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Towards a sustainable future: Bio-hydrogen production from food waste for clean energy generation

Bilal Kazmi [a,1], Tooba Sadiq [a,1], Syed Ali Ammar Taqvi [b], Sidra Nasir [b,1], Mahwish Mobeen Khan [a], Salman Raza Naqvi [c,*], Hamad AlMohamadi [d]

[a] Department of Applied Chemistry and Chemical Technology, University of Karachi, Pakistan
[b] Department of Chemical Engineering, NED University of Engineering and Technology, Karachi, Pakistan
[c] Department of Engineering and Chemical Sciences, Karlstad University, Sweden
[d] Department of Chemical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia

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ABSTRACT

To address climate change, energy security, and waste management, new sustainable energy sources must be developed. This study uses Aspen Plus software to extract bio-H2 from food waste with the goal of efficiency and environmental sustainability. Anaerobic digestion, optimised to operate at 20–25 °C and keep ammonia at 3%, greatly boosted biogas production. The solvent [Emim][FAP], which is based on imidazolium, had excellent performance in purifying biogas. It achieved a high level of methane purity while consuming a minimal amount of energy, with a solvent flow rate of 13.415 m^3 /h. Moreover, the utilization of higher temperatures (600–700 °C) during the bio-H_2 generation phase significantly enhanced both the amount and quality of hydrogen produced. Parametric and sensitivity assessments were methodically performed at every stage. This integrated method was practicable and environmentally friendly, according to the economic assessment. H_2 generation using steam reforming results in a TCC of 1.92 × 10^6 USD. The CO_2 separation step has higher costs (TCC of 2.15 ×10^7 USD) due to ionic liquid washing and CO_2 liquefaction. Compressor electricity consumption significantly impacts total operating cost (TOC), totaling 4.73 × 10^8 USD. showing its ability to reduce greenhouse gas emissions, optimize resource utilization, and promote energy sustainability. This study presents a sustainable energy solution that addresses climate and waste challenges.

1. Introduction

The modern world faces an ever-increasing volume of organic waste, driven by population growth, urbanization, and changing consumption patterns. At the same time, the emission of carbon dioxide (CO_2) into the air, primarily stemming from the combustion of fossil fuels and industrial activities, plays a substantial role in the process of global warming and climate alteration(Khan et al., 2021). In this context, the integration of waste-to-energy technologies with carbon capture and utilization strategies presents a compelling solution, where the circular economy meets the imperative of reducing greenhouse gas emissions.(Madeira et al., 2021).

Bio-hydrogen (Bio-H_2), as a clean and renewable energy carrier, has gathered considerable attention due to its environmental benefits(Ji and Wang, 2021), high energy content, and potential to serve as a bridging fuel in the transition towards a low-carbon future(Muhammad Mustafa Rizvi et al., 2023). Anaerobic digestion (AD), a well-established biological process, offers a sustainable means of converting organic waste, such as food waste, into bio-hydrogen while simultaneously producing valuable byproducts like biogas and biofertilizers(Khawer et al., 2022; Tasnim Sahrin et al., 2022). BioHydrogen (Bio-H_2) can answer the growing energy demand for clean fuel. AD is a proven biological process that can produce biogas and bio-H_2(Kazmi et al., 2023a). In an oxygen-free environment, a community of microbes decomposes organic materials including food scraps, agricultural waste, and wastewater sludge. Biogas is mostly methane (CH_4) and carbon dioxide (CO_2) from these organic components breaking down. Biogas can be used to generate heat and power, but its quality needs to be improved. Harun et al.(Harun et al., 2019) shown that Food waste is a promising substrate for biogas production through the AD process due to its high energy content and large quantity. Biogas-derived H_2 is considered a clean fuel

* Corresponding author.
E-mail address: salman.raza.naqvi@kau.se (S.R. Naqvi).
[1] These are the main authors.

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Nomenclature

AD	Anaerobic digestion
Bio-H_2	Bio-hydrogen
CCU	Carbon capture and utilization
CO_2	Carbon dioxide
CO	Carbon monoxide
FWG	Food waste gasification
GHGs	Green house gases
HRT	hydraulic retention times
H_2	hydrogen
H_2S	Hydrogen sulfide
HTC	hydrothermal carbonization
ILs	Ionic liquids
CH_4	methane
MDEA	Mono diethanol amine
MCDM	multi-criteria decision-making
NRTL	Nonrandom two liquid
ORC	Organic Rankine Cycle
O_2	oxygen
POME	palm oil mill effluent
PEMs	proton exchange membranes
ROI	Return on investment
SESR	Sorption Enhanced Steam Reforming
SMR	Steam methane reforming
TAC	Total annualized cost
VFAs	volatile fatty acids
LT-WGS	low temperature water gas shift reactor
WGS	Water gas shift
γ_{ij}	activity coefficient
J-T	Joule−Thomson
TCC	total capital cost
[Emim][FAP]	1-butyl-3-methylimidazolium tris(perfluoroethyl) trifluorophosphate
CCS	Carbon capture and sequestration
HT-WGS	high temperature water gas shift reactor
aij, bij,	binary interaction parameter
VLE	Vapor liquid equilibrium
Wp	pressure factor
PSA	Pressure swing adsorption
TOC	Total operational cost
H_2O	Steam
W_M	material factor
PR	Peng-Robinson
F_{BM}	bare module factor

source because it has minimal greenhouse gas emissions(Taqvi and Kazmi, 2021). Biogas itself is primarily composed of CH_4, a potent greenhouse gas (GHG)(Kazmi et al., 2022c). By converting biogas into H_2, the process removes a significant portion of methane, which has a much higher global warming potential than CO_2. As a result, utilizing H_2 from biogas helps to address the challenge of climate change and decrease the overall release of greenhouse gases(Chen et al., 2023).

Anaerobic digestion must be combined with other biogas upgrading techniques to improve its quality and make it a greener energy carrier. Biogas purification removes CO_2 and other contaminants to increase methane content for natural gas grid injection or automobile fuel. The purification process may use pressure swing adsorption, water scrubbing, or ILs. (Pellegrini et al., 2018). Ionic liquids (ILs) are potential biogas purifiers due to their selective absorption, high absorption capacity, and impurity stability. Due to their tunable chemical characteristics, ILs can selectively collect CO2 from biogas, making them excellent purifiers (Kazmi et al., 2022c). Their non-volatile nature at ambient conditions ensures that they remain in the system, offering a sustainable and long-lasting purification solution(Kazmi et al., 2022a). The process typically involves absorption of impurities, followed by desorption to release the captured gases, enabling the regeneration and reuse of the IL.

Liquefaction of the acquired CO_2 allows efficient storage and use in industrial applications or carbon sequestration, establishing a closed-loop carbon management method. Liquefaction of CO_2 after biogas purification with IL is crucial to carbon capture and utilization (CCU) schemes. The isolated CO_2 is usually gaseous after biogas purification separates CO_2 and contaminants from methane-rich gas. It's crucial to liquefy CO_2 for efficient storage, transport, and use. CO_2 is compressed and cooled to become a supercritical fluid and then a liquid. Liquefied CO_2 can be kept in tanks or transferred to other industries. This transformation from gas to liquid makes captured CO_2 a versatile resource that can be used in industrial processes, enhanced oil recovery, cooling applications, or geological sequestration, contributing to greenhouse gas mitigation and sustainable carbon management.

H_2 extraction from purified biogas has sustainability and environmental benefits. Steam methane reforming (SMR), water electrolysis, gasification, and pyrolysis convert biogas into H_2. These sophisticated systems efficiently remove H_2 from biogas, making energy more sustainable. SMR, which produces 95% of worldwide H_2, involves the catalytic reaction of steam and methane (natural gas) at high temperatures and pressures to produce H_2 and CO (Khojasteh Salkuyeh et al., 2017). H_2 generation is increased by steam processes, which also produce CO_2. The created H_2 is purified, compressed, and stored for future use. Electrolysis, which carefully disassembles water molecules into H_2 and O_2, is another important method (Song et al., 2022). This technology requires reliable electricity from fossil fuels or renewable sources like solar and wind (Rumayor et al., 2022). Electrolysis can be executed utilizing proton exchange membranes (PEMs) or alkaline electrolysis cells, each possessing its own set of advantages and constraints (Zhang et al., 2023). H_2-rich gas can also be produced by partial oxidation of hydrocarbon fuels like natural gas. Gasification converts coal or biomass into H_2, CO, and CO_2 gas (Gholkar et al., 2021). Thermochemical water splitting uses nuclear reactors or concentrated solar power to divide water molecules into H_2 and oxygen (O_2).

The literature reflects a growing interest in the development of hybrid systems that combine biogas purification, bio-hydrogen production, and other value-added processes, such as the production of biofuels or biochemicals (Musa Ardo et al., 2022; Naveed et al., 2024). Such integrated approaches align with the principles of circular bioeconomy and contribute to the efficient utilization of organic waste streams while reducing greenhouse gas emissions. Studies have investigated various aspects of bio-hydrogen production from purified biogas, R. Tamilselvan et.al optimised biogas-to-H_2 production using Aspen Plus simulation models. The study stresses the importance of high-quality pure methane. Gas generation was best at –30–35 °C, providing 548 mL/g VS. A temperature of 909 K and pressure of 16 bar were found to optimise biogas-to-H_2 production in this investigation. Kourdourli et al. (2023) developed models and evaluated six different H_2 processes through H_2 production, among which the AD-Steam process was found to be the best in terms of H_2 production, energy efficiency, and CO_2 production. This process produced about 5.71 l/day of H_2 with an energy efficiency of 82.72% and the emission of CO_2 gas of about 12.83 kg CO_2 for 1 kg H_2 produced (Kourdourli et al., 2023). A multi-criteria decision-making (MCDM) technique was used to evaluate the performance of three models of H_2 production, and several parameters, including CO_2 flow rates in the feed and flue gas streams, flue gas flow rate, carbon dioxide emission intensity, H_2 product intensity, net energy efficiency, total annual cost (TAC), and annual total production were evaluated (Shamsi, 2023).

Arslan and Yılmaz (2023) assessed the potential of biogas power and green H_2 as energy carriers from biomass. This study used an Organic Rankine Cycle (ORC) to recover waste heat without fuel, improving efficiency and minimising emissions. ORC outperformed Rankine cycle in low-temperature waste heat. Different energy and exergy analyses showed that 41.55% energy efficiency, 36.42% exergy efficiency, 5792 kW net power, and $0.039/kWh unit electricity cost are the best values for the system's effectiveness and cost efficiency (Arslan and Yılmaz, 2023). Sorption Enhanced Steam Reforming optimises biogas H_2 generation. To find the most efficient and self-sufficient process configuration, this study examines H_2 purity, yield, and methane conversion. Three configurations were analysed using Aspen Plus V11 to build an autothermal SESR method. SESR+REG_BG produced 98.5% pure H_2 with 75.7% CGE and 0% carbon emissions. Compared to biogas, SESR+REG_H_2 had the same purity but poorer efficiency (CGE = 65.1%) (Capa et al., 2023). A combined heat and power unit was used to evaluate biogas production from liquid dairy manure waste via anaerobic digestion by Kourdourli et al.(Kourdourli et al., 2023) In Aspen Plus, the ADM1 model was utilised for simulation and sensitivity analysis. Sensitivity research demonstrated that feedstock components and digestion pressure affect biomethane output and ammonia inhibition. This study measures daily biogas and digestate output under certain conditions. Hosseinzadeh et al. (2022) examined the economic and environmental impacts of biowaste-to-H_2 production and offered recommendations for process selection and bottlenecks. Dark fermentation, microbial electrolysis, gasification, pyrolysis, and plasma have been tested using biowaste feedstocks (Ji and Wang, 2021; Yang and Wang, 2018; Ji and Wang, 2021). This study found that dark fermentation is the best economically and environmentally sustainable technique, providing insights into commercialization obstacles and prospects (Wang and Yin, 2018). This work uses computer modelling and lab-scale data to estimate large-scale systems, however it does not specify whether Aspen Plus is employed. Anaya et al.(Anaya Menacho et al., 2022) simulated food waste anaerobic digestion (AD) using organic loading rates, hydraulic retention periods, and fat contents (20%, 40%, and 60%) using Aspen Plus. This simulation will inform industrial biogas production research. It uses the ADM1 model with modified inputs. A 55 °C thermophilic two-stage digester was used. Methane content peaked at 74.82% and 77.10% with organic loading rates of 2–5 l/day and fat concentrations of 40% and 60%. The study also showed no significant differences between experimental and simulated outcomes under different process parameters (OLR, HRT, substrates). The new gasification process by Xu et al. (2022) produces H_2 from food waste. The proposed study examines temperature and regional effects on H_2 production and provides a full economic, environmental, and efficiency assessment. The model predicts syngas composition and H_2 production using food waste content, steam feed rate, and gasification temperature. Validated against experimental data, it helps understand and optimise the FWG process and increase food waste-to-H_2 production efficiency. The food waste-to-H_2 technology produced more H_2 at higher gasification temperatures. The method has 85% exergy efficiency, commercial possibilities, and environmental benefits like reduced greenhouse gas emissions and 1.2 t/h H_2 output. Chisalita and Cormos (2019) examined the techno-economic feasibility of steam reforming palm oil mill effluent (POME) to produce H_2. Heat integration optimises energy efficiency and validates findings against benchmarks and earlier studies for a complete POME-based H_2 production assessment. This study measured H_2 production capacity and purity, economic viability (CAPEX and OPEX), energy savings through heat integration, financial indicators (payback period and ROI), and sensitivity analysis. According to Rodríguez et al. (2022), biogas can be used as a renewable resource to boost H_2 production in biomass-based facilities and enhance energy efficiency. Experimental analysis and thermodynamic assessment were utilised to compare SESR (sorption enhanced steam reforming) for bio-oil/biogas blends to standard SR procedures. Reformer and calciner reactors were simulated with Aspen Plus. The results indicate how biogas blending affects cold gas efficiency, H_2 output, recoverable heat, and SESR temperature for maximum H_2 generation. Ghavami et al. (2022) designed a simulation model for industrial digestate hydrothermal carbonisation (HTC). The model compares property approaches to anticipate and optimise process conditions and products. The study examined reaction kinetics, routes, and transport phenomena and assessed feasibility with pilot-scale data. Energie yield is used as a process performance measure to find optimal settings in this study. Nouwe Edou and Onwudili (2022) found that FB gasification and AD-biogas reforming with carbon capture and storage are economically viable thermochemical technologies for producing H2 from biomass for West Midlands public transport buses.

In a study by Kanatlı and Ayas (2021) three models were developed to simulate the process of producing H_2 from sunflower meal through steam reforming. Model II had the best accuracy in predicting results. With the most accurate model at 91%, a 24:3 water: liquefied product ratio yielded the most H_2. H_2 and CO yields increased with H_2O ratios, but CnHm and CO_2 yields declined. Aim to scale up the method for industrial use. (Kanatlı and Ayas, 2021). Ahmad et.al(Ahmad et al., 2012) examined the techno-economic potential of a novel MBT-v system in the UK for value-added products. A simplified steady-state simulation model was built and validated against published data. A thorough techno-economic examination included technical and economic performance, process description, material and energy balances, and energy production and consumption (Ng et al., 2021). Meanwhile, the techno-economic potential of H_2 production from biogas is achieved using direct thermochemical looping cycles compared to conventional processes. It helps evaluate the advantages of calcium and chemical looping cycles over mono diethanol amine (MDEA) chemical scrubbing and provides insights into the energy efficiency, CO_2 capture rate, and production costs. Liu et al. (2018) study models and simulated scenarios were compared with the experimental data using the Aspen Plus software. This study highlights important design characteristics. Phan et al. (2022), used Aspen Plus® software to model H2 production utilising SRM, DRM, and TRM. This study aims to improve biogas-to-H2 generation. The TRM technique with tail gas recycling was most efficient. This 103.4 kW process uses steam and methane as feedstock. Cerqueira et al. (Cerqueira et al., 2021) examined the efficiency of H_2 production from cassava processing byproduct manure biogas. This study examined how temperature, pressure, and steam-to-carbon ratio affected the process. The results show that biogas, an environmentally acceptable option, may produce H_2 under optimal conditions. It is attractive and valuable to the cassava business. Biorefineries can produce H_2 gas from food waste, according to Tsegaye et al.(Tsegaye et al., 2021) A two-step dark fermentation procedure may efficiently produce H_2 gas from cassava and food waste. A single-stage dark fermentation technique can produce biomethane (H_2 and CH_4) from food waste and concentrated molasses, according to Tsegaye et al. (2021) Operational parameters greatly affect microbial populations and product quality. The acetate and butyrate routes produce more bio H_2, while the alcohol and lactate pathways produce less. Using Aspen Custom Modeler®, Ongis et al. (2023) developed a detailed membrane reactor mathematical model. This platform smoothly integrates with Aspen Plus®, the process modelling software, and has a database of chemical component properties. Thus, this study used Aspen Custom Modeler® and Aspen Plus to build and simulate the membrane reactor's complex mathematical model. This method allows a thorough assessment of the membrane reactor's viability and efficiency from technical and economic viewpoints. The main H_2 production method used by Dou et al. (2019) was biomass thermochemical conversion. Thermal processes like pyrolysis, gasification, and steam reforming turn biomass into H2. This article discusses current research on producing H2 from biomass with or without chemical looping technology. Biomass can be thermochemically converted into H2 from wood, agricultural waste, energy crops, and municipal solid waste. This review covers recent research on producing H2 from biomass utilising pyrolysis, gasification, and steam reforming with or without chemical-looping.

Evidently, there are limited studies in the region involving the food waste utilization for the production of bio-H_2. This study represents a significant step toward developing an environmentally sustainable approach for Bio- H_2 production, emphasizing both energy efficiency and ecological compatibility. The analysis was divided into four phases. Initially, food waste undergoes anaerobic digestion to produce biogas. Subsequently, an innovative ionic liquid-based method was employed to selectively extract CO_2 from the biogas. The separated CO_2 was efficiently liquefied for further processing. Finally, the focus shifted to the conversion of bio-methane into Bio-H_2, offering a clean and sustainable energy source. This significant process not only maximizes the utilization of food waste, but also contributes to mitigating greenhouse gas emissions, making it a highly promising avenue for sustainable Bio-H_2 production.

2. Technical approach for Bio-H_2 production

2.1. Process development

The proposed model is developed by using Aspen Plus®, a highly regarded advanced process simulator renowned for its exceptional simulation capabilities in handling both solids and fluids. The primary focus of this study is the utilization of food waste as the feedstock for biogas production, and Aspen Plus® serves as the indispensable tool for conducting a comprehensive analysis of this critical stage in the process. The overall process simulation diagram is illustrated in Fig. 1. Basic assumptions made for the proposed study are as follows:

- Negligible heat loss (Kazmi et al., 2021)
- Isentropic efficency of turbomachinery equipment 75% (Rogala and Kwiatkowski, 2022)
- Minimum internal temperature approach for the heat exchangers (2-3) °C (Kazmi et al., 2022b)
- Pressure ratio for the compression of $CO_2 \leq 3$
- Purity and recovery of biomethane $\geq$ 99 wt% (Haider et al., 2021)
- Liquefaction rate of $CO_2 \geq$ 99 wt% (Choe et al., 2023)
- Bio-H_2 production should be maximized with reduced specific overall energy demand.

Table 1 presents the conditions of temperature and pressure for the anaerobic digestion and feed stream. Also, the main process constraints to produced high amount of Bio-H_2 with reduced specific energy demand.

2.1.1. Anaerobic digestion of waste fruit for biogas

This study focuses on the production of biogas from waste food through the anaerobic digestion process on Aspen Plus. Aspen plus facilitates the analysis and optimization of key process parameters to evaluate different scenarios and configurations and model a process accurately. The comprehensive approach applied in this study is to maximize biogas yield, improve overall efficiency, and enhance the sustainability of the process.

This anaerobic digestion model assumes that the substrate will consist of proteins, lipids, and carbohydrates. It also includes the reaction kinetics of AD stages and temperature. The physical properties method nonrandom two liquid (NRTL) is used which is useful for liquid and vapor phases and capable of calculating activity coefficients and dealing with polar substrates. As this was based on AD, this model was created by using a previous model developed by Rajendran et al. (2014) Although, a different set of parameters were adjusted at the initial stage of simulation (such as different substrate compositions etc) to get the maximum concentration of methane.

This anaerobic digestion model comprises the two groups of reaction sets,

(a) hydrolysis reactions done by using reaction rate equations and parameters. The impact of pretreatment, which increases the

Table 1
Food waste condition and process constraints to produce Bio-H_2.

Parameters	Value
Feed conditions	
Food waste flow (L/day)	20,000
Feed food waste temperature (°C)	20-25
Feed food waste pressure (Bar)	1
Process constraint	
Biomethane purity (wt%)	≥ 99
CO_2 recovery and purity (wt%)	≥ 99
Bio-H_2 recovery and purity (wt%)	≥ 99

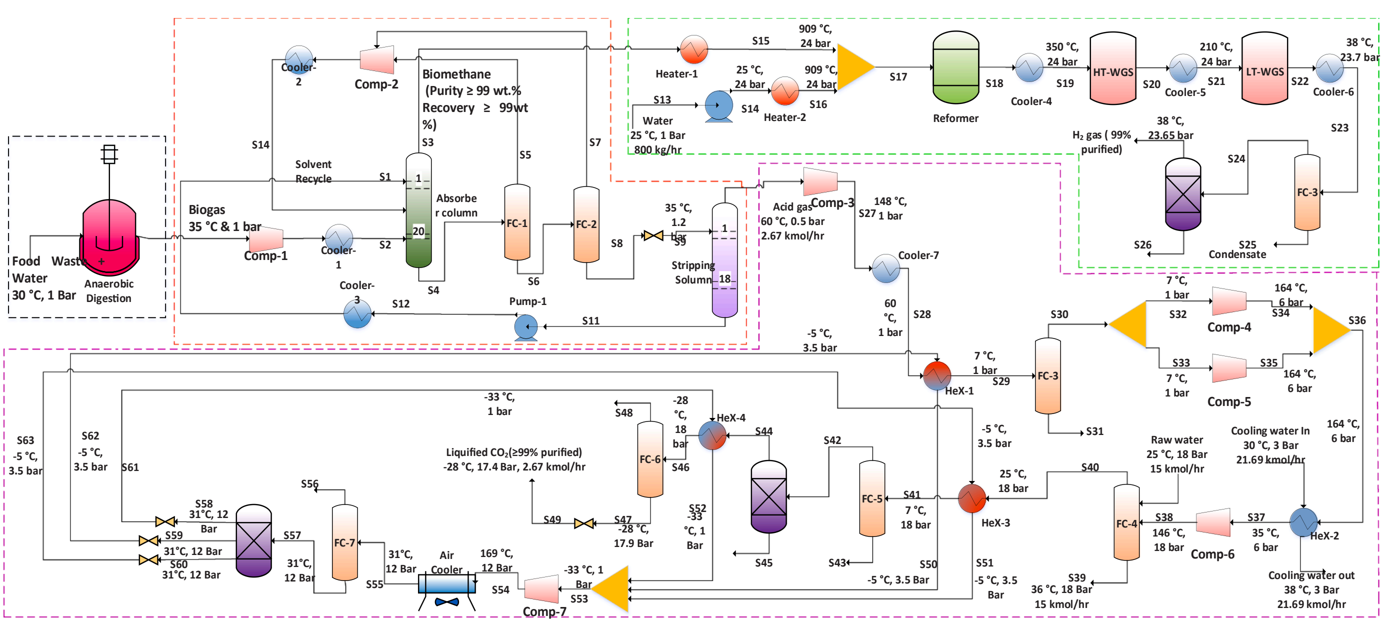

Fig. 1. Process flow diagram of the food waste conversion to biogas followed by biomethane purification integrated with CO_2 liquefaction for the Bio-H_2 production.

hydrolysis efficiency on various substrates, could be further investigated with a separate reaction set for hydrolysis.

(b) Furthermore, for the acidogenesis and acetogenesis stages in which acid-forming and acetogenic bacteria metabolize the hydrolyzed compounds, the model incorporates suitable biochemical reactions and reaction kinetics. This comprehensive representation ensures the conversion of soluble compounds into volatile fatty acids (VFAs), alcohols, and acetic acid is accurately captured in hydrolysis phase. The details of all the reactions for the AD can be found in supporting information (Table S1).

This Aspen plus model collectively developed from a group of stream and blocks. The simulation comprises of stoichiometric reactor (B3) where the hydrolysis reactions take place at thermophilic temperature at 55 °C. Now, the output steam S2 is the feed to next stage in continuous stirred tank reactor (B1) where the Acidogenic, Acetogenic and Methanogenic reactions occur at 55 °C and at different hydraulic retention times (HRT). Once, the digestion process is completed, the biogas is collected and undergoes purification to eliminate impurities such as hydrogen sulfide (H_2S, moisture, and other contaminants, ensuring the quality and usability of the final product.

2.1.2. Treatment of biogas using ionic liquid for CO_2 removal integrated with CO_2 liquefaction process

Biogas, typically consists of CH_4 and CO_2 obtained from the AD process, requires purification before it can be further utilized. IL has been used as the solvent in this process to allow for the selective absorption of CO_2 from the biogas mixture (Kazmi et al., 2022c). In this view, an acceptable IL is chosen based on the Aspen Plus model's consideration of its different properties, including its solubility, selectivity, and CO_2 absorption capability (Haider et al., 2020; Kazmi et al., 2023b; Taqvi and Kazmi, 2021). The process consists of a multistage compressor, a packed absorption column for CO_2 absorption, a flash evaporator for solvent regeneration, a centrifugal pump for solvent recirculation, and a pre-absorber solvent cooler. Since IL is not avaliable on the Aspen Plus domain so a detailed methodology as described in our previous work was performed based on the rigorous regression of the experimental data to obtain interaction between IL and biogas components. Additionally, the properties of the IL are also evaluated. The details can be found in supporting information (Table S3–S8).

The biogas generated from anaerobic digestion of food waste is compressed from atmospheric pressure to the column's operating pressure of 30 bar in a multistage gas compressor with intercooling. The purification process is modeled on Aspen Plus using a Radfrac model to simulate an absorption column. This model represents the counter current interaction between the compressed biogas at 15 °C and 30 bar pressure, and the ionic liquid solvent at 15 °C and 30 bar pressure, enabling CO_2 absorption. Following the completion of the absorption process, the regeneration of the IL is modeled using the air stripping process to release the absorbed CO_2. The regenerated IL is then recirculated for reuse within the process. The purified biomethane stream, containing $\geq$ 99 wt% CH_4, is directed towards the steam methane reforming circuit for the production of bio-H_2.

Gas liquefaction is a process that cools gas below its boiling point, achieving very low temperatures called 'cryogenic' temperatures through complex industrial- scale processes. after CO_2 is being removed from the biogas stream it is then moved towards the liquefaction section. Where, The CO_2 feed stream was first compressed using multistage compressor. The pressurized CO_2 feed stream was subsequently sent to a condenser and liquefied. The liquified CO_2 feed stream is typically intercooled which involves passing the compressed CO_2 through a heat exchanger to remove the heat generated during compression and lowers the liquid CO_2 stream temperature. This final liquid CO_2 stream is sent to a Joule−Thomson (J−T) valve, and a low-pressure liquefied CO_2 stream was obtained through iso-enthalpic expansion. The liquefied CO_2 stream from the J−T valve was recovered as a product, and the effluents of the vapor stream from the expansion were used to lower the temperature of the liquid process stream and recycled back to the multi-stream heat exchangers.

These modifications overcome the main challenge of the conventional CO_2 liquefaction process for ship transportation such as its considerable energy consumption. CO_2 liquefaction consumes the largest amounts of energy among transportation processes, which can reach up to 10% of the total energy consumption in the entire CCS (Carbon capture and sequestration) process. The liquefaction of CO_2 for sequestration purposes is covered in this study. It explains that following liquefaction, CO_2 can be pressurized by pumps and that pumps use less energy than compressors.

2.1.3. Biomethane conversion to Bio-H_2

In this section, an overview of H_2 production from biogas on Aspen Plus® is presented. The process model begins with the heating of purified biogas and mixed with steam and proceeds towards steam methane reforming reactor. Steam reforming is an endothermic reaction that is a high amount of heat is required to further proceed with the reaction. So high temperatures like 900–1000 °C is kept in the reactor. Now, syngas from reforming reactor outlet is cooled and fed to high temperature water gas shift reactor (HT-WGS). The mixture at the HTWGS outlet reaches 457 °C at 15.75 bar due to the exothermic nature of the water gas shift (WGS) reaction. CO is still present in this mixture in non-negligible amounts. It is then cooled to 210 °C at 15.70 bar and moved in the direction of low temperature water gas shift reactor (LT-WGS). This reaction is called water gas shift reaction, which breaks down methane into carbon monoxide and H_2 through the following reaction.

$$CH_4 + H_2O \text{ -> } 3\,H_2 + CO \tag{1}$$

The temperature of the mixture at the LTWGS reactor outlet reaches 238 °C. This mixture is cooled down to 38 °C at 15.65 bar to separate water from the gas. The mixture is sent to the Pressure swing adsorption (PSA) unit (component splitter).

The PSA unit enables the extraction of high-quality H_2 from the gas mixture. For injection into H_2-powered vehicles, this separated H_2 is compressed. Unreacted CH_4, CO_2, leftover CO, and H_2 are present in the tail gas from PSA. The tails gas is mixed with air and preheated before being burned. This preheating enables raising the rate of combustion in order to increase combustion efficiency and to valorize any heat that is lost at low and moderate temperatures. To prevent condensation, flue gas is released into the atmosphere at a moderate temperature after this combustion, which is typically used on an industrial scale.

2.2. Thermodynamic model

Thermodynamic models play a pivotal role in process simulation, offering a robust framework to predict and understand the behavior of complex systems. The Non-Random Two-Liquid (NRTL) model is employed to simulate the behavior of complex liquid-liquid mixtures in the AD process. In AD, organic materials, such as food waste, are broken down by microorganisms to produce biogas. The NRTL thermodynamic model is a powerful tool for understanding and predicting the behavior of complex liquid mixtures in various chemical processes (Domańska et al., 2018). Its ability to account for non-ideal interactions and accurately predict phase equilibrium makes it invaluable, facilitating the design, optimization, and operation of a wide range of industrial processes. The NRTL model is well-suited for systems with molecules exhibiting non-random interactions, such as polar and associating compounds (Verma et al., 2018). It accounts for the asymmetry in molecular interactions that are not adequately addressed by simpler models. The model calculates activity coefficients, which describe the non-ideality of solutions. These coefficients are crucial for determining phase equilibrium, solubility, and separation processes. The incorporation of NRTL model is essential when simulating complicated systems with various components and changing conditions. This mathematical framework ensures precise estimations of phase compositions and distribution coefficients. Precise comprehension of liquid-liquid equilibria is crucial for product purification and the production in the chemical-based processes thereby making its versatility applicable in many fields. The equations used for presenting the NRTL model are as follows:

$$\ln\gamma_i = \frac{\sum_j x_i \tau_{ji} G_{ji}}{\sum_k x_k G_{ki}} + \sum_j \frac{x_j G_{ij}}{\sum_k x_k G_{kj}} \left(\tau_{ij} - \frac{\sum_m x_m \tau_{mj} G_{mj}}{\sum_k x_k G_{kj}} \right) \quad (2)$$

$$G_{ij} = e^{(-a_{ij}\tau_{ij})} \quad (3)$$

$$\tau_{ij} = a_{ij} + b_{ij} \quad (4)$$

Where γ_{ij} is the activity coefficient, a_{ij}, b_{ij}, are the binary interaction parameter determined based on the VLE (Vapor liquid equilibrium) regression as shown in supporting information Table S1.

In the biogas purification, CO_2 liquefaction, and bio-H_2 production process, the Peng-Robinson (PR) equation of state model is instrumental. It accurately describes the thermodynamic properties of gases and liquids, making it suitable for modeling phase equilibria, critical points, and vapor-liquid behavior. This model is applied to predict the behavior of the biogas stream as it undergoes purification, CO_2 sequestration, and subsequent H_2 production. The equation accurately predicts phase behavior, including vapor-liquid equilibrium (VLE) in a wide range of conditions, from low to high pressures and temperatures. The PR model can handle complex mixtures, including those with polar and nonpolar compounds, making it suitable for applications involving diverse hydrocarbon systems and chemical processes (Sarfaraz et al., 2023). It effectively predicts critical points, which are critical in understanding a substance's phase behavior and phase transition properties. This information is vital for the design of separation processes and the determination of optimal operating conditions. The adaptability of the Peng-Robinson equation of state allows it to accurately describe systems under high-pressure and high-temperature circumstances, making it well-suited for a wide range of engineering applications. The strong and accurate nature of the system enhances the effectiveness of processes, promising that engineers and researchers may depend on accurate thermodynamic calculations for crucial decision-making in the design and performing of chemical and hydrocarbon processing facilities. The mathematical model equations for the PR model are as follows:

$$\mathrm{P} = \frac{\mathrm{RT}}{\mathrm{V_m} - \mathrm{b}} - \frac{\mathrm{a}}{\mathrm{V_m}(\mathrm{V_m} + \mathrm{b}) + \mathrm{b}(\mathrm{V_m} - \mathrm{b})} \quad (5)$$

Where:

$$b = \sum_i x_i b_i \quad (6)$$

$$a = \sum_i \sum_j x_i x_j (a_i a_j)^{0.5} (1 - k_{ij}) \quad (7)$$

$$a_i = fcn(T, T_{ci}, p_{ci}, \omega_i) \quad (8)$$

$$b_i = fcn(T_{ci}, p_{ci}) \quad (9)$$

$$k_{ij} = k_{ij}^{(1)} + k_{ij}^{(2)} T + \frac{k_{ij}^{(3)}}{T} \quad (10)$$

$$k_{ij} = k_{ji}$$

2.3. Process optimization approach

The process design methodology for this integrated system is structured to efficiently harness the potential of food waste by converting it into valuable energy resources. It begins with the application of AD, a biological process that effectively transforms food waste into biogas. Anaerobic digestion occurs under controlled conditions, including temperature and pH, ensuring optimal microbial activity and biogas production. Following the anaerobic digestion phase, the generated biogas is subjected to a thorough purification process, primarily aimed at the removal of CO_2. This purification step is crucial to obtaining high purity biomethane, which is being done using ionic liquid as a green solvent to provide effective sequestration of CO_2 with reduced specific energy consumption. Once the biomethane is purified to the desired specifications, it is seamlessly directed to a dedicated steam reforming section. Here, the biomethane undergoes a transformative process, often referred to as steam methane reforming, to produce H_2 gas. The reforming process involves the reaction of CH_4 with steam (H_2O) at elevated temperatures, resulting in the synthesis of H_2 gas. Additionally, the CO_2 separated during the biogas purification phase is systematically collected and subjected to a liquefaction process. This transformation converts gaseous CO_2 into a more manageable liquid state, allowing for efficient storage and transport. The study focuses mainly on the optimization approach to see the effect of operating conditions which includes: flows, and equipment sizes to ensure maximum efficiency and resource utilization. The schematic scheme for the design approach used for the proposed study is shown in Fig. 2.

2.3.1. Design constraints

Designing a system that integrates AD of food waste, CO_2 sequestration from the obtained biogas, and biomethane reforming for bio-H_2 production presents a complex set of constraints that need careful consideration. These constraints encompass technical and economic factors. Here are some of the key design constraints for such an integrated process:

- The success of anaerobic digestion and subsequent processes heavily depends on the consistent availability and quality of food waste. Variability in feedstock can affect the efficiency and stability of the overall system.
- The composition of biogas generated during anaerobic digestion can vary, with CH_4 being the primary component. The process design must account for this variability and ensure effective separation and purification to obtain a high-purity biomethane stream for further processing. The efficiency of CO_2 sequestration using ILs hinges on factors such as the choice of ionic liquid, its regenerability, and its tolerance to impurities present in biogas. Selecting the right IL and designing an effective absorption-desorption system is crucial.

$$f(x_1) = Purity \quad and \quad recovery \quad of \quad biomethane_{CH4} = \dot{m}_{CH4} / \dot{m}_{total \quad flow} \quad (11)$$

- The integrated process consumes energy at various stages, including anaerobic digestion, ionic liquid regeneration, and steam reforming for bio H_2 production. The design must consider the overall energy balance and strive to minimize energy consumption to ensure economic viability.

$$f(x_2) = High \quad production \quad rate_{H2} = \dot{m}_{H2} \quad (12)$$

$$f(x_3) = specific \quad energy \quad minimization = \frac{P_{total}}{\dot{m}_{H2}} \quad (13)$$

2.4. Process analysis

Process analysis involves a systematic and comprehensive examination of a purified and high yield production of biogas from food gas and then integrated it with the bio-H_2 production circuit to optimize its efficiency, reliability, and safety. It entails studying various aspects such

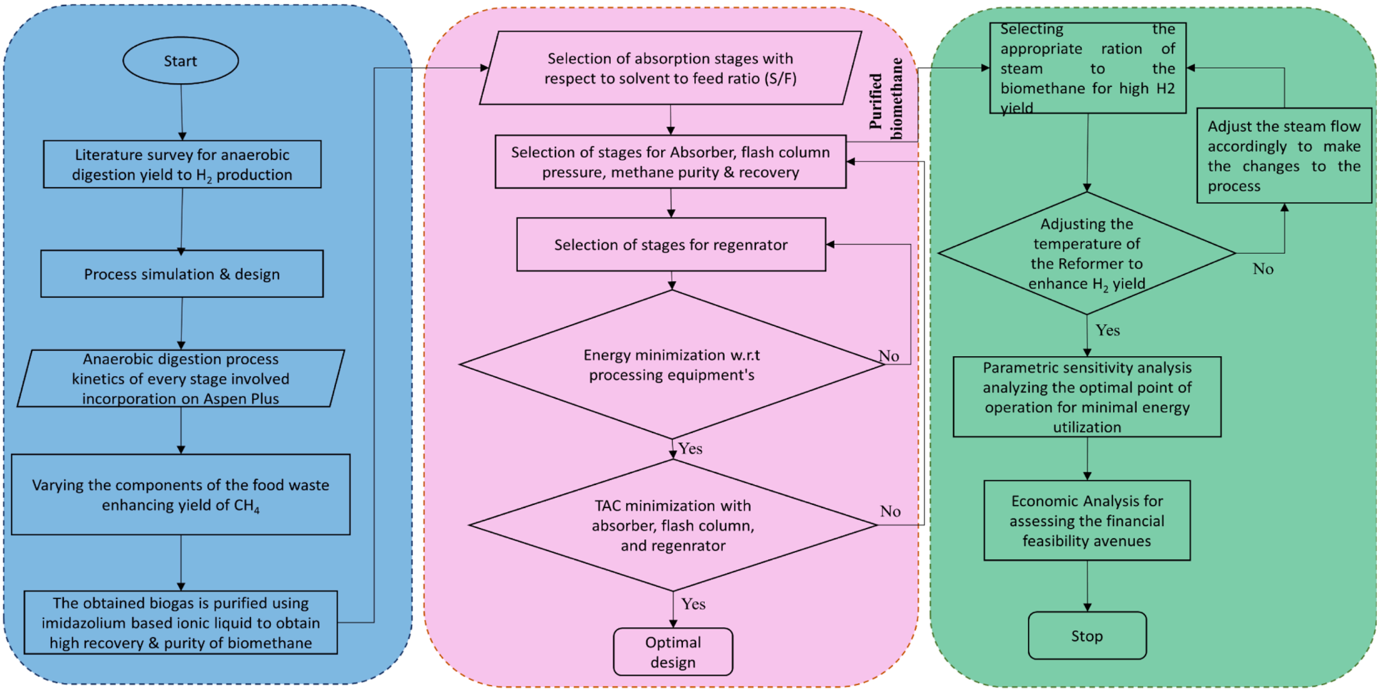

Fig. 2. Process design methodology scheme for the conversion of food waste into biogas followed by steam reforming to yield Bio-H_2 as a product.

as input materials, equipment performance, energy consumption, and environmental impact. By conducting a thorough process analysis, one can identify bottlenecks, inefficiencies, and opportunities for enhancement, ultimately leading to more cost-effective and sustainable operations of bio-H_2 production.

2.4.1. Parametric and sensitivity analysis

The sensitivity analysis for this process involves a meticulous examination of how the diverse components within food waste influence biogas production, with a specific emphasis on achieving a high CH_4 content. This approach enables us to assess the system's robustness and identify critical factors that significantly impact the biogas output. By systematically varying the composition of food waste inputs and closely monitoring resulting biogas yields, we aim to fine-tune the process parameters to optimize CH_4 content, thus advancing the efficiency and sustainability of our biogas production system. This in-depth understanding of sensitivity to input variations is instrumental in designing a more reliable and economically viable waste-to-energy solution.

Likewise, sensitivity analysis is also centered around the purification of obtained biogas from the anaerobic digestion by using IL. The analysis focuses on the critical parameter of the IL to biogas ratio, with the primary objective of achieving an impressive 99% purity and maximizing the recovery of biomethane. By systematically varying the ionic liquid to biogas ratio, we are meticulously assessing its impact on the separation efficiency of methane from the biogas mixture. This variation allows us to pinpoint the optimal conditions necessary to attain the desired 99% methane purity. Furthermore, the influence of the number of stages in the absorber column to optimize the capture of CH_4 and minimize the loss of valuable biogas components. In parallel, investigating the regenerator column's pressure and temperature parameters to enhance the energy efficiency of ionic liquid regeneration. Lowering energy consumption during the regeneration process is essential for the overall sustainability of proposed process. By carefully adjusting pressure and temperature conditions, aim to identify the optimal settings that achieve efficient ionic liquid regeneration while minimizing energy input.

Finally, sensitivity analysis on the bio-H_2 production process through steam reforming of biomethane is a vital step in optimizing performance. Two key parameters under scrutiny are the temperature within the reformer. By systematically varying the reformer temperature, can gauge its impact on the efficiency of the steam reforming reaction. This allows us to pinpoint the ideal temperature range that maximizes bio H_2 yield while maintaining process stability. Secondly, assessing the impact of the ratio of biomethane to steam on bio H_2 yield. This parameter is crucial as it determines the availability of reactants for the steam reforming process. By carefully varying this ratio, one can understand its direct influence on the efficiency of H_2 production.

Through this sensitivity analysis, a comprehensive understanding of how these key parameters interact with the bio H_2 production process is established by identifying the ideal conditions for temperature, pressure and reactant ratios provide us with the avenue to enhance the overall performance of bio-H_2 production system, making it more efficient, cost-effective, and environmentally friendly.

2.4.2. Economic evaluation

The economic assessment of H_2 production focuses on evaluating the economic feasibility and viability of the process, encompassing capital and operational costs, income generation, and assessing CO_2 emissions stemming from the anaerobic digestion of food waste. The cost analysis involves the consideration of all components, including anaerobic digestion, CO_2 scrubbing, and H_2 production, and is based on both total capital cost and operational cost, which encompasses plant overhead and administrative expenses. To ensure a fair comparison across all examined scenarios, employing the Total Annualized Cost (TAC) eq. as follows:

$$TAC = \left(\frac{Total \quad capital \quad investment \quad of \quad project}{paybackperiod}\right) + Total \quad operational \quad and \quad maintenance \quad cost \tag{14}$$

The total capital cost (TCC)is intricately linked to equipment expenses. In our evaluation, we determine equipment costs through parametric relations and constants derived from reputable literature sources. Specifically, for compressors and pumps operating at high pressures, we employ an approach inspired by Towler & Sinnott(Sinnott and Towler, 2013), utilizing equipment-specific constants (α, β) and operation-specific dimensions (S). To assess processing vessel equipment costs, utilize Guthrie (kazmi et al., 2022), which relies on vessel height and diameter. This method is especially valuable when detailed cost data for similar equipment is lacking or when rapid cost estimates are required. Furthermore, Turton's(Turton et al., 2008) bare modulus method is utilized for intercooler purchase cost calculation, taking into account the bare module factor (F_{BM}), pressure factor (Wp), and material factor (W_M). This systematic approach leverages detailed engineering parameters and equipment specifications. The key relationships for conducting this analysis are outlined in Table S9.

3. Results and discussion

3.1. Parametric and sensitivity analysis

This study consists of three sections: (i) Anaerobic digestion, (ii) Purification of obtained Biogas to yield biomethane integrated with the Liquification of CO_2, and (iii) steam reforming of the biomethane to produce Bio-H_2. These steps depend on different parameters to control the overall process. Sensitivity analysis is the way to control these parameters through which we can make some decisions on how we can increase our yield and purity by observing different parameters. The Process paramters for the all the three integrated systems are listed in Table 2.

Table 2
Process variables obtained for bio-H2 production using food waste with minimal energy consumption.

Variables/Parameters	Values
Design Constraints	
Purity of biomethane (wt%)	99.8
Recovery of biomethane (wt%)	99.8
CO_2 removal (%)	≥ 99
CO_2 Liquefaction rate (%)	≥ 99
Anaerobic digestion	
Digestor Temperature (ºC)	20-25
Digestor Pressure (bar)	1
Food to water ratio (m^3/m^3)	1.42
Biogas composition	CH_4 (24.7%), CO_2 (56.7%)
Biogas flow (kg/hr)	516
Biogas upgrading	
Solvent composition (wt%)	EMIMFAP(100)
Biogas flow (m^3 /h)	0.419
Solvent flow (m^3 /h)	13.415
Solvent/Feed gas (F/S) ratio	0.0312
Absorber column stages	8
Absorber column pressure (bar)	24
Absorber column temperature (°C)	30
Recycle gas compressor power (kW)	66.48
Regenerator column temperature (°C)	70
Regenerator column pressure (bar)	0.1
Thermal requirement for regenerator column	110.14
Specific compression Energy requirment (kW/kg of biomethane)	0.58
Steam Reforming of Biomethane to H_2	
Biomethane flow (kg/hr)	126
Steam flow (kg/hr)	800
Biomethane to steam ratio (kg/kg)	0.15
Reformer Temperature (ºC)	909
Reformer Pressure (bar)	24
HT-WGS Pressure (bar)	24
LT-WGS Pressure (bar)	23.7
PSA Pressure (bar)	23.7
Thermal Requirement for Reforming (KW)	397
Bio-H_2 yield (kg/hr)	38.307
Specific thermal energy requirment (kW /kg of H_2)	10.31
CO_2 Liquefaction	
CO_2 liquefaction temperature (∘C)	-28.7
Pressure (bar)	17
Pressure ratio of CO_2 feed compressor	2.4
Minimum internal temperature approach (∘C)	2.5
Liquefaction rate of CO_2 (%)	100
Specific compression power requirement (kW/ kg CO_2)	0.137

3.1.1. Analysis on the biogas production

In the process of anaerobic digestion in which organic materials naturally breaks down into useful bio products, temperature greatly influences enzymes activity, biogas yield and effluent quality. Multiple ranges of temperatures are tested in this study, which showed that medium temperature range of about 20–25 °C is ideal for this case. Furthermore, methane production is increased by varying the feed volumetric flow which aims the decrement in CO_2 and ammonia also as high ammonia concentration can hinder microbial activity, impact biogas production and potentially lead towards ammonia emissions. The ammonia fraction is maintained lower than 3% in this study, which is done by adjusting different parameters (i,e. feed volume flow, feed concentration etc.). The results of this analysis showed that volumetric flow of food waste and water is 20,000 L/day and 14,000 L/day respectively is the optimum condition for this case. However, mass flowrate of water is kept at 0.94 kg/hr the results for the different cases being studied by varying the feed of food waste is shown in Table S2, while the Table S2 also presents the final selected composition for the food waste component based on the studied cases leading towards the higher value methane i, e. 126 kg/hr with reduced impurities.

3.1.2. Analysis on biogas purification process

Biogas purification is performed using imidazolium based ionic liquid 1-butyl-3-methylimidazolium tris(perfluoroethyl)trifluorophosphate [Emim][FAP], which is favorable for high purity of methane and also provides us reduced energy requirement for the solvent regeneration (Althuluth et al., 2012; Bagchi et al., 2016).

For the analysis, different parameters are altered to analyze the results of high purity and lowest energy requirement. Initially, the analysis is done on solvent flow rate concerning the feed biogas because it is directly related to energy usage and, so the optimum flowrate of solvent used in process is 13.415 m^3/h. Next, solvent-to-gas ratio is analyzed to get high purity and recovery of methane greater than 99% with respect to the stages of absorber, as number of stages is a function of solvent to feed ratio, results showed that 8 no. of stages for the absorber gives better results at 24 bar and 30º C, which is illustrated in Fig. 3.

Furthermore, another analysis is done by altering the temperature and pressure of regenerator column is observed the optimum conditions where less duty of column and minimum flow of CO_2 is achieved. Thermal requirement for regenerator column at optimal conditions is observed to be 110.14 KW. Moving towards the column next to absorber which separates purified methane from top and CO_2 and solvent mixture from bottom. The effect of pressure is observed on flow of methane and CO_2. Through results illustrated in Fig. 4, it is shown that column at 8 bar pressure requires less heat. The power requirement of recycle gas column is also taken into consideration which is mounted to recycle the gas to top of this column. So, the flash column in situ pressure with the optimal S/F ratio would also be essential for reducing the gas compression load and the optimum Recycle gas compressor power will be in this case 66.4819 KW.

3.1.3. Analysis on the production of hydrogen

The outcome of parametric and sensitivity analysis for the production of H_2 is depicted in this section. First, Fig. 5 conveys about the effect of variation of reformer reactor temperature on the production of H_2 which shows that the increase in temperature increases the yield of H_2 until reaching specific temperature of about 600–700 °C but, it also

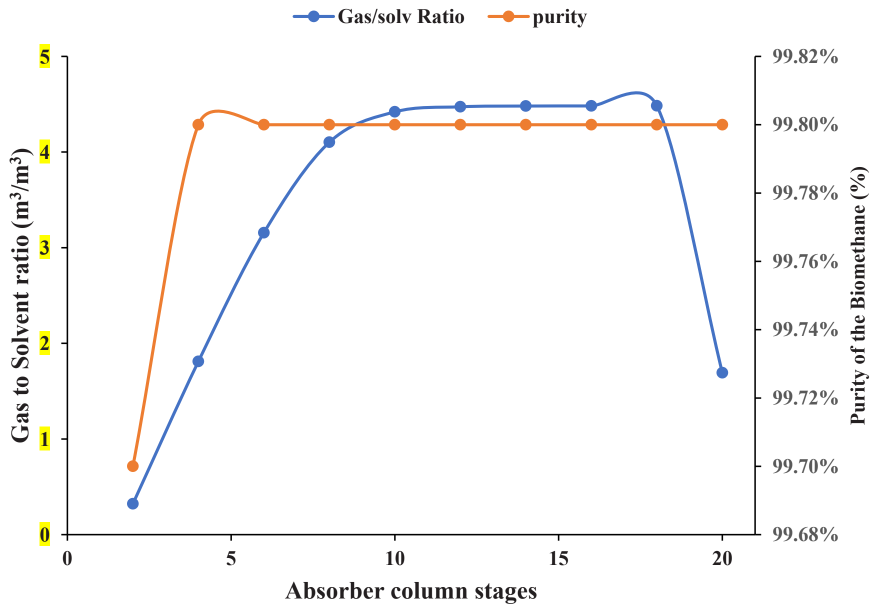

Fig. 3. Analysis on the effect of the absorber stages on the gas to solvent ratio and on the purity of the biomethane obtained.

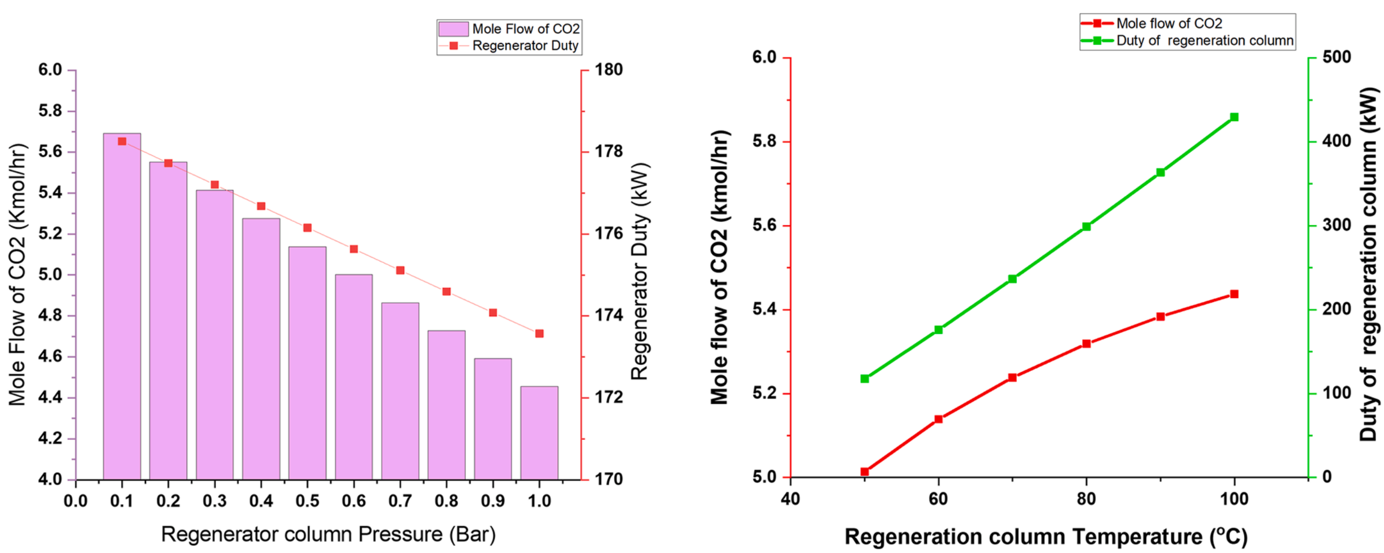

Fig. 4. Analysis on the regenerator by varying the regenerator column pressure and temperature and its effect on the duty of the regenerator and CO_2 removal amount.

reduces the CO_2 capture due to exothermic carbonation reaction. Higher temperature enhances the endothermic calcination reaction. However, because the reforming reaction is endothermic, increasing the temperature favors the forward reaction in accordance with Le Chatelier's principle, enhancing the purity of the H_2 produced during steam reforming. Despite all the favorable conditions in steam reforming, the methanation reaction is thermodynamically unfavorable at high temperature which decreases the CH_4 concentration. In steam reforming, high temperature increases CO and decreases CO_2 due to endothermic reaction and less favored exothermic reaction in WGS. On the other hand, gas to water ratio in the process decreases the flow of H_2 increases and increase in flow of CO_2.

3.2. Economic analysis

The results of the economic assessment for H_2 production from biogas are presented in Table 3. This economic analysis compares the feasibility of each case in terms of cost calculations for the H_2 production process, determining which case holds the maximum financial profits and which cases incur extra costs leading to economic disadvantages. The analysis considers the case based on three different scenarios, Anaerobic digestion, CO_2 Scrubbing and H_2 production and evaluates cost savings related to TCC, TOC, and TAC. The results show that the TCC for Anaerobic digestion is 3.15×10^4 \$ in which Food waste and water are mixed to form Raw Bio-Gas. Now this Raw bio-gas is sent to another case for CO_2 Separation where CO_2 Scrubbing from an ionic liquid and CO_2 liquefication has been done and its TCC is 2.15×10^7 \$ and its TOC is 4.73×10^8 \$ due to electricity consumption in compressors. Then this separated biogas is sent for H_2 production from steam reforming process where bio methane and steam perform reforming reaction and producing Bio-H_2 and its TCC is 1.92×10^6 \$ here since steam is used and require high temperatures so for this different type of reactor vessels are used that is the cause for this cost. The change in all costs for each case is presented in Table 3 respectively.

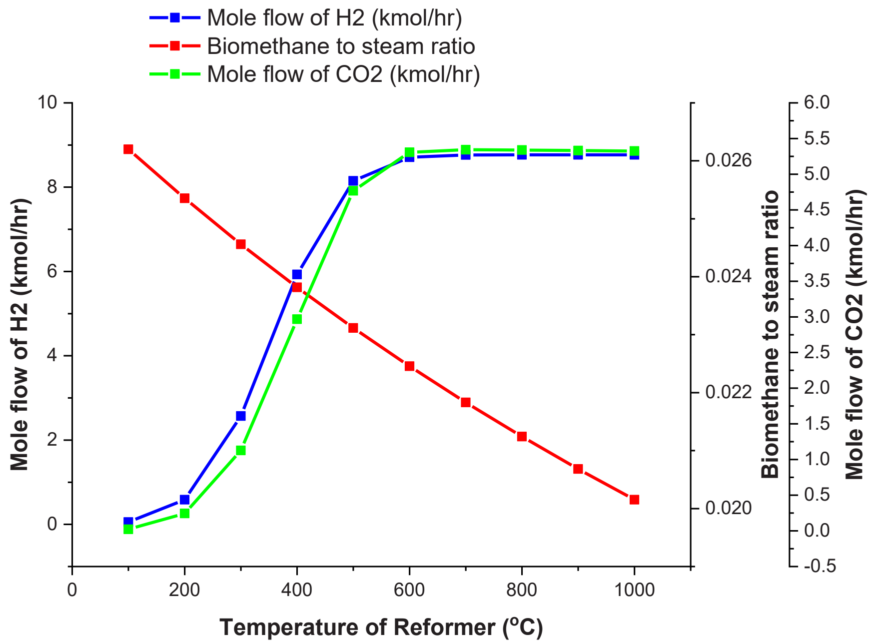

Fig. 5. Analysis on the production of H_2 by varying the temperature of reformer and its effect on the H_2 produced and biomethane to steam ratio.

Table 3
Cost evaluation results of the three section of the studied process.

Parameters/case	Anaerobic digestion	Biogas purification and CO_2 liquefaction	H_2 production
Total Capital Cost, USD	3.15×10^4	2.15×10^7	1.92×10^6
Total Operating Cost, USD/y	8.79×10^8	4.73×10^8	4.41×10^8
Total Utilities Cost, USD /y	8.79×10^8	4.72×10^8	4.40×10^8
Equipment Cost, USD	5.31×10^3	3.63×10^6	32.3×10^6
Total Installed Cost, USD	3.70×10^3	2.53×10^6	22.5×10^6
Total Annualized Cost, $/y	8.79×10^8	4.77×10^8	4.41×10^8

3.3. Comparison with literature

food waste for the production of biogas and subsequently bio H_2 through steam reforming is an innovative and sustainable approach to both waste management and renewable energy production. Overall, the concept of using food waste for biogas and bio H_2 production is an environmentally friendly and sustainable approach to waste management and renewable energy generation. Researchers continue to work on improving the efficiency and economics of this process to make it more widely accessible and economically viable (Fig. 6). Based on the literature utilizing food waste to produce bio H_2, several studies have been conducted using Aspen Plus to simulate different processes related to waste management and bioenergy production. These studies provide valuable insights into the potential of utilizing food waste to produce bio H_2.

In a study conducted by Madeira et al. (2021) a comprehensive analysis of the economic viability of this technology is presented, covering parameters like the payback period and the cost associated with H_2 production. The technical aspects of the process, such as H_2 production capacity and sensitivity analysis of cost-related variables, are also discussed. Various research works have explored H_2 production from biogas using different methods. For instance, Cerqueira et al. (2021) conducted a techno-economic analysis of biogas-to-H_2 production through steam methane reforming, achieving a production rate of 19.57 kg/h H2. Yao et al. (2017) compared various methods, reporting energy efficiencies ranging from 39% to 66% for biogas-to-H_2 production. Kok Siew Ng et al.(Ng et al., 2021) explored the production of H_2 from residual municipal solid waste via mechanical-biological treatment and valorization, obtaining a specific energy consumption of 7.55 KW/Kg and producing 4391.36 tons/year of H_2. Xu et al. (2022) focused on the impact of food waste concentration on biogas conversion to H_2, achieving a production rate of 1.2 tons/h with a specific energy consumption of 0.051 MW/Kg. Kourdourli et al. (2023) assessed H_2

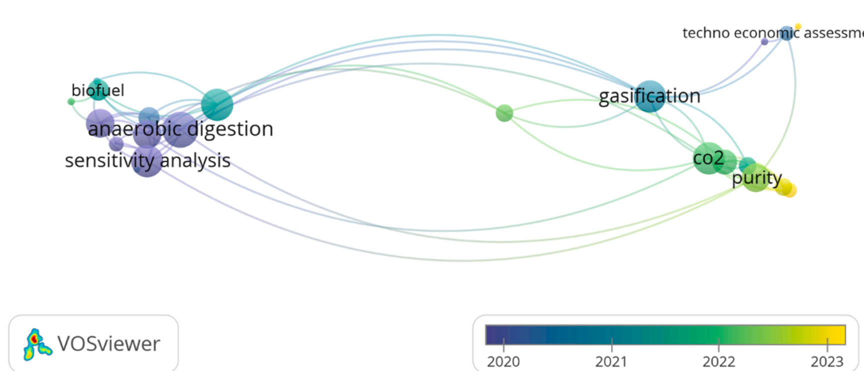

Fig. 6. Literature based various connective aspects for Bio H_2 production.

Table 4
Literature based perspective for the production of Bio-H2 from various feed stocks.

Year	Method used for H_2 production	Substrate	Product	Energy consumption	Specific Energy consumption	Economic Analysis	Reference
2017	Steam Gasification	Biomass	90 Kg/h	-	2.97 kW/kg	TCC= 10 × 10^6 USD	(Yao et al., 2017)
2018	Pyrolysis Gasification Electrolysis	Biomass	114000 kg/h 139700 kg/day 4% recovery	25 kW/h	0.00021 kW/kg	-	(Dou et al., 2019)
2020	Steam Reforming	Biogas	30% production of 99.9% pure H2	-	1.67 × 10^8 kW/kg	-	(Cerqueira et al., 2021)
2021	Steam Reforming	Sunflower meal	44.9 mol H_2/kg sunflower meal	-	-	-	(Kanatlı and Ayas, 2021)
2021	Mechanical-biological treatment and Valorisation of residual	Municipal solid waste	454.76 ton/year H_2 produced	3435.52 kW	7.55 kW/Kg	-	(Ng et al., 2021)
2021	Chemical looping Cycles	Biogas	4400 kg/hr H_2 with 99.95% purity	-	0.40 to 22.73 kg/MWh	-	(Nouwe Edou and Onwudili, 2022)
2021	Dry reforming of biogas	150 m3 /day cow manure.	8.11 kg/h H_2	-	29.71 MJ/kmol	1.39 USD/kg H_2	(Rodríguez et al., 2022)
2022	Gasification	Food Waste	1088.62 ton/h H_2	55.81 MW	0.051 MW/Kg	TCC= 1.61 × 10^7 USD	(Xu et al., 2022)
2022	Pyrolyzing-Gasification	Biogas	2781.79Kg/h	+ 101,906.19 kW	36.63 kW/Kg	TCC=USD54.69 × 10^6	(Nouwe Edou and Onwudili, 2022)
2022	Sorption-enhanced steam reforming (SESR)	Bio-oil+Biogas	92.80% Yield	111.75 kW H2 output	-	-	(Rodríguez et al., 2022)
2022	Anaerobic digestion	Food waste	49.4 mL/g VS H_2 produced	-	-	2.8 and 3.5 USD/kg H_2	(Hosseinzadeh et al., 2022)
2022	Steam Reforming	Palm oil mill effluent 20000 kg	963.31 tonneof H_2 gas	-	-	TCC=USD 30 × 10^6	(Wee et al., 2022)
2023	Dry Reforming	Biogas	9463 Kg/hr H_2	333,783 kW	35.27 kW/Kg	TCC= 282.80 × 10^6 USD	(Shamsi, 2023)
2023	Steam Methane Reforming	Biomass blend	10.15 kg/h H_2 produced	-	206 kJ/mol	-	(Tamilselvan and Selwynraj, 2023)
2023	Reforming	Bio-waste Bio-mass	73.3 kg /hr of H_2	-	-	cost of 1 kg H_2 production is 0.55–2.76€ with biowaste and 0.45–3.31€ with biomass	(Arfan et al., 2023)
2023	Sorption Enhanced Steam Reforming	Biogas	H_2 yield 90.8%	3.9-2.5 MW	-	-	(Capa et al., 2023)
2023	Steam Reforming	cow manure	0.000001 kg/hr of H_2	-	165 KJ/mol	-	(Kourdourli et al., 2023)
2023	Combined heat & power plant	Biogas	446.8 kg/h H_2	5792 kW	12.96 kW/Kg	-	(Arslan and Yılmaz, 2023)
2023	Anaerobic Digestion	Dairy manure	13.2 kg/hr	-	-	-	(Norouzi et al., 2023)
2023	Membrane Reactor	Biogas	4.16 Kg/hr	-	120 MJ/kg	Total production cost= 53% of overall cost	(Ongis et al., 2023)
2023	Photo fermentation	Tequila vinasses,	97.6 mmol/L	-	-	-	(Min Woon et al., 2023; Woon et al., 2023)
	Dark fermentation	Glucose	193.7 mL/g	-	-	-	
2023	Steam Reforming	Food waste	38.35 kg/h H_2	1711.45 KW/h	44.62 kW/Kg	TCC= Capital cost= 1.92 × 10^6 USD Total production cost= 9.65 × 10^7 USD	Our study

production from dairy manure through the reforming process, obtaining a yield of 5.71 l/day H_2 with a specific energy consumption of 165 kJ/mol of H_2. Arfan et al. (2023) investigated green H_2 production from a biomass blend using steam methane reforming, resulting in a production rate of 40000 cum/day H_2. In our current study, in comparison to other studies as shown in Table 4 simulated H_2 production from anaerobic digestion of food waste through steam methane reforming, achieving a production rate of 38.35 Kg/h H_2 with 99.8% purity at a specific energy consumption of 44.62 kW/Kg. An economic analysis revealed a total production cost of 9.6 × 107 USD/yr. While our results demonstrate effective H_2 yield from food waste, improvements in energy efficiency are possible.

To assess competitiveness further, factors like production scale, environmental impact, and specific research goals should be considered. In summary, these studies collectively underscore the potential of food waste for bio H_2 production, using Aspen Plus simulation to optimize processes and align with principles of economic sustainability and waste valorization.

4. Conclusion

This study combines anaerobic digestion, biogas purification, and bio-H_2 production from food waste, reducing emissions and promoting cleaner fuel solutions. Key findings:

- Temperature optimization (20-25 °C) boosted biogas yield. Managing ammonia (<3%) was vital. Optimal food waste and water feed rates were determined.
- Imidazolium-based solvent [Emim][FAP] excelled in biogas purification. A solvent flow rate of 13.415 m^3 /h achieved high methane purity with low energy use.
- Higher steam reforming temps (600-700 °C) enhanced H_2 production and purity.
- Comprehensive economic analysis emphasises the importance of each phase. Significantly, the total capital cost (TCC) for AD is relatively lower at 3.15 × 10^4 USD, suggesting that it is cost-effective during the early phase of producing raw bio-gas from food waste and

water. The CO_2 separation phase incurs higher costs (TCC of 2.15×10^7 $), primarily attributed to the expenses associated with ionic liquid scrubbing and CO_2 liquefaction. The total operating cost (TOC) is notably influenced by electricity consumption in compressors, totaling 4.73×10^8 USD.

The proposed integrated approach for H_2 production from biogas, emphasizing the potential for economic gains and contributing to a cleaner energy landscape.

Declaration of Competing Interest

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2024.01.045.

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