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Research Paper

Hydrogen from food waste: Energy potential, economic feasibility, and environmental impact for sustainable valorization

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ABSTRACT

Globally, inefficient management of municipal solid waste, composed primarily of food waste poses concern for human and environmental well-being. Food waste can be converted into hydrogen gas, which can be utilized to generate power without emitting any harmful pollutants. This solution would also help with the issue of disposing of food waste. The conversion of food waste into hydrogen is a practical energy source with potential financial benefits. This study explores the transformative potential of converting food waste into renewable energy through hydrogen production, focusing on Bangladesh from 2023 to 2042. Notably, the study forecasts a surge in food waste from 23 million tons in 2023–110 million tons by 2042. By 2042, food waste is expected to generate 2480 MW of power, a rise from 489 MW in 2023. Based on the results of the economic study, the food waste into hydrogen via gasification project is financially viable in all of Bangladesh's main cities. Metrics such as internal rate of return, payback period, levelized cost of energy, net present value, and total life cycle cost were used to assess economic viability. The hydrogen production cost, payback period, and internal rate of return are 2.05 $/kg, 11 years and 14% respectively. It was discovered that using the available electricity from hydrogen gas may displace 1428 M liters of diesel fuel combustion. The quantity of diesel fuel saved can cut carbon dioxide emissions by 3.85 million tons. It was also found that using hydrogen as a source of energy generation has an attractive ecological efficiency of 99.98%. This research provides novel and pertinent data for investors contemplating gasification-based energy projects in Bangladesh. It pioneers a path toward eco-friendly waste management, reduced greenhouse gas emissions, and the adoption of sustainable energy solutions for the country.

1. Introduction

Hydrogen, among future energy sources, is poised to play a crucial role in lessening our reliance on fossil fuels and steering us toward a carbon-free future (Nguyen et al., 2023). With a substantial calorific value of 120 MJ/kg—far exceeding that of fossil fuels—hydrogen emerges as an environmentally friendly, abundantly available, and versatile energy source for the twenty-first century (Koshariya et al., 2023). Its potential applications are diverse, ranging from acting as a green fuel for internal combustion engines to powering hydrogen-fueled gas turbines and proton exchange membrane fuel cells (PEMFCs) power (Saqib et al., 2019). Fig. 1 illustrates the burgeoning research landscape in hydrogen production through various biomass-to-energy conversion methods, witnessing a surge from 1000 to over 6000 published papers in the past decade. Notably, pyrolysis and gasification have gained prominence, with 2020 seeing the highest number of papers published on gasification. This underscores the global significance and enthusiasm for producing hydrogen using biomass—a vital and sustainable resource on a global scale.

Currently, prevalent processes for hydrogen production heavily rely on natural gas reforming (48%) and oil reforming (30%), with coal gasification ranking second (18%) (Yukesh Kannah et al., 2021). However, these practices are unsustainable due to their dependence on fossil fuels or non-renewable energy sources. A shift towards sustainability can be achieved by embracing renewable energy sources, such as food waste, for hydrogen production (Badami and Fambri, 2019). Food waste is a potential renewable source for hydrogen production. The different

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Nomenclature

Symbols

P(t)	Forecast population of Bangladesh
P_{old}	Current population
GR_{pop}	The country's population growth rate
FWG_{pc}	Projected per capita food waste generation rate
GDP_r	Quantity of FW that can be fed into the gasifier
$FWG_{pc_{old}}$	The country's existing per capita FW generation rate
$FW_{gas,}$	Quantity of FW that can be fed into the gasifier
WG_{eff}	Waste gathering efficiency of Bangladesh taken as 50%
FW_{comp}	Food Waste Composition of Bangladesh is given as 60%
H_2	The actual volume of H_2 gas produced per kg of food waste
$H_{2_{act}}$	The actual mass of H_2 gas produced (kg)
H_{eff}	Hydrogen conversion efficiency is taken as 50%
C_{eff}	The carbon conversion efficiency for the gasification process is given as 85%
H_{2EP}	Gasification plant capacity in kWh/yr.
G_{plant}	Gasification plant capacity in kW
LCV_{H2}	Hydrogen lower calorific value and is given as 33.33 kWh/kg
$Turb_{eff}$	The electricity production efficiency of the hydrogen-fired turbine is provided as 31.1%
CAP_{fact}	The capacity factor of the plant is given as 85%
π_g	Pollution indicator
Q_i	Fuel's low heating value (LVH) expressed in megajoules per kilogram
$(CO_2)_e$	Carbon dioxide equivalent gas emission represented in kilograms per kilogram of fuel
x	The expected proportion of hydrogen in syngas at 65.4%
GWP	Global Warming potential
γ	Emission factor expressed in kilogram per megajoules
η_{system}	The sum of the boiler and reformer system efficiencies
A_{Fuel}	Amount of fossil fuel displaced
LHV_{Fuel}	Density of diesel fuel
$V_{H2,compressed}$	Volume of compressed hydrogen
M	Ash free biomass required to produce 1 Nm^3 of final product gas in kg
M_O	Ash percentage
A_S	Biomass's moisture
V_{H_2}	Denote the volume fractions of hydrogen contained in 1 Nm^3 of product gas
M_A	Represents the mass of air in kg/kg of biomass
O_A	Mass fractions of oxygen in the air supplied
N_A	Mass fractions of nitrogen in the air supplied
M_S	The mass of super-heated steam provided/kg of dry ash free biomass
M_W	The mass of super-heated steam provided/kg of dry ash free biomass
TLCC	Total life cycle cost
Cap_{cst}	Initial investment cost
Op_{cst}	Operating and maintenance costs
τ	Nominal discount rate, which is specified as 10%
C_n	Net cash flow
Gas_{rev}	Gasification project revenue
Tax	Tax paid on the project profit
π_{fit}	Feed-in tariff for biomass source electricity generation in Bangladesh which is taken as $0.106/kWh
Gas_{profit}	Gasification project's profit
T_r	The marginal tax rate assumed to be 25%
In_r	Inflation rate is considered as 9.3%
α_r	Real discount rate annually
Ξ	Ecological efficiency
SE_F	Air pollutant's specific emission factor
CCF	Conversion coefficient factor for fossil fuels
η_{Fuel}	Diesel fuel generator's efficiency, that is assumed to be 33%

methods for recovery of energy from biomass such as food waste (FW) are shown in Fig. 1. Traditional approaches to managing food waste, such as anaerobic digestion, incineration, and landfilling, face limitations. Garbage and composting can contaminate soil and groundwater, while the availability of land resources for waste treatment is scarce. Direct incineration of high-moisture-content food waste leads to air pollution, necessitates costly investments, and involves extensive heat drying processes. Anaerobic digestion systems, on the other hand, suffer from environmental pollution, extended operating periods, and limited efficacy (Halabi et al., 2008). In contrast, gasification presents distinct advantages. It boasts a high conversion rate, a calorific value higher than syngas from pyrolysis, and is easier to manage than pyrolysis. Additionally, it proceeds more rapidly than anaerobic digestion and has a lower environmental impact than incineration (Midilli and Dincer, 2008; Kruse and Gawlik, 2003).

Steam gasification, involving the controlled interaction of carbonaceous material with steam at high temperatures, is a widely adopted method (Su et al., 2020a). In the steam gasification of food waste, biomass in food waste undergoes heating within a closed vessel known as a gasifier, with the primary objective being the conversion of complex organic molecules within food waste into simpler gaseous components, primarily hydrogen (H_2) and carbon monoxide (CO), accompanied by

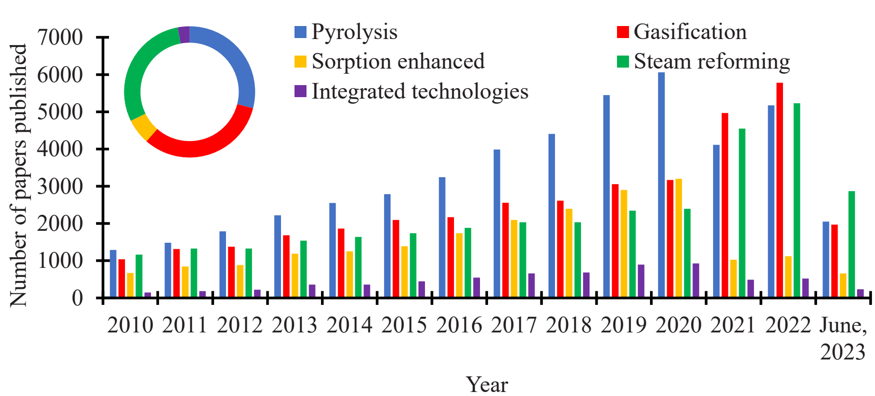

Fig. 1. Number of papers published on Hydrogen production using different methods (Kumar al., 2023).

traces of other gases such as methane (CH_4) and carbon dioxide (CO_2) (Midilli and Dincer, 2008). The carbon monoxide is further converted to hydrogen via steam reforming and the final hydrogen product finds versatile applications in various energy domains, serving purposes such as heat or electricity production and acting as a feedstock for chemical synthesis (Abuadala et al., 2010). The intricate process of gasification, responsible for hydrogen production, is influenced by several factors: catalysts, geometry, steam flow rate, feedstock composition, moisture content, gasifier temperature, and pressure (Ma et al., 2023). Each of these elements plays a critical role in determining the efficiency and outcome of the gasification process, underscoring the complexity involved in harnessing hydrogen from food waste.

Utilizing food waste for hydrogen production addresses the global waste management challenge efficiently. Sharma et al (Ayodele et al., 2018). reported that in 2016, the globe generated 2.01 BT (0.74 kg/person/day) of MSW, with 33% managed unsustainably. Projections indicate a rise to 2.59 BT (7.10 MT/day) by 2030 and 3.40 BT (9.32 MT/day) by 2050 (Sharma and Jain, 2020). Globally, and in Bangladesh, the majority of MSW comprises organic waste, with food waste dominating at 74.4%, followed by paper (9.1%), plastic (3.5%), and other materials (Abuadala et al., 2010). Biomass gasification, a commercially viable hydrogen production alternative, overcomes challenges in processing organic waste while providing environmental benefits (Koroneos et al., 2004). Koroneos et al.'s Life Cycle Assessment (LCA) revealed a 75% reduction in greenhouse gas (GHG) emissions using food waste as biomass compared to natural gas reforming (Koroneos et al., 2004). Susmozas et al (Susmozas et al., 2013). confirmed the environmental advantages, showcasing notable drops in GHG emissions (0.4 versus 10.6 kg $(CO_2)_e$ per kilogram H_2) and reduced reliance on fossil fuels. Tanaka et al.'s study (Cohce et al., 2010) on kitchen garbage gasification highlighted a decrease in final waste generation, favoring steam gasification over pyrolysis ("Chislelnost," chislennost.com, 2023). Globally, over 2450 Waste-to-Energy (WtE) plants process over 330 MT of waste annually (Sharma and Jain, 2020) The market value of WtE technologies, growing at a CAGR of 7.5%, is expected to surpass $40 billion by 2023 (Sharma and Jain, 2020). Overcoming economic challenges is critical for the viability of WtE technologies, particularly in producing economically viable pure H_2 at large scales. Techno-economic assessments are essential for sustainable research and development in this intricate field.

The present study strives to bridge a crucial research gap by thoroughly examining both international and local literature on techno-economic assessments and environmental feasibility of steam gasification. While existing global literature extensively covers these aspects, there is a noticeable dearth of information specific to Bangladesh. The novelty of this research lies in its meticulous evaluation of the economic viability of gasification plant projects employing food waste as feedstock across diverse Bangladeshi cities through techno-economic analysis. The study not only examines the economic aspects but also assesses the electricity generation potential and environmental impact of gasification plant projects in various cities of Bangladesh. Consequently, the findings aim to serve as a robust scientific guide for strategically investing in hydrogen-to-electricity projects within the country. This comprehensive approach ensures a nuanced understanding of the

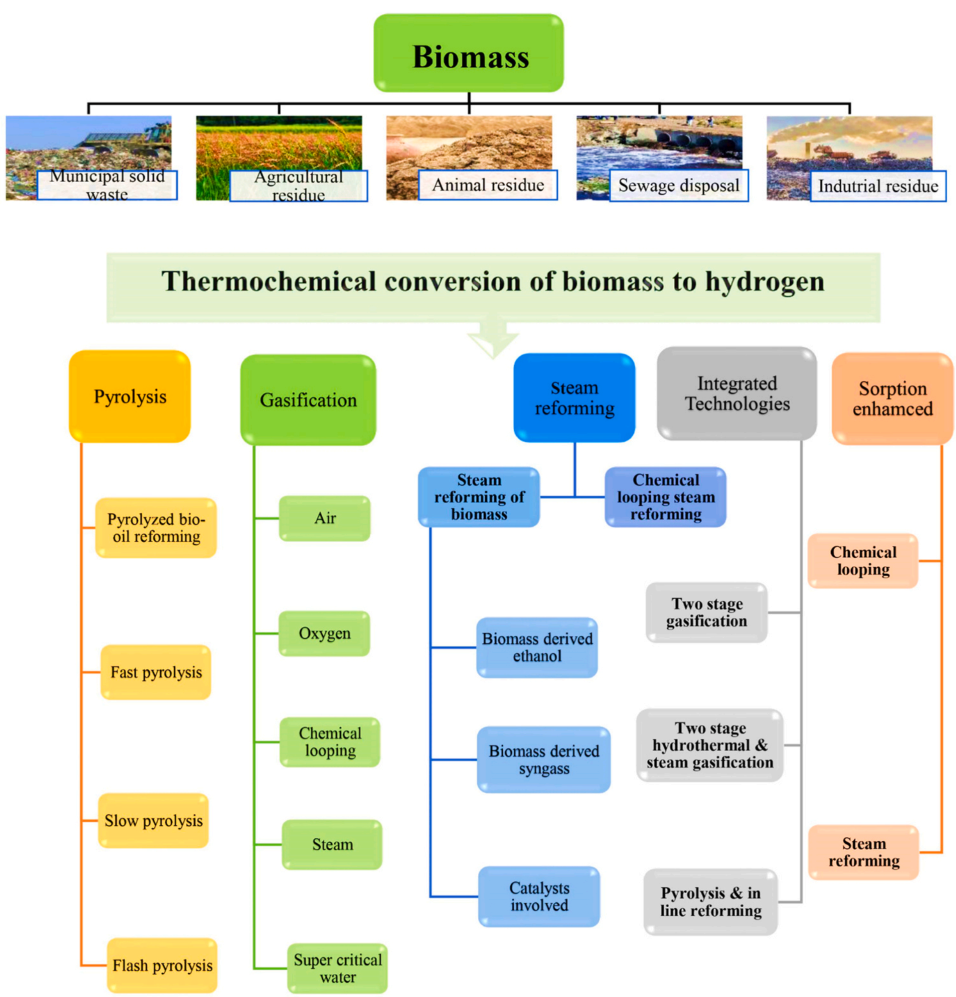

Fig. 2. Biomass to energy conversion technologies (Kumar al., 2023).

challenges associated with gasification plants in Bangladesh and facilitates the development of effective solutions tailored to the local context.

2. Materials and methods

The comprehensive data collection process for this study involved gathering crucial information on food waste characteristics, techno-economic feasibility analysis, and environmental considerations. Both ultimate and proximate analyses of food waste were essential for understanding its composition and energy potential. To ensure accuracy and reliability, data for ultimate and proximate analyses of food waste were sourced from a meticulous review of previous research papers dedicated to food waste analysis. Furthermore, equations crucial for conducting the techno-economic feasibility analysis and environmental assessment were extracted from relevant literature. These equations, derived from prior studies, facilitated the modelling and evaluation of the economic viability and environmental impact of the proposed gasification projects. The techno-economic feasibility analysis focused on assessing the economic viability of the gasification process, considering factors such as capital costs, operational expenses, and potential revenue streams. Environmental considerations were integrated into the analysis through equations derived from studies that quantified the life cycle environmental performance of similar projects. This included evaluating the pollution indicator, ecological efficiency, and overall environmental impact associated with the proposed gasification plants. The selected equations were chosen based on their applicability to the specific context of utilizing food waste as a feedstock in various Bangladeshi cities. The thorough review of existing literature ensured the utilization of robust and validated data for the ultimate and proximate analysis of food waste, as well as for the equations underpinning the techno-economic and environmental analyses. This rigorous data collection approach enhances the reliability and credibility of the findings, laying a solid foundation for the subsequent stages of the research.

2.1. Experimental procedure of steam reforming process for hydrogen production

The steam gasification thermochemical conversion process is employed to transform food waste into a gaseous mixture known as syngas, along with solid residues (biochar). The biomass feedstock, derived from food waste, undergoes a high-temperature endothermic reaction in the presence of water vapor, carbon dioxide, and oxygen, facilitated by a catalyst. It is essential to elucidate the chemical transformations through equations for clarity and accuracy in describing the experimental procedure. The initial high-temperature endothermic reaction is followed by the gasification of water, wherein the water-gas shift reaction plays a pivotal role in converting carbon monoxide (CO) into hydrogen (H_2) (van Selow et al., 2009). Approximately 95% of the generated by-products comprise hydrogen, while the remaining 5% is residual carbon monoxide. The efficiency of the steam reforming process is closely tied to temperature control, given the endothermic nature of the reactions involved. Two cooling procedures are employed to chill the produced hydrogen gas, utilizing reactors with substantial temperature changes or those with more modest temperature shifts. The advantages of steam reforming systems lie in their cost-effectiveness, both in terms of operating and capital expenses (Lv et al., 2008). The syngas is converted to hydrogen via the steam reforming equation: $CH_4 + H_2O \leftrightarrow CO + 3H_2O$ and Water gas shift reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$. Fig. 3 illustrates the steam reforming process flow diagram, wherein nickel-based catalysts are commonly used. However, it is noteworthy that the reforming process remains feasible even in the absence of a catalyst. He et al (He et al., 2010). demonstrated the transformation of municipal solid waste (MSW) into syngas using downstream fixed-bed reactors with calcined dolomite as catalysts. Operating within the temperature range of 750 °C to 900 °C, the researchers observed that higher temperatures, specifically 900 °C, resulted in a superior yield of syngas containing a substantial proportion of hydrogen (36.39%) and carbon monoxide (66.30%). The lower heating value of the produced syngas at this elevated temperature was approximately 13.93 MJ/N m^3, indicating a higher H_2/CO ratio of 1.20

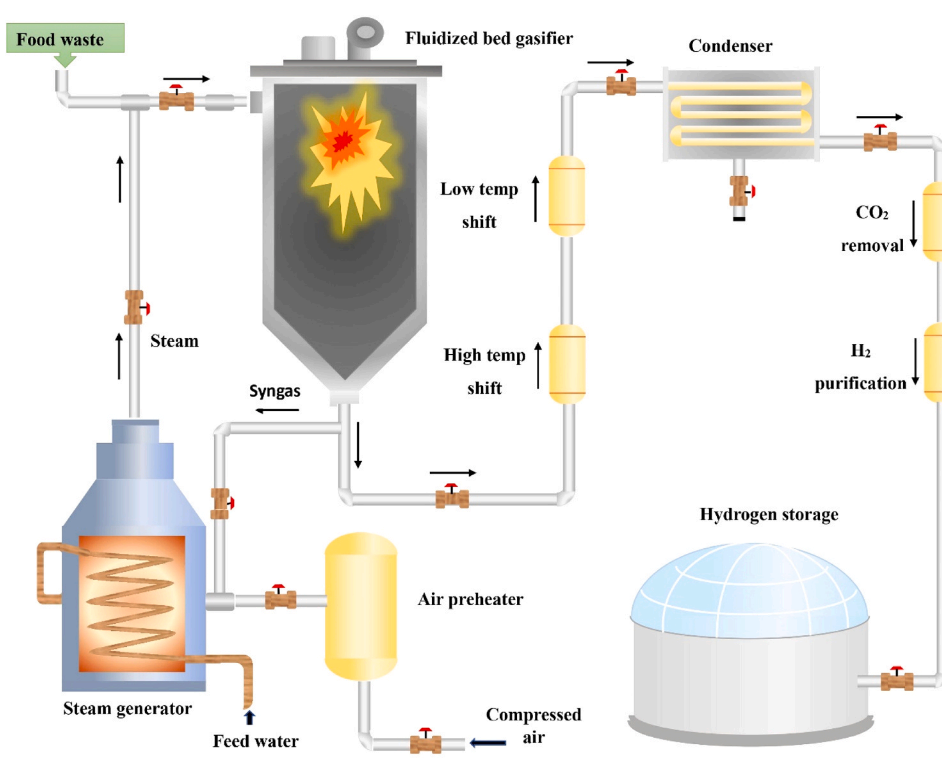

Fig. 3. Schematic diagram of hydrogen energy production via steam reforming process (Kumar al., 2023).

compared to other operating temperatures (750 °C, 800 °C, and 850 °C). These findings emphasize the influence of temperature on the composition and heating value of the syngas produced through the steam reforming process (He et al., 2010).

2.2. Estimation of food waste

Numerous factors, such as population growth and economic development, have an impact on the amount of food that is wasted. Here, Eq. 1 is used to calculate the potential generation of food waste over a given time (t) in tons per year (Ayodele et al., 2018). P(t) is the forecast population of Bangladesh, which is derived using Eq. 2, where P_{old} is the current population and GR_{pop} is the country's population growth rate. $FWG_{pc}(t)$ is the projected per capita food waste generation rate and derived using Eq. 3, where GDP_r is Bangladesh's per capita GDP growth rate, and $FWG_{pc_{old}}$ is the country's existing per capita FW generation rate (Cudjoe et al., 2021a). Eq. 4 used to calculate $FW_{gas,}$ which is the quantity of FW that can be fed in the gasifier, WGeff is the waste gathering efficiency of Bangladesh taken as 50% (Ananno et al., 2021), and FW_{comp} is the food waste composition Bangladesh and is given as 60% (Ananno et al., 2021).

$$FW(t) = \frac{P(t) \times FWG_{pc}(t) \times 365}{1000} \tag{1}$$

$$P(t) = P_{old} \times (1 + GR_{pop})^t \tag{2}$$

$$\mathrm{FWG_{pc}(t)} = \mathrm{FWG_{pc_{old}}} \times (1 + GDP_r)^t \tag{3}$$

$$\mathrm{FW_{gas}}\left(\frac{\mathrm{t}}{\mathrm{yr}}\right) = \mathrm{FW(t)} \times \mathrm{WG_{eff}} \times \mathrm{FW_{comp}} \tag{4}$$

2.3. Hydrogen energy generation potential from food waste

The biomass gasification is a complex process, but the overall chemical conversion can be represented by the global gasification reaction using Eq. 5 (George et al., 2016).

$$M \times \left(\frac{C}{12} + \frac{H}{2} + \frac{O}{32}\right) + M \times \left(\frac{M_S + M_W}{18}\right) + M \times \left(\frac{M_A \times O_A}{32} + \frac{M_A \times N_A}{28}\right) \Rightarrow \left(\frac{V_{H_2} + V_{CO} + V_{CO_2} + V_{CH_4} + V_{H_2O} + V_{N_2}}{22.4}\right) \tag{5}$$

Here, M is the amount in kilogram of dry, ash free biomass required to produce 1 Nm^3 of final product gas, M_O and A_S respectively denote for the biomass's moisture and ash percentages, based on proximate analysis. Let $V_{H_2}, V_{CO}, V_{CO_2}, V_{CH_4}, V_{H_2O}, V_{N_2}$ denote the volume fractions of each element contained in 1 Nm^3 of product gas, including hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), water vapour (H_2O), and nitrogen (N_2). M_A represents the mass of air in kg/kg of biomass while O_A and N_A are mass fractions of oxygen and nitrogen respectively in the air supplied. M_S indicates the mass of superheated steam provided/kg of dry ash free biomass while M_W denotes the mass of moisture content of biomass feedstock/kg of dry ash free biomass (George et al., 2016).

The carbon conversion efficiency (C_{eff}) of the gasification process will be less than 100% since some char will bypass the reaction zone. Experimental research (van der Meijden et al., 2010; Van Der Drift et al., 2001) on carbon conversion efficiency indicate that it varies depending upon the kind of gasification process from 85% to 95% (Baruah and Baruah, 2014). The volume fractions of the constituent gases, $V_{H_2}, V_{CO}, V_{CO_2}, V_{CH_4}, V_{H_2O}, V_{N_2}$and the quantity of dry ash free biomass (M) to create 1 Nm^3 product gas are among the seven unknowns in the modified global gasification reaction equation. Considering the equilibrium of the molar masses of carbon, hydrogen, oxygen, and nitrogen in the intake and outflow streams, four linear equations can be created. On the basis of the assumption that all of the volume fractions of the constituent elements of the resultant gas add up to 1, a fifth linear equation might be created. By assuming that all reactions taking place in the gasification space are in a condition of thermodynamic equilibrium, the following Eqs. 6–10 can be produced (George et al., 2016).

Carbon balancing:

$$V_{CO} + V_{CO_2} + V_{CH_4} = 22.4 \times C_{eff} \times \left(\frac{C}{100}\right) \times M \tag{6}$$

Hydrogen balancing:

$$V_{H_2} + 2 \times V_{CH_4} + V_{H_2O} = 22.4 \times \left(\left(\frac{M_s}{18}\right) + \left(\frac{H}{200}\right) + \left(\frac{M_W}{18}\right)\right) \times M \tag{7}$$

Oxygen balancing:

$$0.5 \times V_{CO} + V_{CO_2} + 0.5 \times V_{H_2O} = \left(0.623 \times (M_S + M_W) \times 0.701 \times \left(\left(\frac{O}{100}\right) + (M_A \times ER \times 0.23)\right)\right) \times M \tag{8}$$

Nitrogen balancing:

$$V_{N_2} = \left(0.8 \times \left(\frac{N}{100}\right) + 0.8 \times M_A \times ER \times 0.75\right) \times M \tag{9}$$

The volume fractions of all the components add up to 1, since the gasification product is considered to be 1 Nm^3.

$$V_{H_2} + V_{CO} + V_{CO_2} + V_{CH_4} + V_{H_2O} + V_{N_2} = 1 \tag{10}$$

The values of $V_{H_2}, V_{CO}, V_{CO_2} V_{CH_4}, V_{RMS}$ are 40.8, 18.37, 31.35, 8.91, 1.35 percent respectively taken from relevant literature (George et al., 2016). The carbon conversion efficiency denoted as C_{eff} is given as 85% (George et al., 2016). By substituting these values into Eq. 6 the amount of the mass of dry ash free biomass (M), in this case food waste, can be determined. The total amount of food waste M_{FW} required to produce 1 m^3 of product gas can then be calculated from M using proximate analysis of food waste using Eqs. 11–12.

The syngas is converted to hydrogen via the following Eqs. 11–12.

$$\text{Steam reforming}: CH_4 + H_2O \leftrightarrow \mathrm{CO} + 3H_2 \tag{11}$$

$$\text{Water gas shift reaction}: \mathrm{CO} + H_2O \leftrightarrow CO_2 + H_2 \tag{12}$$

For steam reforming, the hydrogen conversion efficiency denoted as $H_{eff}$is taken as 50% (Su et al., 2020b). As previously stated, the carbon conversion efficiency for gasification process denoted as C_{eff} is given as 85% (George et al., 2016). Hence the total amount of actual hydrogen produced from M kg of food waste producing 1 m^3 of syngas is calculated using Eq. 13 and values of $V_{H_2}, V_{CO} and V_{CH_4}$ taken from relevant literature (Midilli and Dincer, 2008).

$$H_2 = C_{eff}\left[V_{H2} + V_{co} + (H_{eff})V_{CH4}\right] \tag{13}$$

The amount of hydrogen (m^3) produced by1 kg of food waste is calculated using Eq. 14. The actual mass of hydrogen gas produced per annum from food waste is calculated using Eq. 15.

$$H_2(\mathrm{m^3 per\ kg\ of\ food\ waste}) = \frac{H_2}{M} \tag{14}$$

$$H_{2_{act}}(kg/yr) = H_2 \times FW_{gas} \times H_{2ND} \tag{15}$$

H_{2act} is the actual mass of H_2 gas produced (kg), FW_{gas} be the quantity of FW_{gas} that can be fed in the gasifier, H_{2ND} is the hydrogen gas density at NTP taken as 0.08375 kg/m^3 (Hydrogen).

2.4. Electricity generation potential from hydrogen

The actual hydrogen generated from the food waste fed to the gasifier is used to calculate the potential for electricity generation. The gasification plant's ability to generate electricity in kWh per annum and in kW is used to compute using Eq. 16 and Eq. **17** respectively (Cudjoe et al., 2021b).

$$H_{2EP}(kWh/yr) = H_{2_{act}} \times LCV_{H2} \times Turb_{eff} \times CAP_{fact} \quad (16)$$

$$G_{plant}(\mathrm{KW}) = \frac{H_{2EP}}{8760} \quad (17)$$

Where, LCV_{H2} is the hydrogen lower calorific value and is given as 33.33 kWh/kg (Ayodele et al., 2019). $Turb_{eff}$ is the electricity production efficiency of hydrogen fired turbine and is provided as 31.1% (Wei et al., 2023), *CAPfact*, is the capacity factor and is given as 85% (Ogunjuyigbe et al., 2017). In this study, the potential of FW generation and electricity generation from the FW is calculated for the year 2022–2050. The Bangladesh Bureau of Statistics (BBS) examined data on food waste production and the average per capita waste creation trend to forecast the generation of food waste (FW) till the year 2050. The proximate and ultimate analysis of FW as well as atomic mass ratios of different element are presented in Table 1 and Table 2 respectively.

2.5. Analysis of economic feasibility of biomass to electricity project

Total life cycle cost (TLCC), net present value (NPV), investment payback period (IPBP), levelized cost of energy (LCOE), and internal rate of return (IRR) were the foundations for the projects' economic analyses. The project has a useable life from 2023 to 2042, which is the same time period as the study on the availability of food waste. The total life cycle cost (TLCC) of a project includes the cost of ownership and management in its entirety. The total life cycle cost of projects was determine using Eq. 18.

$$TLCC = Cap_{cst} + \sum_{n=0}^{t} \frac{Op_{cst}}{(1+\tau)^n} \quad (18)$$

Cap_{cst}stands for the project's initial investment cost, Op_{cst} for its operating and maintenance costs, τ for the nominal discount rate, which is specified as 10% (I. and T. Dolf Gielen,Director, 2012), and t is the time period of project.

The calculation of initial investment costs includes capital expenditures for land acquisition, construction, equipment procurement, installation, and other associated infrastructure. Detailed cost estimates are derived from industry-standard databases, quotations from suppliers, and expert consultations which are incorporated into Eq. 20 to give initial investment costs as a function of plant capacity in kW (Cudjoe et al., 2020) $4339 is taken as initial investment cost per unit kilowatt of power produced. The operating and maintenance costs are estimated by considering factors such as labor, raw materials, utilities, and regular maintenance and is considered equal to sum of 3% of initial investment cost and 0.5% of plant capacity in kWh/yr (Cudjoe et al., 2020) Operational costs are estimated using Eq. 21. The gasifier plant's proposed rated capacity in kWh/year and kW is given by Eq. 16 and Eq. **17** respectively (Silveira et al., 2012).

$$Cap_{cst} = \$4339 \times G_{plant} \quad (19)$$

Table 1
Proximate and Ultimate analysis of food waste (Su et al., 2020a), (Kalanatarifard and Su Yang, 2012).

Proximate analysis		Ultimate analysis	
Volatile matter:	5%	HHV (MJ/kg)	18
Fixed Carbon:	6%	C	50.86%
Moisture:	75%	H	7.75%
Ash:	14%	O	42.76%
-	-	N	1.26%
-	-	S	0.13%

Table 2
Atomic ratios of the different element (Su et al., 2020a).

Element	H/C	O/C	S/C	N/C
Molar mass	1.83	0.63	0.001	0.02

$$Op_{cst} = [0.03 \times Cap_{cst}] + [0.005 \times H_{2EP}] \quad (20)$$

Positive and negative cash flows from the project period are both included in the net present value, which is discounted to the present. A project is considered economically unfeasible when the net present value is negative (Cudjoe et al., 2020). Eq. 21-**29** was used to calculate the net present value of the gasification projects.

$$\boldsymbol{NPV}_{(C)} = \sum\nolimits_{n=0}^{y} \frac{\boldsymbol{C_n}}{(\boldsymbol{1}+\boldsymbol{\alpha_r})^n} = \boldsymbol{INV}_{CST} + \frac{\boldsymbol{C_1}}{(\boldsymbol{1}+\boldsymbol{\alpha_r})^{\boldsymbol{1}}} + \frac{\boldsymbol{C_y}}{(\boldsymbol{1}+\boldsymbol{\alpha_r})^{y}} \quad (21)$$

$$C_n = Gas_{rev} - OP_{cst} - Cap_{cst} - Tax \quad (22)$$

$$Gas_{rev} = H_{2EP} \times \pi_{fit} \quad (23)$$

$$\mathrm{Tax} = \mathrm{Gas}_{\mathrm{profit}} \times \mathrm{T_r} \quad (24)$$

$$Gas_{profit} = Gas_{rev} - OP_{cst} \quad (25)$$

$$\alpha_r = \frac{1+\tau}{(1+\mathrm{ln}_r)^n} - 1 \quad (26)$$

C_n is the net cash flow, Gas_{rev} is the gasification project revenue, α_r is the real discount rate annually, *Tax* is the tax paid on the project profit, and π_{fit} is the feed-in tariff for biomass source electricity generation in Bangladesh, which is taken as $0.106/kWh (S. ISLAM). The gasification project's profit is calculated as Gas_{profit} with the marginal tax rate T_r assumed to be 25% (act GRA. Ghana, 2015), the inflation rate ln_r considered to be 9.3% (Ghana Statistical service GSS, 2010) and the project's financial period estimated to be 20 years.

The investment payback period (IPBP) is the time frame in which project investments start to show a return on their investment. The investment cost of the project currently equals its costs for operation and maintenance. The investment payback period (discounted) for the gasification project was calculated using Eq. 27.

$$\mathrm{IPBP}_{(C)} = \frac{TLCC(\$)}{Gas_{profit}(\$/Y)} \quad (27)$$

The levelized cost of energy (LCOE), one of the critical economic metrics used to assess the profitability of projects like waste-to-energy projects, identifies the lowest cost of electricity generated at which the project is commercially viable. the levelized cost of energy ($/kWh) for the projects was calculated using Eq. 28 (Short et al., 1995).

$$LCOE = \frac{TLCC_{(c)}}{H_{2EP}} \times \frac{\tau(1+\tau)^n}{(1+\tau)^n - 1} \quad (28)$$

IRR, which is or internal rate of return, is a rate of discount that causes all projected cash flows to have a net present value of zero. A statistic used in capital planning to evaluate the viability of anticipated investments is the internal rate of return. The project is deemed financially unviable if the internal rate of return is equal to zero or higher than the projected value (De Oliveira-De Jesus, 2019). The internal rate of return for the projects considered in this analysis is determined using Eq. 29, where L_n is the net cash flow, y is the holding period, and n is each period.

$$0 = NPV = \sum\nolimits_{n=0}^{y} \frac{L_n}{(1+IRR)^n} \quad (29)$$

2.6. Environmental feasibility analysis

2.6.1. Pollutant indicator and ecological efficiency

When it comes to environmental considerations, we believe the best fuel is one that burns with the least amount of CO_2 emissions. The pollutant indicator defined in Eqs. 30–31 (Silveira et al., 2012; Coronado et al., 2010) is used.

$$\pi_g = \frac{(CO_2)_e}{Q_i} \tag{30}$$

$$Q_i = LHV_{H2} \times x \tag{31}$$

Where x is the expected proportion of hydrogen in syngas at 65.4% (Silveira et al., 2012), Q_i is the fuel's low heating value (LVH) expressed in megajoules per kilogram and LHV_{H2} is lower heating value of hydrogen taken as 120 MJ/kg. $(CO_2)_e$ is the carbon dioxide equivalent gas emission represented in kilograms per kilogram of fuel and π_g is the pollutant indicator, given in kilograms per megajoule. The Eq. 32 is determined as the equivalent carbon dioxide $(CO_2)_e$ which is a hypothetical pollutant concentration factor (Silveira et al., 2012).

$$(CO_2)_e = a(CO_2) + b(CO_4) + c(CO) + d(SO_2) + e(NOx) + f(PM) \tag{32}$$

In here, on the right side $a = 1, b = 25, c = 1.9, d = 80, e = 50, f = 67$ are the emission coefficients. These are all based on the global warming potential (GWP) of each pollutant and are measured in carbon dioxide (CO_2) equivalent gas emissions. Because it is unlikely to lead to global warming, carbon dioxide released during burning is regarded as carbon neutral and is not taken into consideration. Hydrogen combustion emissions with respect to carbon dioxide equivalent (kg CO_2) is determined by Eq. 33 and Eq**. 34**.

$$(CO_2) = Q_I \times \gamma \times GWP \tag{33}$$

$$\gamma = \frac{\alpha \times 0.4556}{1020 \times 1055} \tag{34}$$

Here γ is the emission factor expressed in kilogram per megajoules, α is the emission factor represented in pounds per standard cubic foot. The values of α for CO, SO_X, NO_X, CH_4 and PM are taken as 84, 0.6, 32, 7.6 and 2.3 respectively (Braga et al., 2013). The term "ecological efficiency" refers to the evaluation of a process based on the pollutants it emits as compared to integrated pollutants emissions $(CO_2)_e$ in a hypothetical comparison to the air quality standards already in place. When determining specific emissions expressed as a fractional amount, the conversion efficiency is taken into account (Coronado et al., 2010; Demirbas et al., 2015).

$$\xi = \sqrt{\frac{0.204 \times \eta_{system} \times \ln(135 - \Pi_g)}{\eta_{system} + \Pi_g}} \tag{35}$$

Where $\eta_{system} = \eta_R + \eta_B$ is the sum of the boiler and reformer system efficiencies, which is 80% in each case (Demirbas et al., 2015). Ecological efficiency has a range of 0–1. The least polluter is indicated by a value of 1, while the biggest polluter is indicated by a value of 0.

2.6.2. Determination of the amount of fossil fuel displaced

The use of hydrogen gas will substitute for some of the diesel or gasoline. As a result, it is possible to determine the amount of fuel (diesel fuel) displaced in liters annually by using the heating values (LHV) of the fuel (diesel fuel) relative to hydrogen. The amount of fossil fuel displaced is calculated using Eq. 36.

$$A_{Fuel} = \frac{V_{H_2,compressed} \times LHV_{H_2} \times \eta_{FC} \times H_{density}}{\left(\frac{LHV_{Fuel}}{3.6}\right) \times D_{Fuel} \times \eta_{Fuel}} \tag{36}$$

Where $LHV_{Fuel}$is the lower heating value of diesel fuel, that is assumed to be 42.5 MJ per kg (Nizami et al., 2017; Ayodele and Ogunjuyigbe, 2015), η_{Fuel} is the diesel fuel generator's efficiency, that is assumed to be 33% (Ayodele and Ogunjuyigbe, 2015; Coronado et al., 2010), 3.6 is the conversion factor from MJ to kWh, and D_{Fuel} is the density of diesel fuel, which is assumed to be 0.837 kg per liter (Nizami et al., 2017).

2.6.3. Estimation of carbon dioxide emission reduction

A lot of CO_2, NO_2, and SO_x gases are released into the atmosphere when too much fossil fuel is burned. We should utilize fewer fossil fuels if we wish to reduce environmental pollution. The Eq. 37 is used to determine how much CO_2 and CO emissions in kilograms annually could be avoided by utilizing H_2-based fuel cells instead of using diesel fuel.

$$E_{CO_2} = A_{Fuel} \times SE_F \tag{37}$$

Where SE_F denotes the air pollutant's specific emission factor, which could be either CO_2 or CO. The emission factor of diesel fuel for CO_2 is estimated to be 2.7 kg per liter (T. and M. L. Kefalew, 2021) and CO is taken to be 0.00766 kg per liter (T. and M. L. Kefalew, 2021).

2.6.4. Equivalence of hydrogen fuel with fossil fuels

We can use the potentiality of hydrogen as an alternative to fossil fuels not only it will help us from environmental pollution but also, we can save money because it is cheaper than fossil fuels. Hydrogen equivalent to different fossils fuels is estimated using Eq. 38.

$$\text{Equivalence} \quad H_2 = CCF \times H_2 \tag{38}$$

Where H_2 is the mass of hydrogen (kg) and CCF refers to the conversion coefficient factor for fossil fuels. CCF for LPG 2.60 kg/kg^3 of hydrogen (Zhang and Yang, 2015). LNG is for 2.46 $kg^{/kg}$ of hydrogen (Zhang and Yang, 2015) diesel is 2.79 kg/kg of hydrogen (Zhang and Yang, 2015) petrol is 2.76 kg/kg of hydrogen (Zhang and Yang, 2015), coal is 4.14 kg/kg of hydrogen (Zhang and Yang, 2015) and for natural gas is 2.55 kg/kg of hydrogen (Amoo and Fagbenle, 2013; Cudjoe et al., 2021c).

3. Results and discussions

3.1. FW, H_2 and Electricity generation potential for various year in Bangladesh

The food waste (FW) generation potential and the hydrogen generation potential per annum during the twenty-year period of 2023–2042 is depicted in Fig. 4 while Fig. 5 illustrates the electricity generation potential per annum during the same period from gasification of food waste. It has been observed that the rates of successive FW generation and hydrogen energy potential from food waste gasification are rising as shown in Fig. 4. It is seen that the FW generation was 23 million tons in the year 2023 and rises to 110 million tons in 2042, a 378% increase. Cudjoe et al (Seglah et al., 2023). did a similar study on two cities of Ghana. According to their findings, Kumasi city generated 915,000 t/y to 3159,000 t/y of food waste during the project's implementation, an increase of 245.2%, while Accra had the potential to generate 899, 000 t/y to 3359,000 t/y during the project's life cycle. This is due to the exponential population growth and the expected economic advancement. A nation's economic development is also correlated with the rate of FW generation. The FW generation rate of a country rises according to its rate of economic expansion. From Fig. 4, it is seen that the hydrogen generation potential calculated for the year 2023 is 0.52 million tons, while it is projected to be around 2.46 million tons in the year of 2042. Seglah et al (Batteries). discovered that the hydrogen gas potential for four Ghanaian cities had a capacity of 0.08639 million tons of hydrogen per year and 2.073 million tons of hydrogen for all locations from 2007 to 2030. Their findings also indicated that the four cities' combined electrical potential from 2007 (98.20 GWh) will steadily rise to 215.42 GWh by 2030, a net 119.5 increase. Similarly, from Fig. 5, it is observed

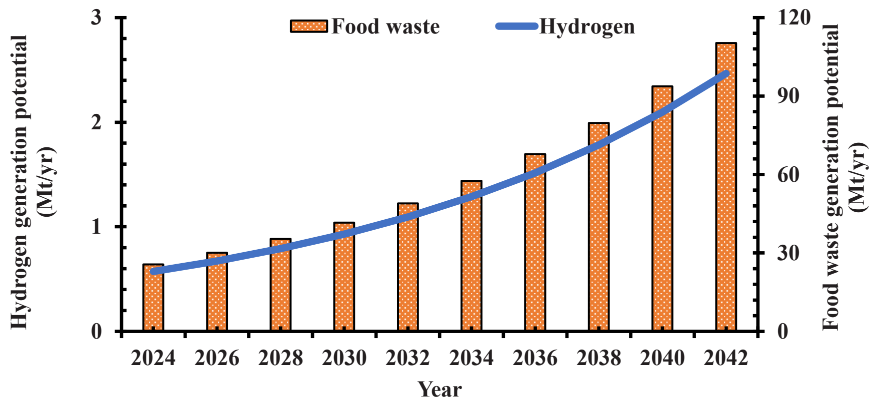

Fig. 4. Food waste generation trend and hydrogen generation potential per annum in Bangladesh.

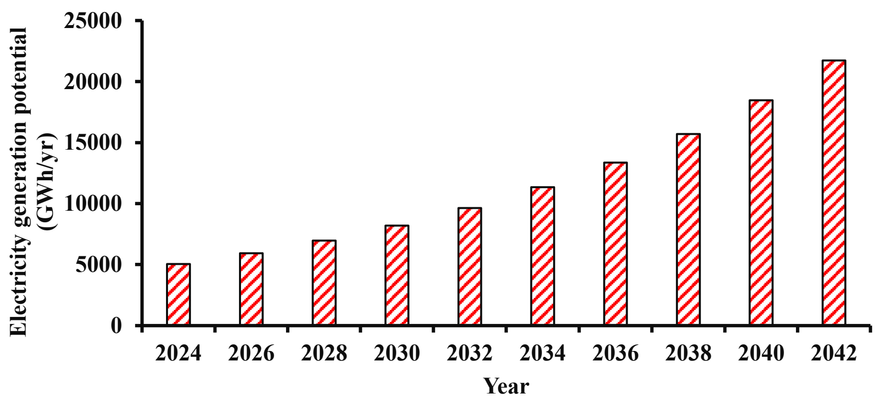

Fig. 5. Electricity generation potential from FW in Bangladesh.

that the electricity potential estimated in the year 2023 is 4657 GWh, which is projected to increase to 21,729 GWh in the year of 2042 in Bangladesh, a net 366% increase. As FW generation has expanded, so has the possibility for producing corresponding amounts of energy. The findings showed that the potential of hydrogen and electricity were positively correlated. This huge increase in electricity generation potential makes hydrogen energy a viable option for future power generation.

Fig. 6 depicts the hydrogen and electricity generation potential for different cities in Bangladesh during the year 2023. Due to its high population density, Dhaka has the highest potential for both hydrogen generation and electricity production among all Bangladeshi cities, with a projected capacity of almost 2340 GWh in 2023. Additionally, Rangpur in Bangladesh has the lowest potential for producing electricity, which is 19.56 GWh.

3.2. Analysis of the proposed gasification plant's economic viability

Total life cycle cost (TLCC), net present value (NPV), investment payback period (IPBP), levelized cost of energy (LCOE), and internal rate of return (IRR) were the foundations for the projects' economic analyses. The project's useable life is from 2023 to 2042, which is the same time period covered by the availability study of organic waste. The following are the anticipated key costs for generating hydrogen using a fluidized bed gasifier and food waste biomass: The fluidized bed gasifier, furnace, PPS system, and construction expenditures are all included in

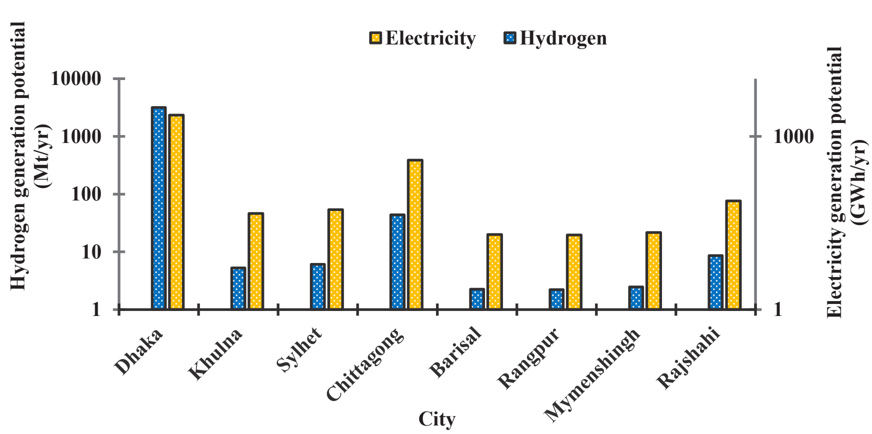

Fig. 6. Hydrogen and Electricity generation potential for different cities in Bangladesh during the year 2023.

the system's planned capital cost of 11,669.4 million USD. The costs of operation, interest, maintenance, and other charges are displayed in Table 3. The net operational and maintenance cost, revenue and profit for the project are 1468.745 million USD, 23,715.63 million USD and 22,246.89 million USD respectively. The hydrogen production cost was found by dividing annual hydrogen production by annual total cost. The levelized cost of energy is 0.0668 /kWh and cost of hydrogen per kg of food waste is 2.05 $/kg. The results of the planned gasification plant's economic viability analysis are also shown in Table 3. Despite having a projected 12,358.48 million USD 20-year total life cycle cost, the project's investment payback period (IPBP) is only 11 years. The project also has a positive net present value (3669.52 million USD), making it an economically viable one. It is obvious that the project's owner, policymakers, and a developing country like Bangladesh will all profit from its successful execution. For the goal of validating this study, the resulting hydrogen cost values ($/kg of H_2) are compared with some experimental work in Table 4. It is seen that the results found in this study are remarkably similar to other gasification results in the relevant literature.

Fig. 7 explains the cost analysis for the different cities. Among the several cities examined in this research, Dhaka has the highest net present value (2365 M$), as shown in Fig. 7. In addition, Dhaka city requires the greatest initial investment of 7197 M$, followed by Chittagong with a 1012 M$ requirement. Rangpur requires the least amount of investment ($50 M) of the cities under consideration. Dhaka has the largest income of $14,800 M$ and Chittagong has the second-highest revenue of $2200 M$, with Barisal, Rangpur, and Mymensingh having the lowest revenue of about $100 M$. The payback period for Dhaka City is the shortest (5.48 years), while those for the remaining study locations range from 9 to 13 years, as illustrated in Fig. 8. Dhaka generates substantially higher initial revenues than other cities, which shortens the payback period. The investment payback period estimates in this study are very comparable to those in a study identical to it done by Cudjoe et al (Batteries). on the Ghanaian cities of Accra and Kumasi. According to their findings, Accra's project has an investment payback duration of 7.9 years, whereas Kumasi's is 8.1 years. The levelized cost of electricity for every city in Bangladesh examined in this study is 0.06 dollars per kWh. These figures closely resemble those from the Cudjoe et al (Batteries). study, which found that Accra's value was $0.0891/kWh and Kumasi's was $0.0906/kWh. Additionally, IRR levels in Bangladesh's cities are all around 14%. Accra's project has an internal rate of return of 20%, whereas Kumasi's is 19.6%. Chittagong's projects have a net present value of 254 million USD, which is comparable to the findings of Cudjoe et al (Batteries)., who found that Accra's projects have a net present value of 217.8 million USD and Kumasi's projects have a net present value of 156.1 million USD.

3.3. Ecological efficiency

The carbon dioxide equivalent $(CO_2)_e$ of burning hydrogen in the boiler is calculated to be 0.10845 kg per kilogram of syngas. The pollution indicator has a value of 9.038 $\times 10^{-4}$ kg per MJ. The ecological efficiency (ε) is calculated which takes into consideration the entire process efficiency (boiler and reformer considered as 80% respectively) (Demirbas et al., 2015). The results are shown in Table 4. The steam reforming process for the production of hydrogen achieves an incredible ecological efficiency of 99.98%, this study demonstrates unequivocally that it is ecologically friendly. This number is strikingly similar to the ecological value of 94.95% established in a previous investigation (Demirbas et al., 2015).

Table 3
Techno-economic feasibility of the proposed project.

Components	Unit	Value
	Cost	
Initial investment cost	M$	11,669.4
Operation & maintenance cost	M$	1468.74
Total Life Cycle Cost	M$	12,358.48
Tax paid on profit	M$	22,246.89
	Benefits	
Net present value	M$	3669.52
Investment Payback Period	Year	11
Revenue	M$	23,715.63
Profit	M$	22,246.89
Net Cash Flow	M$	16,685.17
Internal Rate of Return	%	14
Hydrogen production cost	$/kg	2.05
Levelized Cost of Energy	$/kWh	0.067

Table 4
Result for ecological efficiency.

Element	$(CO_2)_e$ (kg/kg of syngas)	π_g(kg/MJ)	ε(%)
Value	0.10845 s	9.038 $\times 10^{-4}$	99.98

3.4. Reduction of diesel fuel usage, carbon dioxide, and carbon monoxide emissions

Fossil fuels are costly and damaging to the environment. The majority of cars in Bangladesh are powered by fossil fuels. Typical fuels for vehicles include diesel, gasoline, LPG, and HFO. When these fuels are used, the environment is exposed to greenhouse gases and other air pollutants. Fuel cells can take the place of diesel-fueled engines in both the propulsion of vehicles and the production of energy (diesel engine generators). The amount of diesel fuel that can be displaced is presented in Fig. 9. It has been found that Bangladesh as a whole may save 1428 million liters of diesel fuel year in 2023. This would save roughly 1470 million USD based on the present regional selling price of 1.033 USD per liter of fuel. The national budget may include a large percentage of this enormous figure. Fig. 9 also displays the outcomes of carbon dioxide and carbon monoxide that was stopped from entering the atmosphere. According to estimates, using diesel fuel to generate electricity might prevent 10000 kg of carbon monoxide and 3.55 million kg of CO_2 from being released into the atmosphere. These values are similar to study by Seglah et al. (2023) which showed by avoiding the consumption of diesel fuel, of 7.446 million liters of diesel fuel were used in all the chosen cities, preventing 16.031 million kg of CO_2 and 45.47 thousand kg of CO from entering the atmosphere as a result of the burning of diesel fuel to produce electricity. Savings of 42.04 million tons CO_2 equivalent are possible. In all the chosen cities, using fuel cells powered by hydrogen gas instead of diesel fuel could save 7.44 million liters of diesel fuel, preventing 16.031 million kg of CO_2 and 45.47 thousand kg of CO from entering the atmosphere from the burning of diesel fuel for electricity production.

Fig. 10 shows the projected financial gains and decrease in CO_2 emissions from using gasification technology to generate electricity from Bangladesh's largest cities between 2023 and 2042. The city of Dhaka gains a lot from the electricity produced by gasification technology. According to Fig. 10, the city of Dhaka will see a rise in revenue from 272 million dollars in 2023–1540 million dollars in 2042. In Rajshahi, electricity-related income was 8.75 M$ in 2023 compared to a 40 M$ increase in 2042. Chittagong is second in terms of economic and environmental advantages, followed by Rajshahi, while Khulna provides advantages comparable to those of Rangpur. A sizable quantity of CO_2 reduction is accomplished throughout the gasification process (Fig. 10). For instance, in the city of Dhaka, a reduction in CO_2 of 1.9 million tons is noted in the year 2023, rising to 12 million tons in the year 2042. The other big cities show comparable tendencies as well.

Fig. 11 displays the amount of equivalent fossil fuel that was replaced by hydrogen produced via FW gasification in various cities in Bangladesh from 2023 to 2042. Dhaka is seen to save the largest amount of diesel fuel, followed by Chittagong and the Rajshahi while Rangpur, Mymensingh and Barisal has the least. Sylhet is seen to surpass Rajshahi

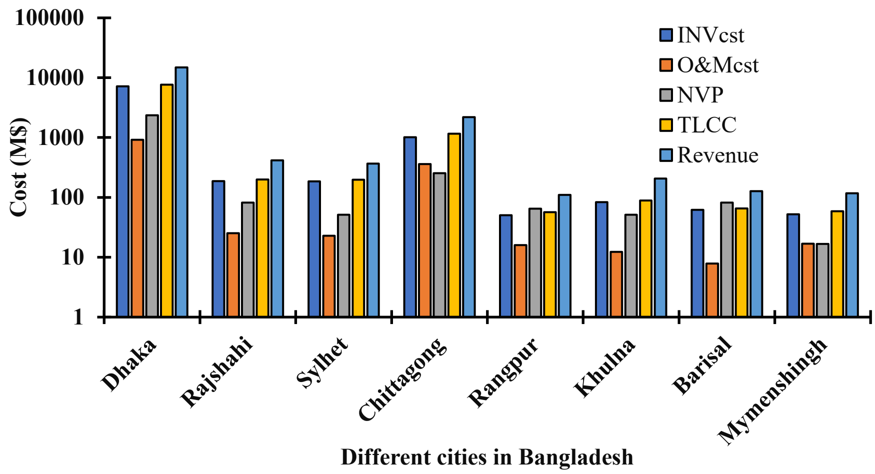

Fig. 7. Economic analysis of gasification plant for different cities in Bangladesh.

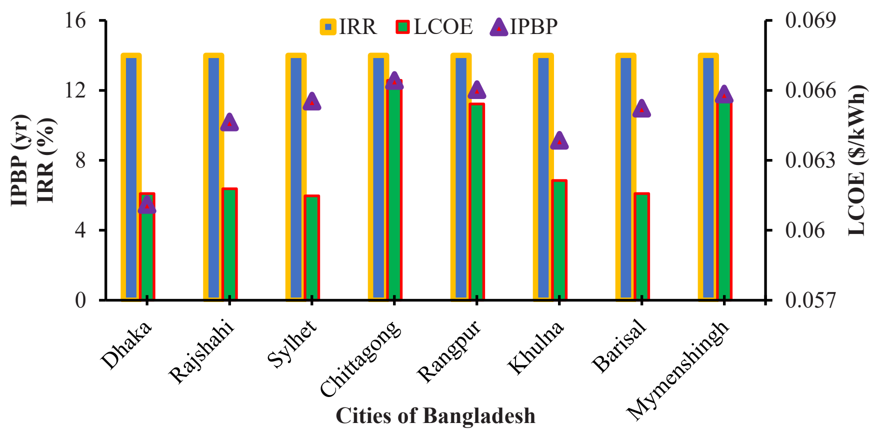

Fig. 8. Economic analysis of gasification plant for different cities in Bangladesh.

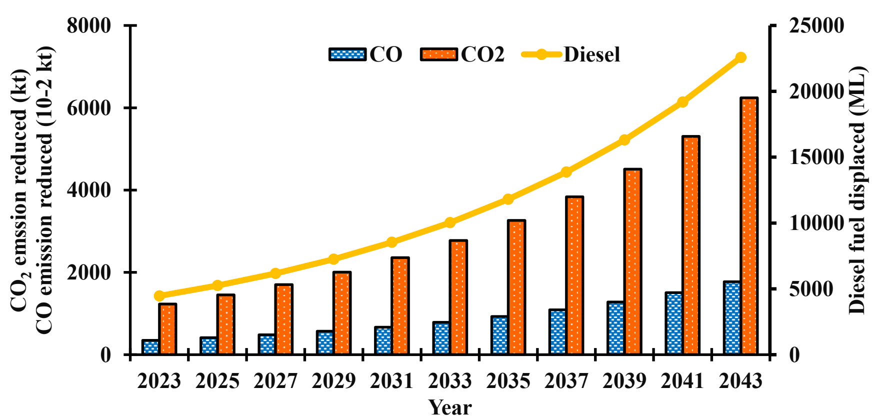

Fig. 9. Fossil fuel displaced, CO_2 and CO emission reduction per year from 2023 to 2043.

in terms of saving fossil fuel using gasification technology by 2043. In 2023, Dhaka saves 717 million liters of diesel fuel; in 2042, that number rises to 4067 million liters. Similar rising trends are visible in the other cities.

3.5. A comparative analysis of hydrogen and fossil fuels consumption

Hydrogen is considered as one of the most promising clean and renewable fuels. The hydrogen fuel generated from food waste in 2023 is 0.46 million tons as calculated in this study. Fig. 12 shows the equivalent mass of different fossil fuels of the same energy potential as that of hydrogen generated from food waste. As the HCV of hydrogen is high compared to fossil fuels, a significantly smaller mass of hydrogen can displace a larger mass of fossil fuels. The hydrogen potential in 2023 can substitute 1.9 million tons of coal, 1.3 million tons of diesel and 1.19 million tons of natural gas. The largest quantity of fossil fuel that can be replaced by H_2 is coal, closely followed by diesel. Hence hydrogen generation potential from food waste from gasification can save 228

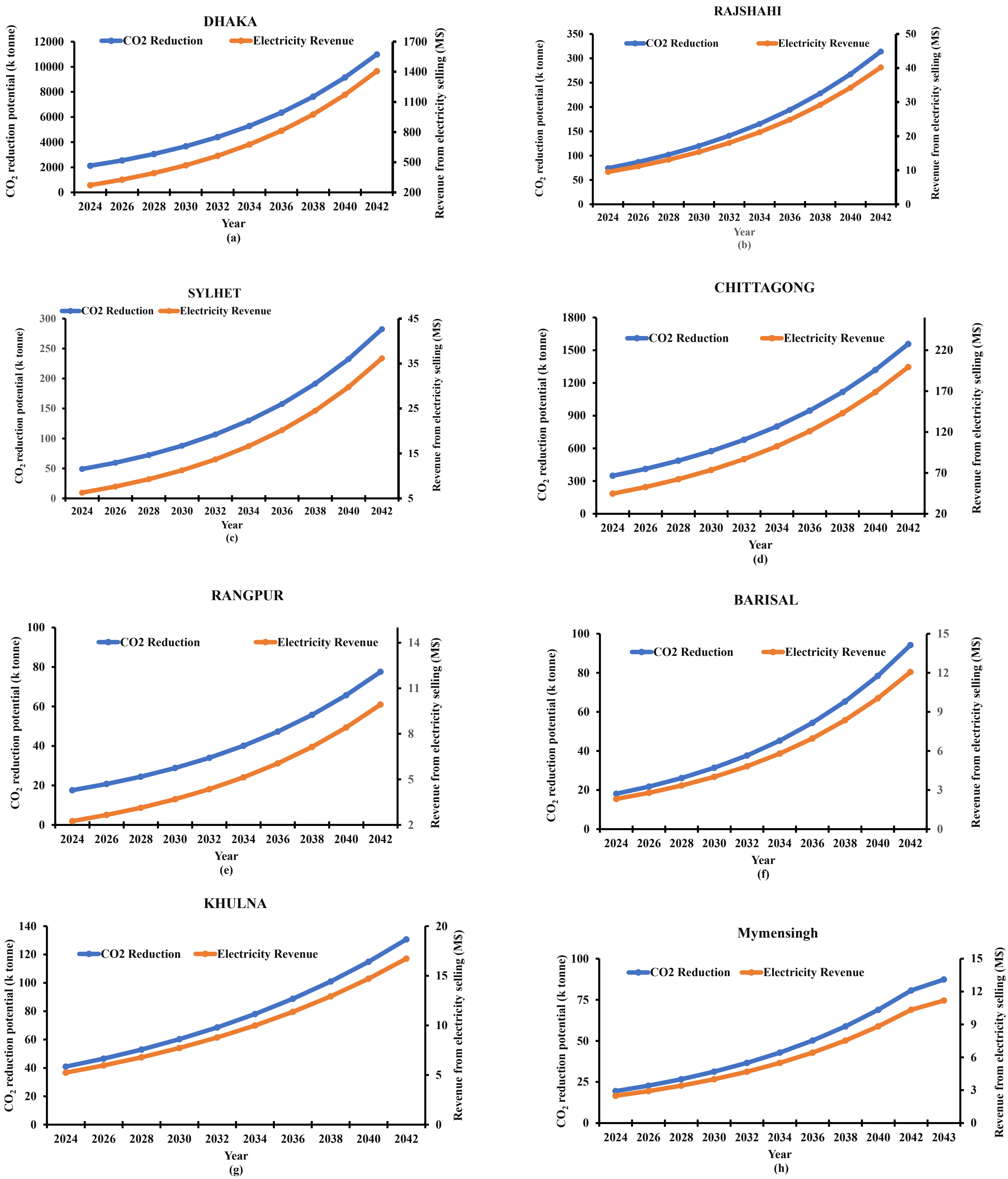

Fig. 10. Estimated CO_2 emission reduction and electricity revenue for different regions in Bangladesh.

million USD of coal.

3.6. Outcomes of food waste to hydrogen with existing literature

Several important causes can be linked to the observed increase in the potential for food waste generation from 2023 to 2042. Waste output has increased overall as a result of changes in lifestyle and consumption patterns brought about by rapid urbanization and industrialization. The amount of food waste generated also follows an increasing trajectory as urban centers grow and industrial activity increases. This pattern emphasizes how crucial it is to adjust waste management techniques in light of changing society dynamics. The potential for producing power

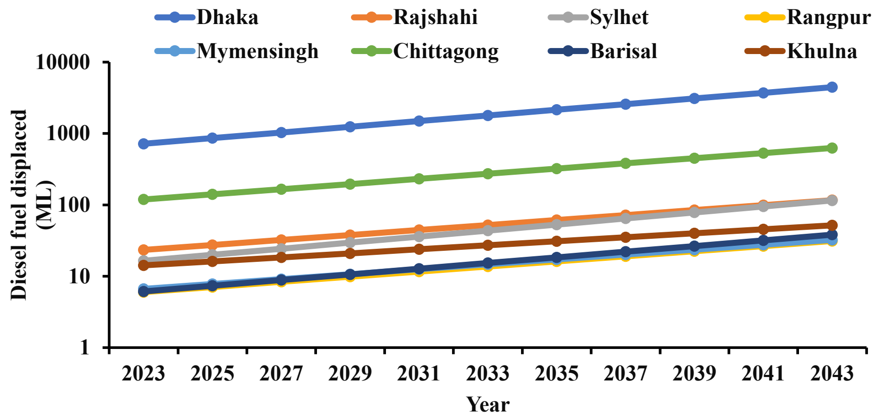

Fig. 11. Amount of equivalent fossil fuel displaced by hydrogen from gasification of FW in different cities of Bangladesh.

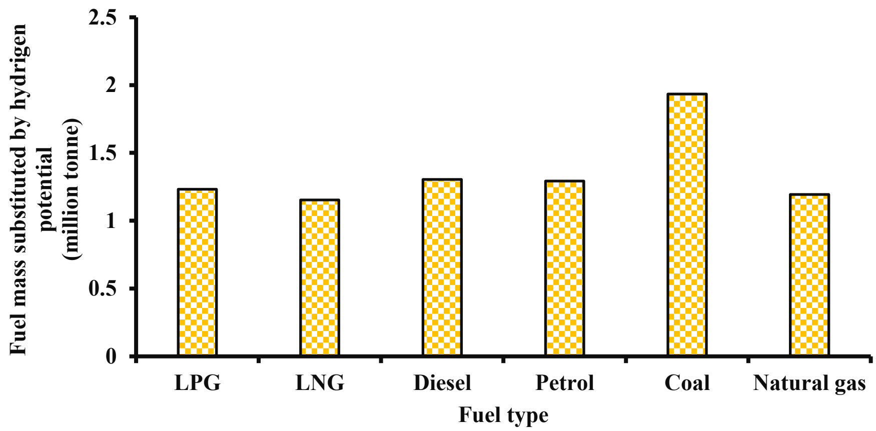

Fig. 12. Hydrogen equivalent to different fossil fuel.

from food waste has increased significantly, from 489 MW in 2023–2480 MW by 2042. This indicates that there is still undiscovered energy in organic waste. This increase can enhance infrastructure and expanding operations help to extract more energy from food waste, establishing it as a viable source of renewable energy. The analysis shows that it is economically feasible to use gasification to turn food waste into hydrogen in all of Bangladesh's main cities. This result supports the viability of waste-to-energy initiatives from an economic standpoint in highly populated urban regions. Factors including the quantity of food waste, the affordability of gasification technology, and the rising demand for alternative energy sources are probably going to have an impact on the economic viability. Table 5 offers a thorough analysis of the expenses associated with producing hydrogen utilizing different methods and input materials. This comparison sheds light on the process's viability from an economic standpoint. With a production cost of $2.05 per kilogram of hydrogen, the use of the steam reforming process on food waste in Bangladesh is found to be a cost-effective approach in the current study. According to this research, food waste can be used as a competitive and profitable feedstock to produce hydrogen in Bangladesh. When comparing alternative techniques, such as electrolysis in China, the production cost is significantly greater, at $10 per kilogram. The data also demonstrates the wide variety of feed sources available, with woody biomass in Japan and biomass residue in China exhibiting varying cost structures per kilogram at $1.69 and $4.28, respectively. This comparative research highlights how crucial feed material selection and technology selection are to the economic feasibility of hydrogen production. The results of this study add significantly to the body of knowledge by demonstrating the possibility of food waste as an economically advantageous fuel for the production of hydrogen sustainably.

It is possible to replace a large portion of the combustion of diesel fuel with power produced from hydrogen gas. A significant decrease in the use of conventional fossil fuels is shown by the reported displacement of 1428 million liters of diesel fuel. This decrease tackles issues with diesel combustion pollutants, such as particulate matter and nitrogen oxides, and also represents a step toward cleaner energy. The

Table 5
Comparison of Hydrogen production cost with previous literature.

Techniques	Research type	Location	Feed materials	Production cost ($/kg)	References
Steam reforming process	Technical	Bangladesh	Food waste	2.05	**Present study**
Electrolysis	Technical	China	Food waste	10	(Iwasaki, 2003)
Pyrolysis with high-pressure	Technical	Japan	Woody Biomass	4.28	(Lv et al., 2008)
Gasification with CO shift	Technical	China	Biomass residue	1.69	(Sara et al., 2016)
Gasification	Technical	India	Biomass	2.11	(Yukesh Kannah et al., 2021)
Gasification	Technical	Italy	Food waste	13.55	(Dinesh et al., 2018)
Dark fermentation	Technical	India	Food waste	3.20	(Mohammed et al., 2011)

amount of diesel fuel that can be saved by using hydrogen results in a noteworthy decrease in carbon dioxide emissions. There will be a significant environmental benefit from the estimated 3.85 million tons of carbon dioxide emissions that are prevented. This is in line with international efforts to slow down climate change by switching to greener forms of energy, indicating that hydrogen made from food waste can be a useful addition to these programs. With an astounding efficiency rate of 99.98%, the study highlights the ecological effectiveness of employing hydrogen as a source of energy generation. Because hydrogen burns cleaner than other fuels, it has a high ecological efficiency and leaves a smaller environmental impact. The results demonstrate hydrogen's potential as a green energy source that supports ecological preservation and sustainability objective.

4. Applications and storage techniques of hydrogen energy

The term "hydrogen economy" in the context of transportation refers to the widespread adoption and use of hydrogen as a sustainable and clean energy source for a variety of transportation modes, including vehicles like automobiles, trucks, buses, trains, ships, and even aircraft. The goal is to employ hydrogen as a cleaner alternative to conventional fossil fuels, which increase glasshouse gas emissions and air pollution. Both fuel cell electric cars (FCEVs) and hydrogen internal combustion engine vehicles (HICEVs) use hydrogen as a fuel in the hydrogen economy for mobility. In FCEVs, hydrogen and oxygen combine to form electricity in a fuel cell, which drives the vehicle's electric motor. Since water vapor is the only result of this process, FCEVs are emission-free at the point of usage (Zeng and Zhang, 2010). Vehicles fueled by hydrogen emit no harmful pollutants, improving the air quality and lowering glasshouse gas emissions. Although only a few of these are currently commercially viable, hydrogen may be produced from a variety of sources, including renewable energy (such as wind, solar, and hydroelectric power), offering a method to decarbonize transportation. It functions with fuel cells, and the two together might be one of the answers for a sustainable energy source (Semente et al., 2023a).However, as will be covered later, there are a number of obstacles to be solved before hydrogen is widely used in transportation. Green hydrogen is a type of hydrogen created by the electrolysis of water (H_2O), which uses electricity to separate the two elements into hydrogen (H_2) and oxygen (O_2). Since the electricity required for this procedure is produced using renewable energy sources like hydropower, wind, or solar energy, the creation of hydrogen is both carbon dioxide-free and environmentally friendly. Green hydrogen is thought of as a clean and sustainable energy carrier because the source of the electricity is renewable (Veziroğlu and Şahin, 2008). Numerous industries, including those in the home, workplace, and even space, use hydrogen. The biggest users of hydrogen are ptero-chemistry, various chemical products, and ammonia production (Sharma and Ghoshal, 2015; Zheng et al., 2012; Xu et al., 2009). The synthesis of ammonia, fertilizers, desulfurization, hazardous waste treatment, chemical plants, food preparation, and the synthesis of different fuels including methanol, ethanol, and DME are just a few of the many uses of hydrogen. Additionally, hydrogen is used in high-temperature industrial furnaces, gas to liquid technologies, rocket fuel, IC engine fuel, and Fischer-Tropsch synthesis (Sharma and Ghoshal, 2015). Future applications of hydrogen are anticipated to take the place of fossil fuels frequently, especially in transportation, resulting in less pollution and a cleaner environment (Xu et al., 2009). There is various method of hydrogen storage such as compressed gaseous hydrogen storage, liquid hydrogen storage, cryo-compressed hydrogen storage, metal hydride hydrogen storage etc. All of the methods have their advantages and disadvantages as well.

Compressed Gaseous Hydrogen Storage is basically a high-pressure storage which is a popular technique for storing hydrogen, but it has drawbacks because of its pricey production and development (Barthelemy et al., 2017). Worldwide, high-pressure hydrogen storage is used in over 80% of hydrogenation processes for both storage and delivery (Principi et al., 2009; Sakamoto et al., 2016). In addition, up to 700 bar or 1000 bar of pressure are required for vehicle applications (Barthelemy et al., 2017). The advantages of this method, which is commonly employed, include low energy consumption during storage, lower costs (at moderate pressures), rapid hydrogen inflation and release, and the capacity to release hydrogen at normal temperature even in cold. The density and energy volumetric density of hydrogen are improved as the pressure is increased, but safety issues are raised. Other techniques called Liquid hydrogen storage having substantial storage density of 70.9 kg-H_2/m^3 including advantages of storing pressure are two features of it, which requires a temperature of 20 K. For the liquefaction of hydrogen, large-scale liquefiers with huge capacities have been constructed (Hassan et al., 2021). LH_2 storage is appropriate for aviation and space applications that need large volumetric and gravimetric energy storage densities because it only uses around 35% of the energy in the hydrogen that is being stored (Blackman et al., 2006). Additionally, it is utilized for gas supply using big capacity vehicles. Another method called Cryo-compressed hydrogen storage technology in which, hydrogen is kept chilled below 21 K and stored as a cryogenic liquid. High energy consumption during liquefaction (approximately 30% of total hydrogen energy) and issues in creating adequate thermal insulation to reduce evaporation loss and assure safety are two main technical challenges it faces despite offering high mass and volume densities (Hong and Song, 2013). Another, attractive techniques named Metal hydride hydrogen storage which is use for storing and releasing hydrogen in a metal hydride, which is produced when molecular hydrogen interacts with metals or alloys (Hong and Song, 2013). Metal hydrides, composed of lightweight elements such as lithium, boron, nitrogen, magnesium, and aluminum, have shown potential for hydrogen storage when subjected to moderate pressure and low temperatures (Ma et al., 2013a). They are viewed as a safe way to store hydrogen due to their endothermic hydrogen release and relatively moderate working temperatures (Ma et al., 2013a, 2013b; Herbrig et al., 2013). Metal hydride hydrogen storage vessels have a high hydrogen storage volume ratio, high mass hydrogen storage density, excellent reversible cycle performance, and exceptional security (Hong and Song, 2013). However, there are certain disadvantages to metal hydrides, such as their weight for on-board storage, slow kinetics, low reversibility, and high dehydrogenation temperatures (Garrison et al., 2012). To improve their performance, processes of substitution and modification are studied. The three different kinds of metal hydrides are intermetallic, complex, and elemental; some of the latter are the most promising. The use of many chambers, the addition of aluminum foam or graphite, the use of heat exchangers, physical mixing, and the use of phase-change materials are just a few of the strategies that have been researched to address these issues (Hong and Song, 2013; Semente et al., 2023b; Sharma, 2022). Overall, metal hydride hydrogen storage is promising, but more study is needed to maximize its use and performance.

5. Challenges and solutions in implementing gasification projects in Bangladesh

Green hydrogen utilization possesses some technical challenges. Due to significant energy losses during the green hydrogen production process, fuel cell and electrolyzer systems are currently not competitive for a wide range of electrical end-use applications. Only roughly 38% of power can be converted to hydrogen and back to electricity (Agaton et al., 2022; Yue et al., 2021). The amount of energy needed to produce green hydrogen must come from renewable sources, which raises the investment cost in energy production. By making electrolyzer more efficient at working at partial loads and by putting waste heat recovery and reuse systems in place, efficiency might be raised by up to 70% (Yue et al., 2021). Because of their sensitivity to impurities, fuel cells require high-purity green hydrogen. For electrolysis at this purity level, clean water is necessary (Ishaq et al., 2022). If operating conditions are not properly optimized, the durability of electrolyzer and fuel cell components could result in performance losses, maintenance costs, and probable component degradation (Ren et al., 2020). The challenges for implementing hydrogen economy in renewable energy sector is presented in Fig. 13.

Given that hydrogen has a gas density of only 40.8 g/m^3, storing it is difficult. Due to the fact that hydrogen is a secondary (storage) energy source that must be produced from a main energy source and because reactions always experience losses throughout the conversion process, the cost of producing hydrogen is higher than the cost of the energy used to do so (Mah et al., 2019). Due to its low density, hydrogen must be stored at extreme pressure or in a liquefied state, both of which have consequences for safety and cost. Alternative storage technologies including liquid organic hydrogen carriers (LOHCs) and metal hydrides are now being researched. Besides technical barriers implementation of green hydrogen must overcome infrastructure challenges. Due to a lack of transportation and distribution networks, there is currently restricted access to and availability of green hydrogen. Infrastructure deployment is difficult because of geographic factors, especially in isolated or rural areas and island nations (Agaton et al., 2022). To fully realize the potential of green hydrogen, infrastructural development must accelerate (Zou et al., 2022). Some of the obstacles that many nations encounter include high expenses, technical difficulties, and international cooperation. The majority of green hydrogen is produced locally, close to the place of application (Yue et al., 2021). The availability of refueling stations is an important component of infrastructure. The broad use of green hydrogen applications is hampered by the lack of refueling facilities. To meet rising supply with rising demand, more refueling stations are required. Governments ought to work with knowledgeable businesses to develop strategic strategies for putting in place green hydrogen infrastructures [83].

Fly ash and char are the most common solid byproducts of gasification, however there are many others. Like dust and biomass ash, these are a problem. It is important to keep ash moist and sealed because it can also be a fire threat (Yue et al., 2021). Pollution of the environment and hazards to occupational health and safety can arise from biomass gasification plants if adequate and consistently enforced preventative measures are not put in place [83]. Combined garbage and the plastic-only portion of trash are both amenable to gasification. Less air is needed for the process, which means less pollution from things like nitrogen oxides and better efficiency in recovering energy. Tars, heavy metals, halogens, and alkaline compounds are released into the product gas during gasification, which can lead to operational and environmental issues (Zou et al., 2022). According to the results, there are a lot of dangers associated with biomass gasification, such as the possibility of explosions and fires and the leakage of harmful gases into the environment through various channels [83].

The biggest barrier to the path of green hydrogen implementation is the economic factors involved in integrating green hydrogen in the energy market. Even in nations with plenty of renewable resources, electrolysis is still the prominent method of producing green hydrogen and makes up a sizeable share (50%–70%) of the costs of producing green hydrogen (Ishaq et al., 2022; $author1$ et al.,). Currently, it costs very much to produce green hydrogen using water electrolysis; the cost per kilogram ranges from USD 6–12 (Agaton et al., 2022; Yue et al., 2021). Green hydrogen needs to be cost-competitive and accessible in order to be a viable alternative to fossil fuels. Gasification of biomass might be a workable approach. The intermittent nature of some of the promising renewable energy sources, such as solar and wind, makes it difficult to optimize green hydrogen systems (Mah et al., 2019). High manufacturing costs are a result of the expense of parts used in fuel cells and electrolyzer systems, notably noble metals like platinum-based materials used as catalysts, co-catalysts, and in bipolar plates. Due of their rarity and geopolitical factors, these comsmodities are pricey. Funding and particular economic methods for green hydrogen are required to overcome the high production costs. Governments should set aside more money for energy and gradually reduce their support for fossil fuels, diverting their cost savings to green hydrogen subsidies (Ishaq et al., 2022). The public's propensity to use renewable energy is directly impacted by its cost [83]. Renewable energy sources present a viable option for energy generation as they are further investigated and become more affordable.

6. Conclusions

The current study examined Bangladeshi gasification plants that used hydrogen gas produced from food waste to generate power, as well

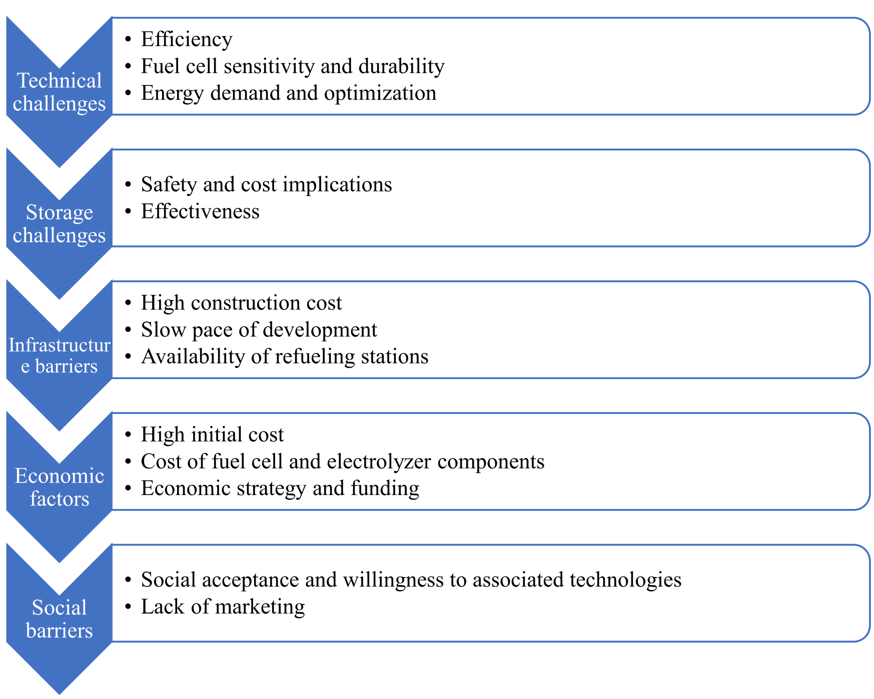

Fig. 13. Challenges in implementing hydrogen-based economy.

as their economic viability and environmental evaluations. According to the results, Bangladesh's food waste might be used to produce an estimated 0.5 million tons of H_2 gas by the year 2023. This amount of hydrogen gas may potentially generate 4287 GWh of electricity per year. It was discovered that the project's potential for producing electricity grew with each passing year. According to the economic feasibility analysis, the project is possible from 2023 to 2042 because the initiatives have produced a positive net present value. The project is quite viable in Bangladesh thanks to a larger net present value, a shorter payback period, and a lower levelized cost of energy. The study's conclusions suggest that big cities in Bangladesh and other developing countries should think about using hydrogen produced by gasifying food waste as a replacement for fossil fuels. By encouraging hydrogen-to-electricity projects, we believe Bangladesh's government can significantly contribute to the country's goal of increasing renewable energy in the mix of electricity generation by 10%. It was feasible to achieve an ecological efficiency of 99.98%, which is a positive outcome for the steam reforming process' environmental concern. A total of 1314 million liters of diesel fuel could be saved if hydrogen gas produced in 2023 was used in fuel cells to power vehicles instead of diesel fuel, preventing 3549 million kg of CO_2 and 10 million kg of CO from being released into the atmosphere from the combustion of diesel fuel for the generation of electricity. In addition, 1347 million USD are saved by not using as much diesel fuel. Large portions of this massive money may be included in the national budget. Therefore, it could be a solid guideline for the researcher and investor as well. The energetic, exergetic, and sustainability analysis along with experimental validation with technical one can be investigated in future studies.

CRediT authorship contribution statement

Md. Sharul Islam Khan Shawon Shawon: Validation, Writing – original draft. **Barun K. Das:** Supervision, Visualization. **Md. Sanowar Hossain:** Conceptualization, Formal analysis, Supervision, Writing – review & editing. **Fairuz Wasima:** Data curation, Formal analysis, Methodology. **Pronob Das:** Investigation, Methodology. **Sanjay Paul:** Writing – original draft.

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.

Data availability

Data will be made available on request.

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