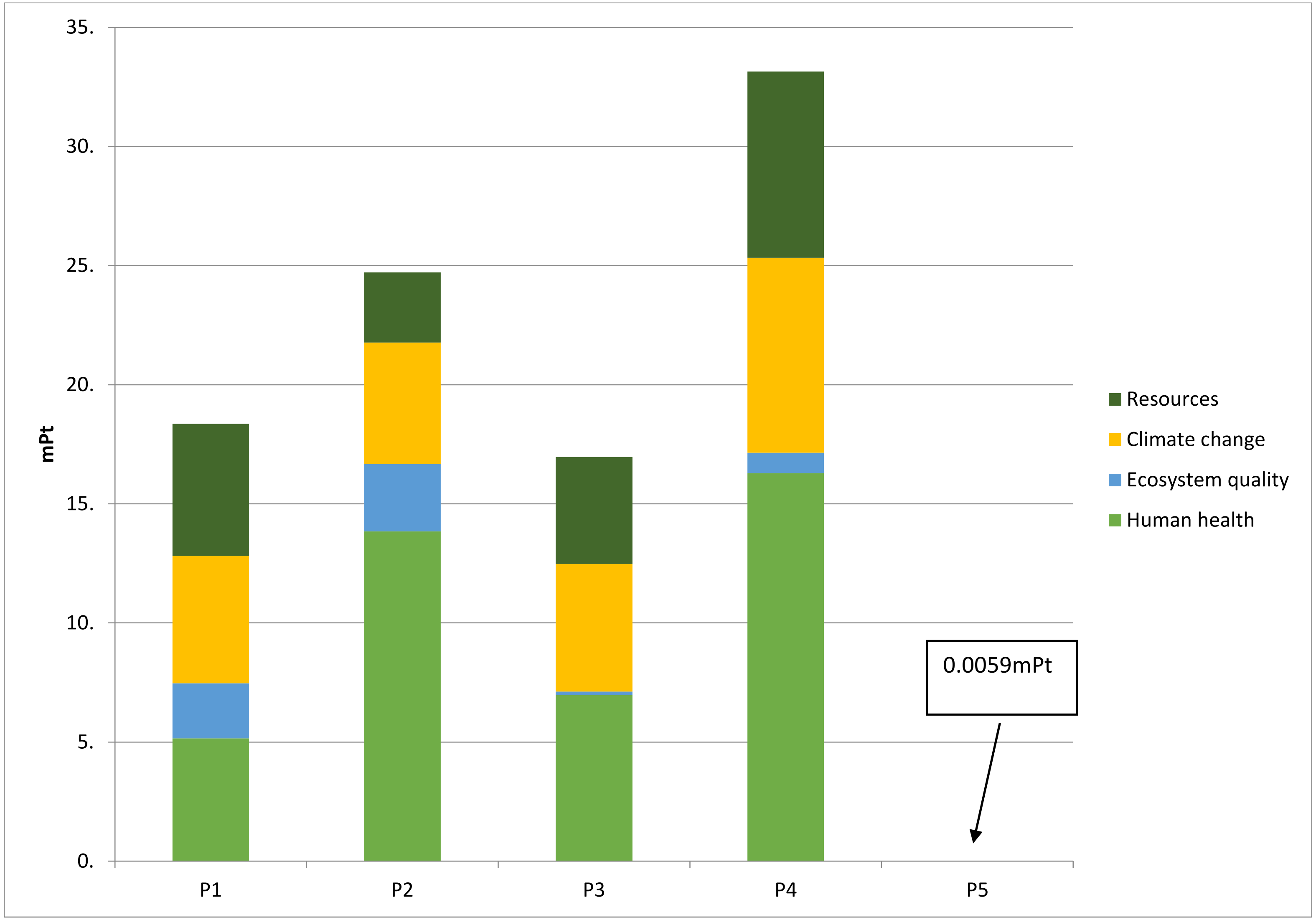

Fig. 3. Contribution analysis of human health, ecosystem quality, climate change and resources in 5 different units.

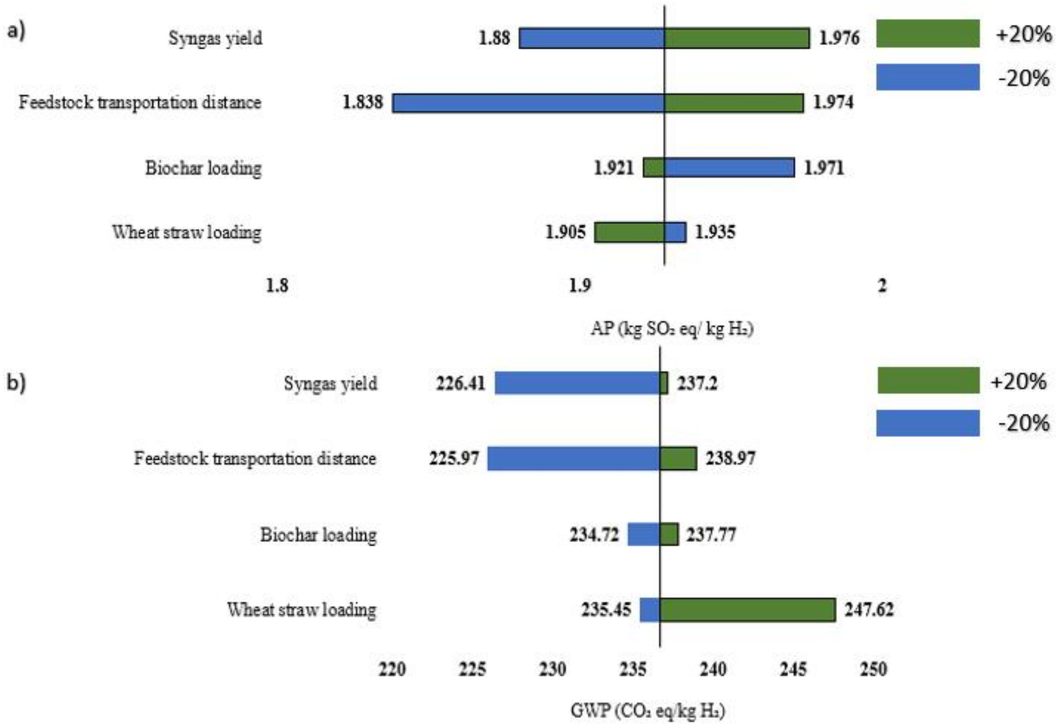

Fig. 4. Sensitivity analysis of significant parameters for aquatic acidification depletion (AP, a) and global warming potential (GWP, b) of hydrogen production *via* catalytic gasification of wheat straw

Table 1. Mid-point impacts of hydrogen production *via* catalytic gasification of wheat straw

Impact category	Unit (per kg H_2)	P1	P2	P3	P4	P5
Carcinogens	kg C_2H_3Cl eq	0.5016	0.1286	0.0141	0.0410	2.13E-05
Non-carcinogens	kg C_2H_3Cl eq	0.9625	1.3562	0.0586	0.7091	2.08E-04
Respiratory inorganics	kg PM2.5 eq	0.04613	0.09582	0.0390	0.1078	1.77E-05
Ionizing radiation	Bq C-14 eq	404.7977	105.1269	108.3498	27.1100	1.10 E-04
Ozone layer depletion	kg CFC-11 eq	9.23E-06	8.76E-07	2.26E-07	3.43E-07	9.41E-12
Respiratory organics	kg C_2H_4 eq	0.0222	13.8634	6.7869	18.092	4.98E-06
Aquatic ecotoxicity	kg TEG water	4138.1792	4442.6763	403.3099	3800.3279	1.3023
Terrestrial ecotoxicity	kg TEG soil	2892.09	1482.9228	26.5880	326.6058	0.0266
Terrestrial acid	kg SO_2 eq	0.9848	3.6619	1.4891	3.9373	4.12 E-04
Land occupation	$m_2$org.arable	6.9382	29.3288	0.0315	6.1323	3.93E-06
Aquatic acidification	kg SO_2 eq	0.2031	0.7801	0.2747	0.7683	1.79 E-04
Aquatic eutrophication	kg PO_4 P-lim	0.0079	0.0066	6.6 E-0.4	0.0023	7.89E-08
Global warming	kg CO_2 eq	52.8928	51.9777	50.4356	81.347	1.98E-02

Table 2. End-point impacts of catalytic gasification of wheat straw using biochar catalyst.

Damage category	Unit	P1	P2	P3	P4	P5	Total
Human health	mPt	5.1516	14.2103	5.9234	16.3716	1.84 E-03	41.6587
Ecosystem quality	mPt	2.3119	3.48427	0.1324	0.98939	5.18E-05	6.91801
Climate change	mPt	5.3421	5.24974	5.0939	8.2161	2.00 E-03	23.9038
Resources	mPt	5.5492	3.05417	4.4793	7.8366	1.90 E-0.3	20.9212

4

Life-cycle assessment of hydrogen production *via* catalytic gasification of wheat straw in the presence of straw derived biochar catalyst

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Abstract (130 words)

The environmental footprints of H_2 production *via* catalytic gasification of wheat straw using straw-derived biochar catalysts were examined. The functional unit of 1 kg of H_2 was adopted in the system boundaries, which includes 5 processes namely biomass collection and pre-treatment units (P1), biochar catalyst preparation using fast pyrolysis unit (P2), two-stage pyrolysis-gasification unit (P3), products separation unit (P4), and H_2 distribution to downstream plants (P5). Based on the life-cycle assessment, the hot spots in this process were identified, the sequence was as follows: P4 > P2> P1 > P3 > P5. The end-point impacts score for the process was found to be 93.4017 mPt. From benchmarking analysis, the proposed straw-derived biochar catalyst was capable of offering almost similar catalytic performance with other metal-based catalysts with a lower environmental impact.

Keywords: Life-cycle analysis; Biochar; Gasification; Hydrogen; Biomass

1. Introduction

With the alarming demand of global energy and rapid growth of the world population across the globe, the necessity in searching for alternative renewable and carbon-neutral energy sources is vital to meet the soaring global energy needs. From both economic and environmental standpoints, valorization of agricultural crop residues to platform chemicals is deemed as a feasible and attractive approach to achieve a circular carbon economy (Alhazmi & Loy, 2021). Owing to the infinite, cheap, and environmentally friendly properties of agricultural crops, its extensive utilization as renewable energy resources can be observed lately with the emerging closed-loop economy and the on-going transition towards post-fossil-carbon societies (Giuntoli et al., 2013). According to the UN Food and Agriculture Organization (FAO) 2018, the global production of agricultural crops is growing exponentially due to the drastic demand from human mankind, specifically the agricultural crops of wheat, maize, and rice (Roser, 2020). Among the agricultural crop residues reported in the literature, wheat straw is one of the most widespread residues readily available in Europe, America, and Western Asia continents with an annual global production of 132.59 million tonnes per year (Ingrao et al., 2021).

Instead of landfilling or direct combustion of wheat straw (after harvesting), such abundant lignocellulosic wastes can be transformed into sustainable renewable bio-based products *via* thermochemical methods. Among all the thermochemical pathways, gasification is one of the key technologies that has been extensively investigated. Over the years, many experimental studies have successfully demonstrated a high production of H_2 from biomass gasification process, including wheat straws as feedstock. In 2017, Cao and co-authors have investigated supercritical water gasification of wheat straw soda black liquor in a batch reactor system (Cao et al., 2017). Notably, high yield of H_2 (62.38 mol/kg) with carbon content

(98.17%) was attained at 1023 K with a diluted black liquor of 2.5 wt% as reactant. Another similar finding reported by Hu and co-authors, showing that 36 vol% of H_2 was attained with the aid of 60% Fe_2O_3/Al_2O_3 at 5g of wheat straw, reaction time of 10 min, and temperature of 1123 K (Hu et al., 2018).

Over the decades, non-noble metal-based catalysts (e.g. Ni, Cu, Co) have been reported as the best reforming catalysts for industrial applications in biomass gasification (Cao et al., 2020). They have shown great potential as reforming catalysts given its high selectivity, cheap cost, and high availability. Nevertheless, some drawbacks (e.g. large amount of loading, short lifespan, and easy scaling) are inevitable. Whereas, noble metals (e.g. Pt, Ru, and Rh) have both high catalytic activity and long lifespan, but they cannot be applied on a large scale due to economic consideration (Cheah et al., 2021). In this sense, the search for an affordable and highly active reforming catalyst is essential to support the realization of the circular gasification economy.

Lately, biochar has emerged as a new class of biomass-derived functional materials that can be applied as a catalyst in various energy recovery applications (Do Minh et al., 2020; Waqas et al., 2018). The rise of the application of biochar as a support material for the preparation of tar cracking/reforming catalysts, particularly, for the synthesis of char-supported metal nanoparticles has attracted large interest from both industrial and academic communities (You et al.,2018; Guo et al., 2020). For instance, Yao and co-authors have investigated the effect of Ni-based biochar catalysts for H_2 production *via* gasification process (Yao et al., 2016). Notably, cotton-char supported Ni catalyst demonstrated the highest catalytic activity of H_2 production (64.02 vol.%) as compared to its counterparts (rice husk char, activated carbon char, and wheat straw char). In 2021, Farooq et al. reported that the presence of silica in the rice husk chars can reduce coke formation in Ni- char supported catalysts (Farooq et al., 2021). Most importantly, the metal oxides in the rice husk char induced a positive synergistic effect to pure Ni catalyst and thus, a higher tar conversion and H_2 yield were obtained in contrast to the bi-functional Ni/α-Al_2O_3. Emerging knowledge and evidence on the applications of biochar as a reforming catalyst with high effectiveness in tar cracking, and low cost, suggesting that the valorization of biochar can be a feasible alternative that can improve the overall economic and environmental values of a gasification system.

To the best of the authors' knowledge, the analysis of environmental impacts of H_2 production from gasification of wheat straw using straw-derived biochar catalyst is still yet to be reported in the literature. The environmental aspect of a wheat straw-based gasification plant is important to be examined since it is one of the key considerations for future technology investment. Thereby, the whole gasification process starting from the raw materials to the end product should be analyzed and optimized from the perspective of the life-cycle of resource and environment performance. Hence, this work aims to assess and identify the possible environmental impacts of carbon chain of wheat straw gasification from the beginning (biomass collection and pre-treatment of wheat straw) until the end process (H_2 distribution to petrochemical plant). Based on this framework, the hypothesis of " the monetary value of the environmental impact of biochar production and the application as as biochar catalyst" can be elucidated. Moreover, the comprehensive performance of each process unit on the environmental impact can be evaluated without value-choices based weighting factor (Li et al. (2020).

The case study was modeled based on a gate-to-gate view, taking consideration from biomass collection and pre-treatment units (P1), biochar catalysts production in fast pyrolysis unit (P2), two-step pyrolysis -gasification units (P3), products separation unit (P4), and lastly H_2 product distribution to downstream plants (P5). Furthermore, a sensitivity analysis was also performed to identify and ascertain the most significant input parameters in affecting the environmental impacts based on the gate-to-gate LCA boundaries. This study provides a postulated assessment of the environmental impacts with regards to catalytic gasification process of wheat straws using straw-derived biochar catalyst and knowledge to support future decision-making in moving towards higher TRL based on the LCA with the selected boundaries.

2. Methodology

2.1 Method

According to the ISO 14040 (Principle and framework) and 14044 standards (Requirement and guidelines), the LCA method comprises of four independent phases: (1) goal and scope definition; (2) life-cycle inventory analysis; (3) impact assessment; and (4) interpretation (Alhazmi & Loy, 2021). This LCA case study was carried out based on the IMPACT 2002+, where the environmental impact categories include but not limited to global warming potential, ozone depletion potential, aquatic acidification potential, aquatic eutrophication, aquatic ecotoxicity, terrestrial ecotoxicity, ionizing radiation, mineral extraction, non-renewable, land occupation, and respiratory inorganics were analyzed. The damage categories such as human health, ecosystem quality, climate changes, and resources were also being investigated. Most researchers have applied IMPACT 2002+ in their study because this method considers the environmental impacts on both a midpoint and endpoint level (Hong, Li, & Zhaojie, 2010; Jolliet et al., 2003).

2.2 Goal and Scope Definition

The goal of the present LCA study was to evaluate the environmental assessment of H_2 production in catalytic wheat straw gasification using straw-derived biochar catalysts. The environmental footprints of all input processes of the defined life-cycle from raw material pre-treatment to the final product (H_2) were included in this study (Fig. 1). The system boundary of this case study was adopting a 'gate-to-gate' approach. It includes biomass collection and pre-treatment units (P1), biochar catalyst production using fast pyrolysis unit (P2), two-stage pyrolysis- gasification unit (P3), products separation units (P4), and H_2 distribution to downstream plants (P5).

2.3 Life-cycle inventory (LCI)

Wheat is one of the most important staple grains in the Kingdom of Saudi Arabia where most of it is consumed in the form of pita or bread. According to the U.S. Department of Agricultures' Foreign Agricultural Service (FAS), wheat production in Saudi Arabia is expected to escalate in the next two market years due to intensive government policy to reduce irrigation. The production is forecasted to increase by 40 % in the year 2019-2020 relative to production capacity of 500,000 tonnes in 2018-2019 (World Grain, 2021). The pilot-scale catalytic gasification plant was proposed to be located at Al-Hasa Oasis, Saudi Arabia, which has about 30,000 acres of agricultural land that are irrigated by the flow of more than 60 artesian springs. More importantly, there are a few downstream plants located nearby.

Meanwhile, the data of biochar catalyst production was adopted based on authors' previous works (Loy, et al.(a), 2018; Loy, et al.(b), 2018) and the remaining units was retrieved from literature (Kalinci, Hepbasli, & Dincer, 2012; Wang, You, Lu, Chen, & Xu, 2020; Yao et al., 2016) and Ecoinvent database v3.6. All the data used were based on the optimum conditions of the bench to pilot scale experimental work. The environmental performance of H_2 production from the catalytic gasification was evaluated following the LCA approach. Note that the functional unit was fixed at 1 kg of H_2, while the project lifespan is assumed to be 15 years with an annual operating day of 300 days. The plant capacity is assumed to be 200,000 tonnes of wheat straw per year. Full details on input and output of the whole process (see supplementary material), and the explanation of each process are shown in the following section.

2.3.1 Biomass collection and pre-treatment units (P1)

Pre-treatment process is an important stage in upgrading biomass to reduce its size; thus increaseing the accessible surface area (Chiaramonti et al., 2012). The wheat straw was sieved to approximately 50 mm^2 using a vibration ball milling machine; to increase the reaction surface area (Kumar et al., 2020). After milling, the wheat straw was fed into the mixing tank to wash out the unwanted alkali and alkaline earth metals using a diluted acid mixture of hydrochloric acid solution (30 vol.%), which can lower the reagent cost without affecting its effectiveness (Solarte-Toro et al., 2019). Then, the wheat straw and the acid mixture were then transferred into an ultrafilter (50 m^2 of active surface per module) to remove the impurities (Waste 1). “Waste 1” mainly includes chlorides, water, alkali, and alkaline metals. Whereas the drying process was modeled to produce wheat straw (dry basis) at less than 2% w.c. In order to produce 36.23 kg of wheat straw at 2% w.c. (Base = wheat straw at 5 % w.c), 3.46 kg of water (unremoved waste) was assumed to be evaporated.

2.3.2 Biochar catalyst production using fast pyrolysis unit (P2)

Fast pyrolysis is reported to be a suitable technology to produce microporous and fragmented chars that are potentially favorable for biochar catalyst usage (Brewer et al. 2009). Thus, the biochar catalyst in this work was produced *via* fast pyrolysis of wheat straw in a semi pilot-scale tube furnace at 773 K (Yao et al., 2016). In order to gasify 36.23 kg of wheat straw, a 30.81 kg biochar catalyst (i.e., biochar catalyst-to-feedstock ratio= 1:0.85) was required (Yao et al., 2016). Meanwhile, the wheat straw loading (205.4 kg) was calculated based on Pfitzer's study (Pfitzer et al., 2016), where approximately 15 wt% of biochar can be obtained *via* fast pyrolysis of wheat straw. The electricity consumption of the semi-pilot pyrolysis unit was assumed to be 0.0281 kWh per kg biomass as reported (Brassard, Godbout, & Hamelin, 2021). The carbon emissions attributed to catalyst loading was assumed to be negligible since it will only be conducted manually once after every few years (Montoya et al., 2020; Gholizadeh et al., 2021).

2.3.3 Two-stage pyrolysis-gasification unit (P3)

The catalytic gasification process of wheat straw was operated in a two-stage fixed bed; thereby it has the advantage of producing gaseous products with higher calorific value as compared to conventional gasifiers (Kosov and Zaichenko, 2016). During the first stage, the feedstock was pyrolyzed under inert condition. Then, the pyrolysis volatiles were catalytic steam reformed in the presence of biochar catalyst to enhance the yield of H_2. Nitrogen flow (99.99%) was supplied as carrier gas to prevent any unwanted oxidation in the pyrolysis zone (773 K). Whereas, the gasification temperature was set to be 1173 K, while steam was introduced into the system to aid the water gas shift, catalytic reforming, and boudouard's reactions (Loy, et al., 2018 (a)). The H_2 yield attained was reported to be 27.61 g/kg biomass or 52.35 wt.%, respectively.

2.3.4 Product separation units (P4)

This process can be divided into 3 sub-processes, namely 1) cyclone separation unit (biochar), 2) condensation unit (biooil) and, 3) gas separation unit (biogas). The full explanation of each unit operation is discussed in the section below:

2.3.5.1 Cyclone separation unit

Among all the industrial cyclone separators, square cyclone separators have vast advantages that include simplicity, lower cost, small volume, shorter start time, and shorter separation time compared to the single stage and two stages cyclones (Zhang et al., 2021). Thus, a square cyclone separation unit was selected in this study to remove the biochar produced from the catalytic two-stage pyrolysis-gasification process. Three-square aluminum steel cyclone was modeled with a thickness of 0.002 m based on the functional units. The energy consumption of the side channel cyclone blower was 1.5 kW/hr and single phase (220-240 V) (Venkatesh et al., 2021).

2.3.5.2 Condensation unit

The condensation process was proposed for the condensable vapors produced from the catalytic gasification of wheat straw using biochar catalyst (Brassard et al., 2021). In order to calculate the energy consumption of water pumping, a submersible pump of 1 HP with a capacity of 10 L/min at 20 PSI was modeled (a typical submersible pump of 1 HP with a capacity of 43.2 L/min at 20 PSI and 20-foot depth was selected (Monarch Industries, Model MST5-100). Based on the catalytic gasification experiments of 1 kg of wheat straw per hour using a water flow of 180 Lwater/h, it was estimated that 6521 L of water was pumped and recirculated for the gasification of 36.23 kg of wheat straw (Brassard et al., 2021). The electricity consumption of the pumps (in MJ) was calculated by the total energy consumption of the pump (0.7 kW) with the time needed to pump 6521 L of water (~12 hr) and divided by a factor of 3.6. Also, it was assumed that 5000 L of water per year was used in each condenser (1st condenser: 100 % water and 2nd condenser: 50/50 ratio water to ethylene glycol to prevent boiling issue). The specific volume of each liquid annually was attained using Eq. (1) as shown:

$$Unit\ volume\ (L\ Mg^{-1}) = \frac{Total\ volume\ (L\ year^{-1})}{200000\ Mg_{biomss}\ year^{-1}} \quad (1)$$

The water circulating in the two condensers was maintained at 393 K and 278 K, respectively. In the 1st condenser, the temperature was set to beat 333 K and 393 K each day, considering that the heat losses were compensated by hot gases heating during pyrolysis. For the 2nd condenser, the temperature has to be in the range of 294 K to 278 K each day. The energy consumption was calculated based on Eq. (2) as shown:

$$Q = mCp\Delta T \quad (2)$$

where m is the mass of water circulated in the condenser for 36.23 kg of biomass, Δt is the difference of temperature for heating or cooling (in K) and Cp = 4.185 kJ kg $^{-1}$ K^{-1}.

2.3.5.3 Gas separation unit

In this gas separation phase, the dry syngas (16.12 kg) was fed to a pressure swing adsorption (PSA) unit where H_2 was fully adsorbed on the adsorbent (e.g. zeolite and silica) of the unit, before being transferred to the petrochemical plants (Kohlheb et al., 2020). The electricity of the PSA was found to be around 1.26-1.52 kWh/Nm^3-CO_2 depending on the capacity of H_2 production. The unadsorbed flue gases (e.g 9.07 CH_4 vol%, 26.31 CO vol%, 18.01 CO_2 vol%) can be incinerated in a flame oxidation burner which can be utilized as an energy source. However, in this study, we did not consider the fraction gaseous mixture as a source of energy.

2.3.5 H_2 distribution to downstream plants (P5)

There are a few downstream petrochemical plants located at or near to Al-Hasa Oasis region such as Saudi Aramco and SATORP. As such, the average pipeline distance was calculated based on Eq. (3). The calculated pipeline distance from the gasification site to the downstream plant in terms of -kilometers was around 2-km, and the pipeline was assumed to be made of chromium steel 18/8 – GLO steel 9.

$$r = \frac{1}{6}\tau\sqrt{\frac{F}{yf}(\sqrt{2} + \ln(1 + \sqrt{2}} \tag{3}$$

where r = average pipeline distance, F is the H_2 delivered annually to the plant (t/year); y is the annual yield of feedstock (t/year); f is the fraction of acreage around the plant devoted to feedstock production; τ is the ratio of the actual distance to the straight-line distance from the plant.

2.4 Sensitivity analysis

Sensitivity analysis was carried out to examine the effects of individual input parameters on the environmental impacts based on the gasification process. A ± 20 % variation of the input parameters, including the feedstock transportation distance, biochar loading, syngas yield, and wheat straw loading was studied. With the sensitivity analysis, process engineers and academicians will have a better overview of the evaluation by minimizing the uncertainty attributed to the empirical data.

3. Results and discussion

3.1 Interpretation of LCIA results

3.1.1 Impact 2002+ Midpoint Categories

The results of LCIA of the 5 different processes involved in catalytic biomass gasification for H_2 production using biochar-derived catalyst are reported in Table 1 in terms of Impact 2002+ midpoint categories. Significant midpoints that contributed to the damage categories in section 3.1.2 have been elucidated in the following:

With respect to aquatic ecotoxicity, the environmental impact was found to be the most significant among all categories, whereby the major contributions were dominated by P2 unit (4443 kg TEG water), followed by biomass collection and pre-treatment unit (4138 kg TEG water), products separation unit (3800 kg TEG water) and two-stage pyrolysis-gasification unit (403 kg TEG water). Although the Environment Protection Agency (EPA) has not published any water quality guidelines for TEG, there are still several aspects with relation to the environmental readiness level of the whole process from the point of view of legislation should be incorporated (EPA, 2006). Since the outputs from P2, P3, and P4 units include biooil, which contains organic aromatic compounds that were acidic in nature, whereby the low pH of biooil obtained was expected to produce significant ecotoxicity upon exposure to aquatic organisms and systems (Oasmaa, Elliott, & Korhonen, 2010). On the other hand, the toxic effect of biomass pre-treatment was due to the washing out of alkali and alkaline earth metals from the biomass. A substantial quantity of alkali and alkaline metals, such as Si (31.86 wt%), K (19 wt%), Ca (4.14 wt%), Cl (2.67 wt%), and Mn (1.10 wt%), was being removed into Waste 1. It has been reported that the Si component, which can be easily oxidized into silica, contributes to total suspended solid (TSS) in water. Thus, it should be carefully practiced to meet the 10 mg/L as regulated by “2003-Ministry of Municipal and Rural Affairs (MMRA)” and ‘2006-Ministry of Water and Electricity (MWE) of Saudi Arabia” (MMRA, 2003; MWE, 2006). In addition, the washed ions in the wastewater, typically, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and chlorides (Cl^-), that are released into aquatic ecosystems have been reported to be responsible for physiological irregularities of aquatic lives while distracting ion regulatory mechanism in the living organisms (Hansen, Olsen, & Rosenkilde, 1996).

Another environmental impact that demonstrates a significant point was terrestrial ecotoxicity. Although it was consistently less severe as compared to aquatic ecotoxicity from all processes, the impact on terrestrial ecosystems was considered high and should never be neglected. The environmental impact towards terrestrial ecotoxicity was found to be mostly contributed by P1 (2892.09 kg TEG soil) and P2 (1482.92 kg TEG soil). The terrestrial ecotoxicity potential value from P1 was about 10-fold that of P3, due to the attribution of the presence of alkaline earth metals in wheat straw that may potentially affect soil ecosystems. Previous study has reported that poor quality irrigation water that contains certain ions at concentrations above the threshold values (>3.00 dS/m) can cause plant toxicity problems by impairing growth, reducing yield, changing morphology of agriculture plants (Memon, Kuboi, Fuji, Ito, & Yatazawa, 1983).

Viewing from the aspect of terrestrial acid and aquatic acidification, the midpoint impact point was found to be smaller than the ecotoxicity potential. The processes that contribute the most to acidification were product separation, and catalyst preparation. These processes produce biooil and biogas that contain mainly acid components and gases, such as SO_X and NO_X. These gas components were accumulated in the atmosphere to be captured by the moisture to form acid rain that contributed to terrestrial and aquatic acidification ultimately (Plens, Monaro, & Coutinho, 2015). This shall be given utmost consideration since EPA has regulated Primary National Ambient Air Quality Standard (NAAQS) for SO_X and NO_X to be at a maximum concentration of 75 ppm and 100 ppm for 1 hr, respectively (EPA, 2010, 2018). It was seen that the midpoint score that originates from carcinogens (<0.5 kg C_2H_3Cl eq.) was smaller in impact points as compared to non-carcinogens (<1.4 kg C_2H_3Cl eq.) consistently. The EPA has regulated the toxicity threshold of C_2H_3Cl to 1×10^{-4} mg/L since it has been demonstrated to be highly potential to induce cancer (EPA, 2000) and therefore, exhibiting detrimental health effects. The impact of carcinogens was mostly from P1 process since it involves washing out of alkali and alkaline earth metals that are toxic to the environment (Ge & Li, 2018). In addition, it was found that the presence of chloride in the wastewater may lead to the generation of toxic and carcinogenic by-products (Prasse, von Gunten, & Sedlak, 2020). In a similar manner, the contribution from ionizing radiation was found to be from P1, followed by P3 that exhibited a very similar impact point. The apparent impact from P1 was due to the diesel fuel used in wheat straw transportation, while P3 produce aromatic hydrocarbons biooil that have ionizing radiation potential. On the other hand, impact of non-carcinogens was found to be consistently higher than the carcinogenic counterparts and were mainly contributed by P2, followed by P1 and P4, respectively. This has been attributed to usage of electricity that consumes sources of energy in these processes, such as 577.17 and 342.51 kWh, for catalyst preparation and product separation, respectively. The electricity consumption and reactions involved in the processes emit substances, such as PM_{10}, SO_X and NO_X, that are not categorized as carcinogens but detrimental to human health with prolonged and high dosage exposure (Lock et al., 2019).

On the other hand, ozone layer depletion demonstrated a negligible effect with minimum gaseous emission from fossil fuels and chlorofluorocarbons (CFCs) from the utilization of renewable biomass resources, which aligns with the initiative of Montreal Protocol to alleviate ozone depletion issue (OEQ, 1988). By evaluating the effect of global warming, it was found that the processes contributed to moderate consequences with the dominant phase originating from P4, while P1, P2, and P3 demonstrated a similar impact. P5 acts as an indirect GHG through its effect on hydroxyl radicals (Derwent et al., 2006). As a whole, the results from the environmental indicators show that both aquatic acidification depletion and global warming potential have remarkably influenced the life-cycle environmental performance of the gasification system. Thus, both parameters were selected for the sensitivity analysis to provide an in-depth understanding of the relationship between the input variables with both individual environmental impacts.

3.1.2 Impact 2002+ Damage Categories

All midpoint scores as discussed in section 3.1 were related to the four damage categories, which are human health, ecosystem quality, climate change, and resources, respectively. The percentage contribution of each mid-point impact to the four end-point impacts for H_2 production *via* catalytic gasification of wheat straw using biochar as catalyst is shown in Fig. 2. The “human health” damage category is the sum of the midpoint categories “carcinogenic and non-carcinogenic toxicity”, “organic and inorganic respiratory effects”, “ionizing radiation”, and “ozone layer depletion”. The “ecosystem quality” damage category is the sum of the midpoint categories from “aquatic ecotoxicity”, “terrestrial ecotoxicity”, “terrestrial and aquatic acidification”, “land occupation”, and “aquatic eutrophication”. On the other hand, the damage category "climate change" is the same category as the midpoint category "global warming". Finally, the damage category "resources" is the summation of the midpoint categories from "non-renewable energy consumption" and "mineral extraction".

The damage assessment based on the 5 different processes involved in catalytic biomass gasification for H_2 production using straw-derived biochar catalyst is summarized in Table 2. In this context, the value was calculated as the average person's annual share of the environmental impacts of the entire population in Europe. The scale was chosen in such a manner that the value of milli-point (mPt) represents one thousandth of the annual load from one average European inhabitant. The purpose of normalization was to facilitate interpretation and comparison between respective shares of each impact to the overall damage.

From Fig. 3, it was found that the impact of the different processes was in the order of P4> P2> P1> P3> P5. Based on the findings, the most detrimental contributing criterion that exemplifies impact of the different processes arises, particularly from the human health, resources, and climate change damage categories. The damage impact of P5 was considered minor and negligible as compared to the other units Since the human health category was dominated by respiratory effects caused by substances emitted into air, the product separation phase that has the highest middle point category exhibited the greatest damage potential. In a similar manner, P4 yielded the highest point due to the generation of GHG radicals and components from the process that can be potentially inhaled. Resource depletion impact was also the highest from the P4 since it utilizes several equipment, such as cyclones, pumps, condensers, and PSA, that requires energy consumption from combustion of non-renewable fuels. In addition, it also involves the usage of water with high capacity for the condensation process to convert condensable vapours into biooil. The findings pinpoint that the feasibility and sustainable circular carbon benefits of catalytic biomass gasification for H_2 production using biochar catalysts can be enhanced by improving the separation efficiency of the process.

Subsequently, P2 has the second highest damage potential from the Impact 2002+ assessment, with the greatest point contributed by human health, climate change, and ecosystem quality, respectively. Human health was significant due to similar reasoning attributed to respiratory effects due to the emission of organic and inorganic substances, such as PM_{10} and VOCs. Energy consumption was also necessary for the catalyst preparation phase, which produces potential GHG components, typically CO_2 and CH_4. The ecosystem quality carries the third-highest contribution in the damage assessment since it produces several air emissions and organic compounds that can potentially affect the aquatic and terrestrial balance.

P1 was the third-highest contributor to the damage assessment with the most detrimental impact originating from the resources, human health, and climate change. The highest contributor from resource utilization inherited similar points to product separation and two-stage pyrolysis-gasification units. This has been attributed to the similar usage of energy, water, and feedstocks from wheat in these processes. Viewing from the impact of human health, the biomass pre-treatment was found to be much lower as compared to the product separation and catalyst preparation phases. This demonstrates that although the biomass pretreatment involves the production of wastewater with alkali and alkaline earth metals, the ultimate impact was not dominant since it has a lower score point for respiratory substances.

Fourthly, P3 exhibited the damage impact in the order of human health > climate change > resources. In fact, the score points between two-stage pyrolysis-gasification and biomass pre-treatment were quite similar when comparing the contribution by these two categories. The difference lies in lower contribution in the two-stage pyrolysis- gasification *via* the ecosystem quality since it has a smaller impact that originates from lower aquatic and terrestrial ecotoxicity as well as acidification properties. The reasoning has been attributed to lower concentrations of emissions and organic outputs from the process. In addition, on the contrary, climate change contributes to a higher score in the impact assessment since the process still emits greenhouse pollutants albeit at lower concentrations. Based on the findings, the main trade-off concerning environmental impacts was not found to be associated with the initial upstream nor end-user distribution units but with the downstream separation unit (P4). This suggests that more emphasis on the strategic tactical and operational planning on this unit is required to produce a more environmentally friendly catalytic gasification system.

3.2 Sensitivity Analysis

Sensitivity analysis of significant parameters in the input for aquatic acidification depletion and global warming potential of H_2 production *via* catalytic gasification of wheat straw is depicted in Fig. 4. From Fig. 4 (a), it can be seen that a 20 % reduction in the feedstock transportation distance has the highest decrease of aquatic acidification. The findings suggest that the soot emissions from vehicles during transportation, which contain NOx, SO_X, and CO_2, contribute to acid gas formation. Such environmental impact can be reduced by strategically locating the plant site (i.e., locate at a closer vicinity). It is then followed by the syngas yield, where its reduction will result in a significant drop in the acidification potential. This is due to the presence of acidic NOx, SO_X, and CO_2 gases in the compositions. On the contrary, the reduction of the biochar and feedstock loading by 20 % increased the aquatic acidification with the biochar loading showed a more significant impact. The analysis highlights the importance of having sufficient biochar and feedstock to facilitate efficient conversion performance as well as minimize the production and emission of acidic NOx and SOx. On the other hand, a 20 % increment in the syngas yield and distance of feedstock transportation could lead to an approximately similar increment in the aquatic acidification potential. The increment in aquatic acidification potential with increasing feedstock transportation distance by 20 % was found to be not that significant as compared to its counterpart when the distance was decreased. In a similar manner, the 20 % increment in biochar and feedstock loading leads to the opposite impact in the reduction of aquatic acidification, whereby the decrement was exceptionally observed with the alteration in feedstock loading, due to the enhancement in reaction efficiency of catalytic biomass gasification.

From Fig. 4(b), it was found that the decrement in the input parameters by 20 % caused a reduction in global warming potential consistently with the descending order of feedstock transportation distance > syngas yield > biochar loading > wheat straw loading. The decrement in the transportation distance and syngas yield demonstrated a higher reduction due to a reduction in CO_2 produced during the process. On the other hand, CO_2 emission was less affected by the reduction of biochar and wheat straw loading, mainly attributed to the nature of the reactions involved in the biomass gasification that produce GHG. The increment in 20 % of the input parameters was depicted to be increasing persistently in the order of wheat straw loading > feedstock transportation distance > biochar loading > syngas yield. The wheat straw loading was found to be much higher in increment as compared to the other input parameters. The findings suggest that a high loading necessitates a bigger capacity and consumption of resources that release an exemplified amount of GHG to the atmosphere.

As a whole, the most significant input parameter that contributes to a reduction of aquatic acidification depletion and global warming potential with a 20 % decrease was the feedstock transportation distance. Whereas, with an increment in the inputs by 20 %, the most significant parameters were found to be biogas yield and wheat straw loading to aquatic acidification depletion and global warming gas potential, respectively. From the sensitivity analysis, different uncertainty factors in the system with respect to environmental burdens have been determined. The integration of the sensitivity analysis with energy and exergy assessment should be carried out to provide a bigger picture of the biomass sustainability frontier.

3.3 Benchmarking study

This subsection aims to benchmark the proposed biochar-based catalytic gasification of wheat straw to other existing relevant works. Based on the findings, although the studies are not conducted under the same conditions, it can still be seen that the straw-derived biochar catalysts proposed in this work, are capable of offering a decent H_2 yield as compared to other studied catalysts for wheat straw gasification. It is interesting to note that H_2 yielded through straw-derived biochar gasification (25.59 g H_2/kg wheat straw) is comparable to other metal oxide catalysts such as Ni-based catalysts (5.6~ 25.3 g H_2/kg wheat straw), Rh-based catalyst (8.4 g H_2/kg wheat straw), and Fe-based catalyst (16.02-23.93 g H_2/kg wheat straw). Moreover, biochar catalysts are known as a promising substitute for traditional metal-based catalysts, given their cost effectiveness and environmentally friendly-nature (Lee, Kim, & Kwon, 2017). Given that there is only a scarce amount of literature that has performed LCA study for a wheat straw catalytic gasification process, benchmarking analysis on the environmental performance is difficult to be performed. Nevertheless, one can still qualitatively justify the environmental benefit of using char-based catalysts as compared to other metal-based catalysts in two ways. Firstly, its relatively high H_2 yield simply indicates a more efficient use of resources (e.g. lower amount of feedstock required, and lower energy consumed), which further results in lower environmental impacts. Secondly, the catalysts are derived purely from biogenic resources which do not add significant burden to the carbon cycle. This, therefore, leads to a lower environmental impact as compared to metal-based catalysts. Using Ni catalyst as an example, every kg of Ni contributes 13 kg CO_2-eq (LCA, 2020)), which is about 7.7 times higher than that of the proposed straw-derived char catalysts (equivalent to 1.69 kg CO_2-eq/kg catalyst). This is in agreement with the comparative study made by Frazier et al. (Frazier RS, 2015)), where the GWP of metal-based catalysts is significantly higher (>10 folds) than that of the char-based catalysts. As the world is marching towards sustainable development, the use of catalysts that were derived from natural renewable resources are deemed favourable. Policymakers can put efforts in encouraging such applications to promote green economy development in the industry sector including the hydrogen production industry.

4. Conclusions

The LCA results showed that environmental impact of the different processes was in the descending order of P4 > P2 > P1 > P3 > P5. The P4 was found to be the targeted hotspot in this study, which yields the highest greenhouse gas and resource depletion impacts. Thus, it is recommended to take into consideration the "separation unit, P4" thoughtfully in any decision making of scaling up this process. Also, future research direction should be pivoted towards metal-based supported biochar catalysts to provide a more in-depth understanding of the feasibility of biochar catalyst application.

*E-supplementary data for this work can be found in e-version of this paper online

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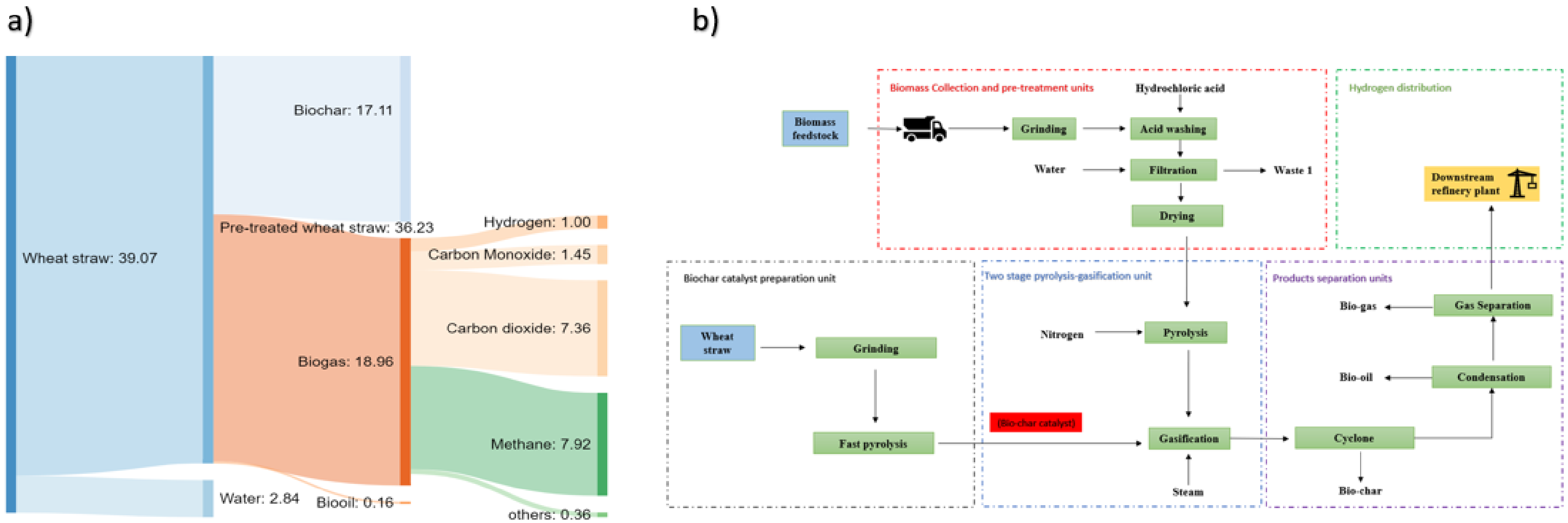

Fig. 1. a) Sankey diagram of the product distribution of catalytic gasification of wheat straw. b) System boundaries of catalytic gasification of wheat straw using straw derived biochar catalyst, which includes biomass collection and pre-treatment units (P1), catalyst preparation using fast pyrolysis unit (P2), two-stage pyrolysis and gasification unit (P3), and products separation units (P4) as well as hydrogen distribution to downstream plant (P5)

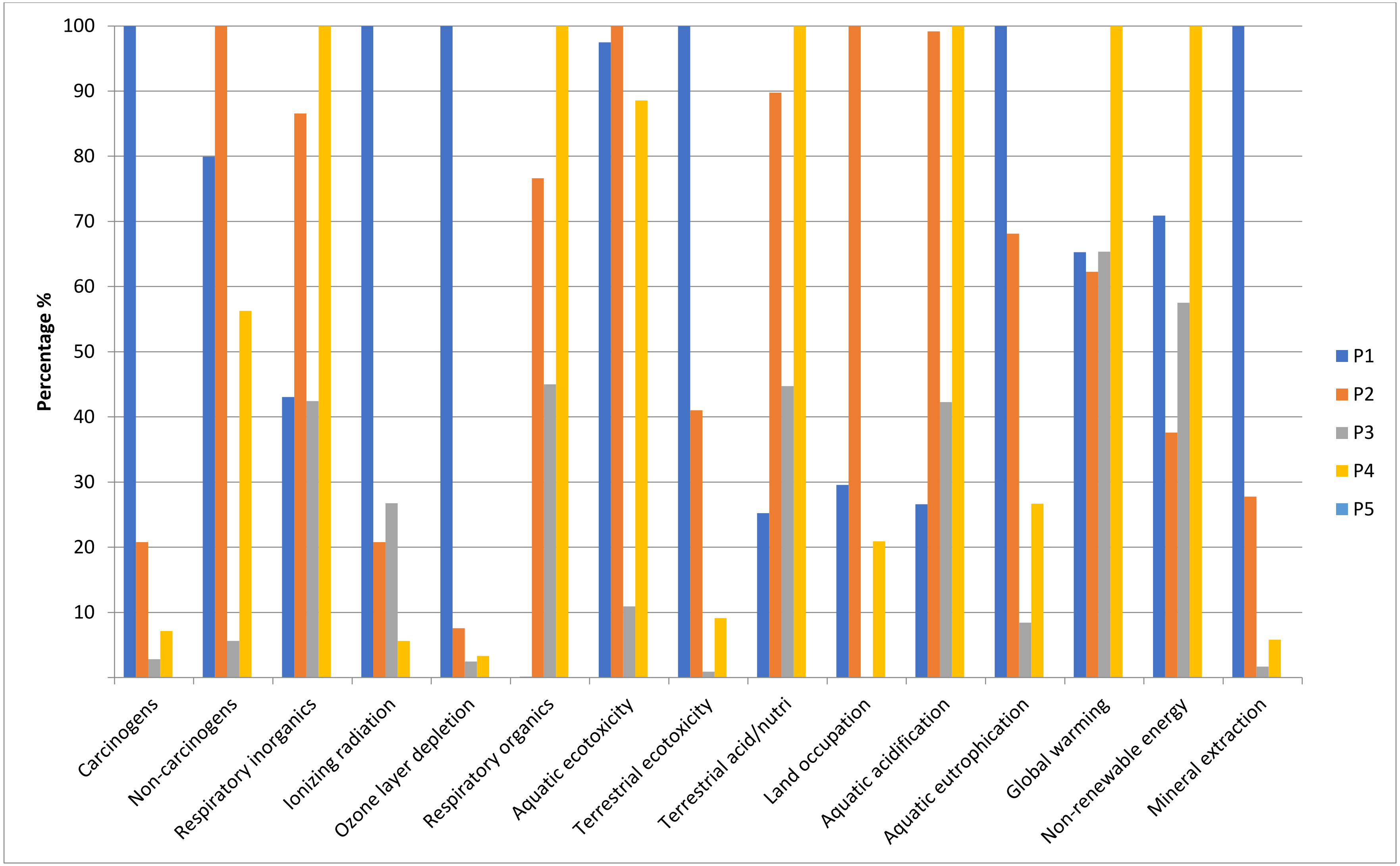

Fig 2: Comparison of the life-cycle environmental impacts of P1, P2, P3, P4 and P5 processes.

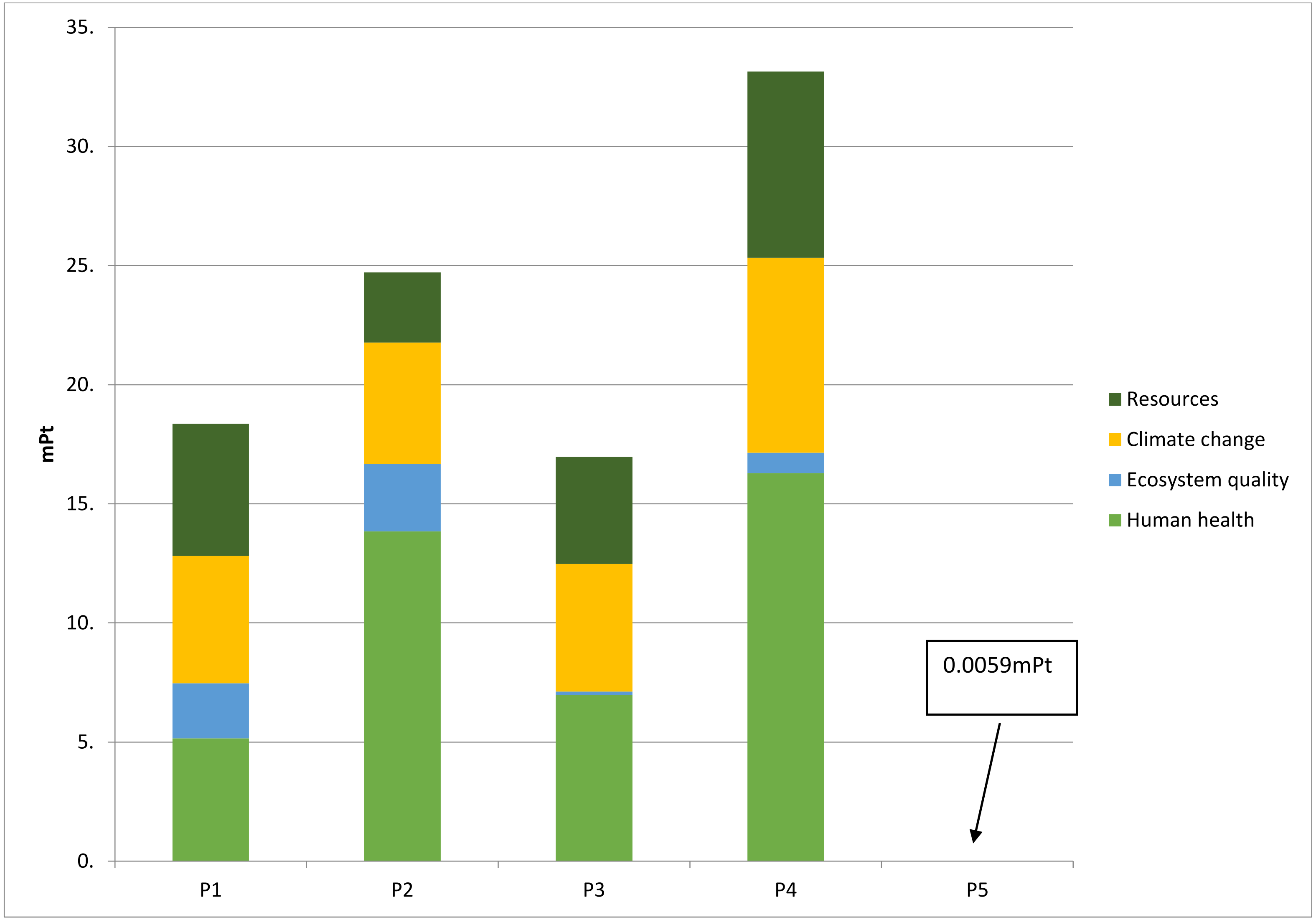

Fig. 3. Contribution analysis of human health, ecosystem quality, climate change and resources in 5 different units.

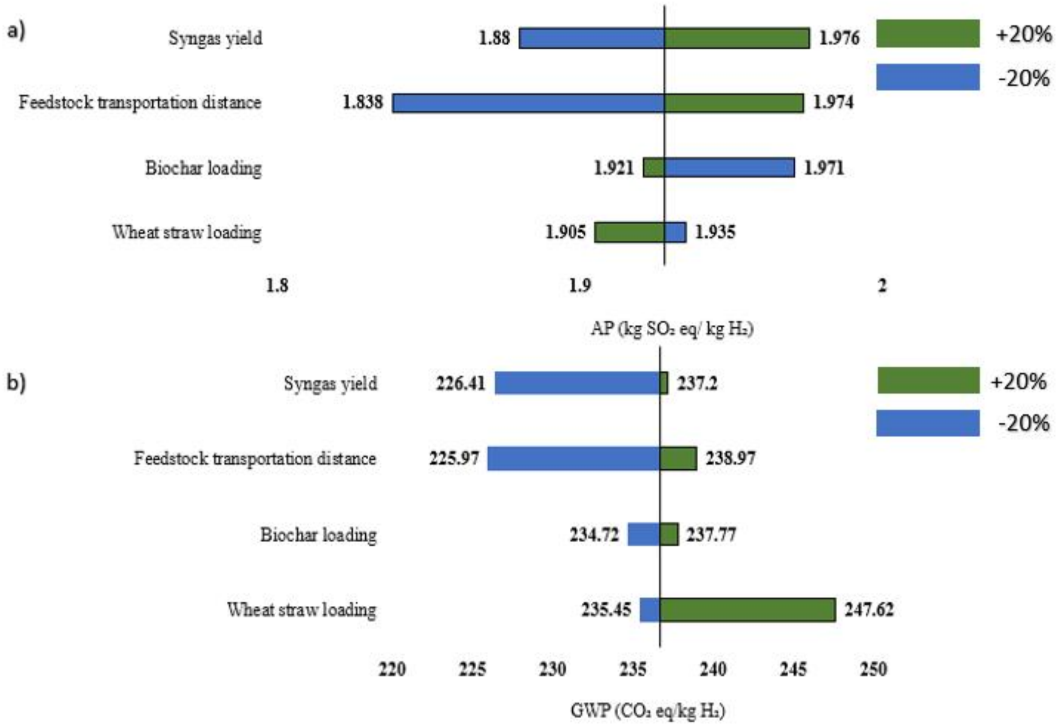

Fig. 4. Sensitivity analysis of significant parameters for aquatic acidification depletion (AP, a) and global warming potential (GWP, b) of hydrogen production *via* catalytic gasification of wheat straw

Table 1. Mid-point impacts of hydrogen production *via* catalytic gasification of wheat straw

Impact category	Unit (per kg H_2)	P1	P2	P3	P4	P5
Carcinogens	kg C_2H_3Cl eq	0.5016	0.1286	0.0141	0.0410	2.13E-05
Non-carcinogens	kg C_2H_3Cl eq	0.9625	1.3562	0.0586	0.7091	2.08E-04
Respiratory inorganics	kg PM2.5 eq	0.04613	0.09582	0.0390	0.1078	1.77E-05
Ionizing radiation	Bq C-14 eq	404.7977	105.1269	108.3498	27.1100	1.10 E-04
Ozone layer depletion	kg CFC-11 eq	9.23E-06	8.76E-07	2.26E-07	3.43E-07	9.41E-12
Respiratory organics	kg C_2H_4 eq	0.0222	13.8634	6.7869	18.092	4.98E-06
Aquatic ecotoxicity	kg TEG water	4138.1792	4442.6763	403.3099	3800.3279	1.3023
Terrestrial ecotoxicity	kg TEG soil	2892.09	1482.9228	26.5880	326.6058	0.0266
Terrestrial acid	kg SO_2 eq	0.9848	3.6619	1.4891	3.9373	4.12 E-04
Land occupation	$m_2$org.arable	6.9382	29.3288	0.0315	6.1323	3.93E-06
Aquatic acidification	kg SO_2 eq	0.2031	0.7801	0.2747	0.7683	1.79 E-04
Aquatic eutrophication	kg PO_4 P-lim	0.0079	0.0066	6.6 E-0.4	0.0023	7.89E-08
Global warming	kg CO_2 eq	52.8928	51.9777	50.4356	81.347	1.98E-02

Table 2. End-point impacts of catalytic gasification of wheat straw using biochar catalyst.

Damage category	Unit	P1	P2	P3	P4	P5	Total
Human health	mPt	5.1516	14.2103	5.9234	16.3716	1.84 E-03	41.6587
Ecosystem quality	mPt	2.3119	3.48427	0.1324	0.98939	5.18E-05	6.91801
Climate change	mPt	5.3421	5.24974	5.0939	8.2161	2.00 E-03	23.9038
Resources	mPt	5.5492	3.05417	4.4793	7.8366	1.90 E-0.3	20.9212

4

CRediT author statement

Adrian Chun Minh Loy: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original Draft, Review & Editing, Visualization. **Hatem Alhami**: Conceptualization, Methodology, Writing – Original Draft, Review & Editing, Formal analysis. Validation. **Serene Sow Mun Lock**: Data curation, validation. **Chung Loong Yiin:** Data curation, validation. **Kin Wai Cheah**: Data curation, validation., **Bridgid Lai Fui Chin**: Review & Editing, Formal analysis. **Bing Shen How:** Review & Editing, Formal analysis. **Suzana Yusup**: Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: