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A R T I C L E I N F O

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A B S T R A C T

Waste is the most abundant biomass worldwide for renewable energy and value-added products generation. While technologies for the treatment of multiple waste categories continue to evolve, frameworks that facilitate strategic decision-making within bio-economies are required. Therefore, the aim of this research is to develop a framework that can identify optimal processing route for converting different biomass wastes into valuable products. This study considers five different waste types available in Qatar, including date seed, camel manure, municipal solid waste (MSW), food waste, and sewage sludge. Whereas the investigated technologies include pyrolysis, gasification, and hydrothermal liquefaction (HTL). The three processes were simulated in Aspen Plus® and evaluated in terms of their technical, environmental, and economic performance for the different selected biomass feedstocks. A two-stage optimisation framework was then developed to identify the optimal processing technology for each biomass considering multiple products generation (i.e., syngas, biochar, and bio-oil). Investigating the waste to energy pathways, the presented model maximised net profit and energy generation while minimised the total associated emissions. The model indicated that gasification is the optimal processing technology to achieve higher economic return. While pyrolysis is recommended for the achievement of highest energy return. Nevertheless, HTL exhibited the best environmental performance with the lowest associated emissions. In addition, various wastes such as MSW and food waste are best processed by gasification to fulfil the environmental and economic criteria, while pyrolysis is more energy efficient in processing these wastes. Whereas HTL has been recommended only for high moisture containing biomass like manure and sludge, demonstrating relatively high energy efficiency, but lower economic return relative to gasification and pyrolysis. The presented optimisation framework may provide insights for decision-makers to optimally valorise waste considering national priorities.

1. Introduction

The growing global population and societal advancements have tremendously increased the demand for energy worldwide. Global energy demand projections indicate an upward trend, with annual consumption expected to reach around 778 Etta Joule by 2035 (Rafiee and Khalilpour, 2019). Until today, about 80 % of the global energy demand is met by consuming fossil fuel resources. However, fossil fuel reserves are rapidly depleting due to their limited availability and increased exploitation in recent times. Petroleum, natural gas, and coal are expected to run out by 2052, 2060, and 2088, respectively, based on current consumption rates. As a result, no fossil fuels will be available in the next century (Kalair et al., 2021). The intense exploration and consumption of fossil fuels that has occurred in recent decades has resulted in massive CO_2 emissions. Currently, approximately 37 giga tonnes of CO_2 are released globally (Kramer, 2020). CO_2 is the most significant contributor to global warming, which has significantly disrupted the Earth's climatic pattern. Renewable energy resources such as solar, hydro, wind, biomass, *etc.* are considered as potential remedies to counter the energy and environmental crisis, as they can provide clean, sustainable, and affordable energy. However, the aforementioned resources are weather-dependant, hence their availability is intermittent across the globe (Alao et al., 2020). On the other hand, municipal (e.g. municipal solid (MSW)) and agricultural *(e.g.* animal manure) wastes are readily available everywhere. Furthermore, they are quite similar to biomass plant wastes, and hence the established technologies for transforming the biomass wastes into energy can also be extended to

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Nomenclature

AHP	analytic hierarchy process
DEMATEL	decision-making trail evaluation laboratory
EC	European commission
GHG	greenhouse gases
GRA	grey relational analysis
HTL	hydrothermal liquefaction
HHV	higher heating value
MCDM	multi-criteria decision-making
MSW	municipal solid waste
OECD	organization for economic operation and development
SAW	simple additive weighting method
TOPSIS	technique for order of preference by similarity to an ideal solution
WTE	waste-to-energy
WGS	water-gas-shift

municipal and animal wastes, which would definitely bridge the gap between energy demand and environmental sustainability in the near future.

Generally, wastes are from forestry, agricultural, and municipal waste sources. The forestry wastes entail plant biomass wastes from forestry operations, the agricultural wastes cover wastes from agro and livestock farming, while the municipal wastes include domestic and industrial wastes. Due to steep increasing population, fast socioeconomic development, and growing urbanization the generation of waste particularly from the agricultural and municipal sources is increasing rapidly worldwide. This increasing waste production poses a serious threat to the environment and the ecology, thus challenging the scientific community to develop and achieve a sustainable waste management system (Giang, 2017).

1.1. Transitioning to closed/circular systems

The concept of circular economy is one example of a system that address issues related to waste in a sustainable manner. It strives to sustain resources, materials, and products, while minimizing waste. The objective of the circular economy is to make the most use of the resources and to reduce the waste to a least minimum (Alibardi and Ragazzi, 2016). Implementation of the circular economy can render numerous benefits such as reduced greenhouse gas emissions, reduced consumption of resources, increased job opportunities, and improved societal and economic growth (Khan and Kabir, 2020). As such, shifting towards a circular economy is viewed as a potential means to develop a sustainable society and environment (Ibarra-Gonzalez et al., 2021). In this regard, the introduction of closed loop ensures that the resources, materials, and products are utilized optimally. It also safeguards that the material, energy, and economics are available and affordable for a longer period (Tomić and Schneider, 2018). The concept was first proposed by European commission (EC) in 2015 by introducing a circular economy package covering many legislative proposals and initiatives. The commission in its endeavour has set a target for 2030, which is aimed to recycle 65 % of total MSW, 70 % of the construction waste, 75 % of packing waste and reduce MSW landfilling to 10 % and promote industrial cooperation and developing an eco-design strategy (Zeller et al., 2018).

Today's global and chemical demand is mostly met using fossil fuels. As fossil fuels are limited and prone to emit greenhouse gases (GHG's), some alternate, sustainable, and clean sources of energy and chemicals are being explored. Biomass is amongst the possible sources, as it can serve as it is abundant and can be a potential source of energy, chemicals and fuels (Pang, 2018). Furthermore, if biomass wastes are not properly utilized it may lead to some serious environmental issues. As biomass waste generation is expected to increase with the increasing population and consumption, it is essential to implement the concept of circular economy and closed loop systems, so as to preserve the environment and the natural resources for the benefit of the future generations. In this regard, and in line with the fundamentals of the circular economy, a bio-economy can be defined as the sustainable transformation of renewable organic resources into food, energy, and other essential products in an environmentally benign manner (Antar et al., 2021). The schematic representation of the bioeconomy is presented in Fig. 1, which considers the generation of renewable and sustainable resources, transforming those resources into food, energy, and value-added products eco-efficiently, converting the wastes (produced during the transformation process) into feed, energy, and value-added commodities. The organization for Economic Operation and Development (OECD)

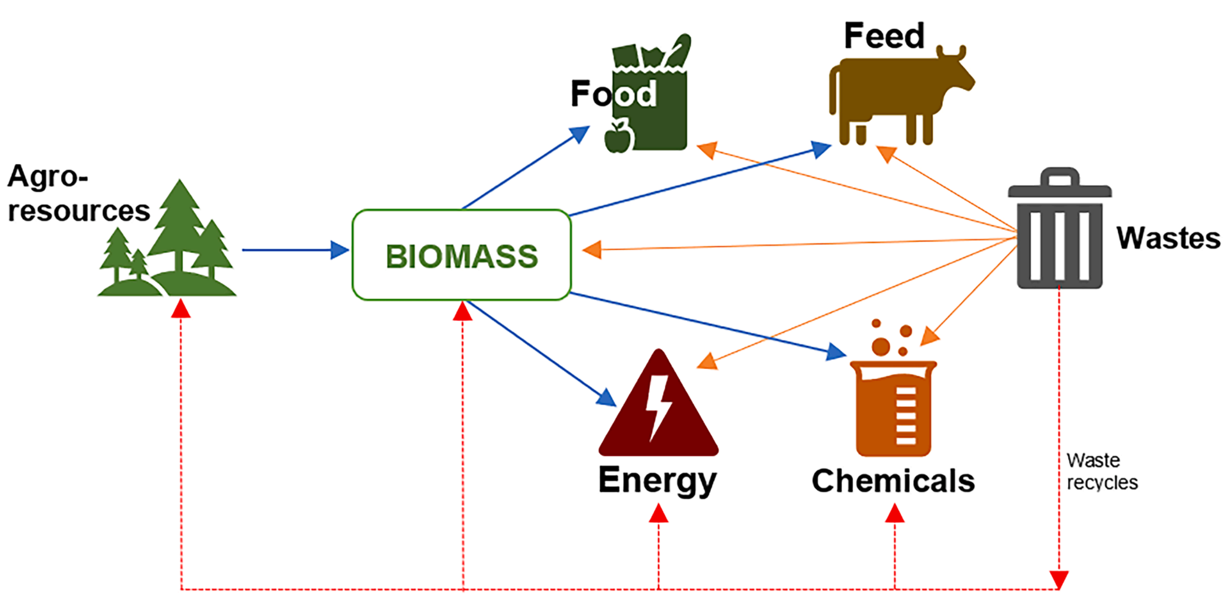


Fig. 1. The schematic representation of the bioeconomy.

Table 1
The environmental impacts of the selected wastes.

Waste	Practiced disposal methods	Reported Environmental impact	Refs.
Date seed	Date palm wastes are burnt in open fields.	The emissions of burning pollute air affecting environment as well as human health.	Usman et al. (2015)
Camel manure	Camel manures are generally dry and odourless. They readily can be used as fuels and fertilizers.	The excess application of camel dung as fertilizer can contaminate groundwater.	Ziadat (2009)
MSW	Municipal solid wastes are dumped in open areas. The wastes are also disposed by open burning.	The open indiscriminate dumping of wastes emits greenhouse gases contaminating air. The runoff and leachates from the dump yards pollute water resources. While the open burning of wastes significantly affects the air quality there by endangering the physical conditions of humans and other floras and faunas.	Beyene et al. (2018), Madi et al. (2012)
Cooked food waste	Food wastes are generally disposed of as livestock feed. They are also dumped in landfills.	The dumping of wastes generates foul rotten smell making the vicinity unpleasant. The accumulation of food wastes attracts pests, rodents leading to hygienic concerns. The decomposition of wastes also discharges a significant amount of greenhouse gases that can adversely affect the environment. The landfill leachate, on the other hand, can contaminate groundwater and other water resources.	Sulaiman et al. (2014), Negro et al. (2016)
Wastewater sludge	The sludge is normally openly dumped.	The open dumping of sludge is an eye sour. Furthermore, the sludge generates an unpleasant odour polluting the air. The piling of sludge also attracts pests and rodents through which some contagious diseases can be spread. The discharge of sludge into the water bodies can severely affect the water quality and life of marine species.	Garg (2010), Ahmad et al. (2016)

emphasises that for the successful implementation of the bioeconomy model, there is a need to enhance knowledge on biotechnology, biomass/feedstock and integration of applications (Mohan et al., 2018). Implementation of the bioeconomy can support the sustainable supply of food, feed, and products, improve the health of people and animals, and improve the biodiversity of the environment (Nicolae Scarlat et al., 2015). In addition, the implementation of the model will create many green employments, ensure industrial sustainability and products availability, and increase the income of the people (Boccia et al., 2019).

In line with the development of a bio-economy motivated by the circular economy, in this study, three major common wastes such as municipal solid waste, food waste, and sewage sludge and two local

Table 2
Merits and demerits of pyrolysis, gasification, and liquefaction.

Process	Merits	Demerits
Pyrolysis	About 70–90 % of waste volume reduction can be attained. Only phenomenon that delivers significant composition of solid, liquid, gas products.	The process can treat only relatively dry wastes, or it requires pre-treatment of wastes. Involves high capital and operational costs.
	Only least amount of pollutants is produced as the process is carried-out at relatively low temperatures and in the absence of oxygen.	The operational challenges such as blockage removal, reactor, and equipment cleaning, *etc.* are inevitable.
Gasification	The process can reduce the volume of waste by 90 %.	The process can treat only relatively dry wastes, or it requires pre-treatment of wastes. Involves high capital and operational costs.
	The produced syngas can be used as a versatile commodity to generate power, run vehicle engines, produce liquid fuels such as methanol.	
	Only limited emissions of hazardous pollutants such as furans and dioxins are produced since the process is carried out at an oxygen-deficient atmosphere.	The process is prone to cause some operational difficulties such as tar formation, agglomeration, slagging, clinkering, and sintering.
Liquefaction	Can handle even wet organic wastes. No pre-drying or pre-treatment of wastes is needed for the process.	The process delivers only a low biocrude oil yield. High energy intensive process.
		Limitations in the scale-up of the process.

wastes such as date seed and camel manure are considered. To operationalise the bio-economy, the utilisation of waste-to-energy (WTE) conversion technologies is inevitable (Qazi et al., 2018). Through the technologies, the zero-value wastes can be converted into commercial commodities such as heat, power, fuels, and chemicals. These technologies not only mitigate the issues associated with waste disposal, but also provide a platform to generate revenue. Although biochemical and thermochemical routes of waste conversion are in place, the thermochemical mode is of huge interest because of its ability to handle different waste feedstocks, versatile products (solid, liquid, and gaseous fuels) delivery, and short processing time (Tanger et al., 2013). In this study, four thermochemical processes are considered for a case study in Qatar, including pyrolysis, gasification, and hydrothermal liquefaction (HTL) as detailed below, with an explanation for chosen waste streams.

Considering valuable commodities, char is a solid byproduct of pyrolysis/gasification/HTL with a variable carbon content ranging from 60 to 90 %. It is primarily used as a fuel due to its higher heating value (HHV) of about 32 MJ/kg (Diebold and Bridgwater, 1997). Because of its high surface area, char is also used for filtration and pollutant adsorption. It has recently been widely applied to soils to improve their fertility (Abdelaal et al., 2021). The liquid by-product of pyrolysis/gasification/HTL is known as 'biooil' or 'biocrude oil,' and it has an HHV of 16 to 19 MJ/kg (Mohan et al., 2006). Although it has a reasonable HHV, it cannot be used as a transportation fuel due to its high viscosity, high corrosivity, and low volatility. However, with further upgrading, it can be converted into a palpable fuel. Aside from fuel, it can be used as a lubricant and to produce a variety of chemicals such as acetic acid, methanol, turpentine, phenols, and so on. Syngas is a gaseous byproduct of pyrolysis/gasification/HTL that typically contains hydrogen, carbon monoxide, carbon dioxide, methane, aliphatic hydrocarbons, benzene, and toluene. Syngas is used for a variety of applications due to its high energy content, including power generation, ammonia synthesis in the fertilizer industry, methanol synthesis in the chemical industry, hydrogen and diesel gasoline production in refineries, and so on. The

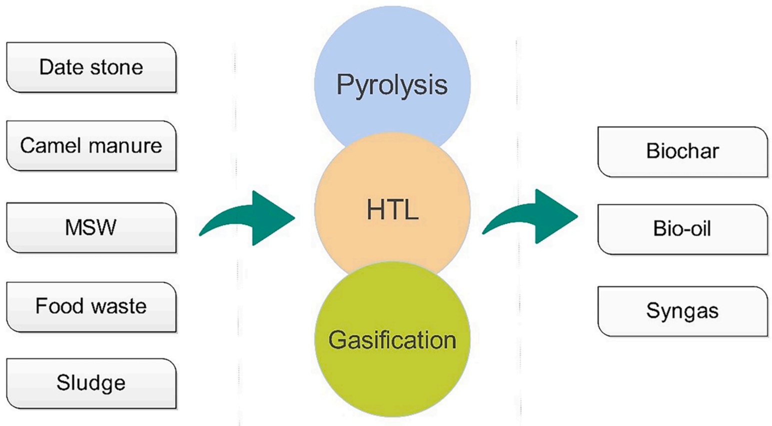


Fig. 2. Waste types and WTE conversion pathways investigated in the study.

Table 3
Characteristics of Date seed, Camel manure, Municipal solid waste, Food waste, and Sewage Sludge.

Biomass	Date seed	Camel manure	MSW	Food waste	Sludge
Proximate analysis (%)	Air dried-basis	Air dried-basis	Air dried-basis	Air dried-basis	Air dried-basis
Moisture (Case 1)	8.00	8.00	8.00	8.00	8.00
Moisture (Case 2)	10.20	38.00	35.00	88.00	85.00
Fixed carbon	14.99	12.53	23.45	33.07	6.47
Volatile matter	83.61	66.25	59.32	61.14	55.93
Ash	1.40	21.22	17.24	5.79	37.60
Ultimate analysis (%)	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis
Ash	1.40	21.22	17.24	5.79	37.60
Carbon	46.48	27.83	38.65	55.27	25.27
Hydrogen	6.54	1.02	4.30	5.91	2.81
Nitrogen	0.89	2.18	1.82	1.39	3.42
Cl	0	0	0	0	0
Sulphur	0	0	0.17	0.34	0.63
Oxygen	44.69	47.75	37.82	31.30	30.27

versatility and wide range of applications of these valuable commodities has been the impetus for this research.

1.2. Biomass waste and thermo-chemical conversion processes

Every year over 1300 million tonnes of municipal solid waste, 1.3 billion tonnes of food waste, and 75 million tonnes of sewage sludge are being generated globally. In the state of Qatar, about 120,000 tonnes of camel manure and 3250 tonnes of date seed are being produced annually (Campuzano and González-martínez, 2016; Demirbas et al., 2017; Vaccani and Salimova, 2017). As the quantity of the aforementioned wastes is massive, they are mostly dumped in landfills. However, these wastes possess high energy content thanks to their rich organic presence (Scarlat et al., 2015). Hence, in this study, the focus is on these wastes because of their availability and rich energy content.

1.2.1. Waste types

The Date palm is a flowering plant species belonging to the family of *Palmae (Arecaceae)*. It is one amongst the oldest cultivated plants of the mankind (Jamil et al., 2016). It grows well in the arid and semi-arid regions and is mainly cultivated for its edible nutritious fruit. The fruit of the date palm is dates which is pretty much rich in essential nutrients comprising carbohydrates, salts, minerals, dietary fibre, vitamins, fatty-acids, amino-acids, and proteins. Dates are marketed as a nutrition-rich confectionary all across the world. Owing to this, the demand for dates is increasing every year so as its production. The worldwide production of dates as on 2017 is 8.38 million Tonnes with Egypt, Iran, Algeria, Saudi Arabia, and Iraq being the top 5 leading producers of dates (FAOSTAT, 2017). The dates contain a seed referred to as pits, pips, stones, kernels, etc. The seed constitutes 10 % of total weight of the fruit (Suresh et al., 2013). The seed are mostly light to dark brown in colour, odourless and tasteless with slight bitterness. The seed possess high biodegradable matter containing proteins, carbohydrates, fibres, and lipids. Mostly seed are discarded once the fruits are consumed. They are also used as an animal supplement and to produce date seed-oil (pharmaceuticals), and bio-oil (fuel). A study by Parthasarathy et al. (2022b) reported that date seed can also be used for generating biochar, while Hijab et al. (2020) reported that biochar can be upgraded to activated carbon that can be used to remove pollutants from wastewater.

The camel *(genus Camelus)* have been domesticated some 5000 to 6000 years ago (Abdallah and Faye, 2012). As they are best suited for

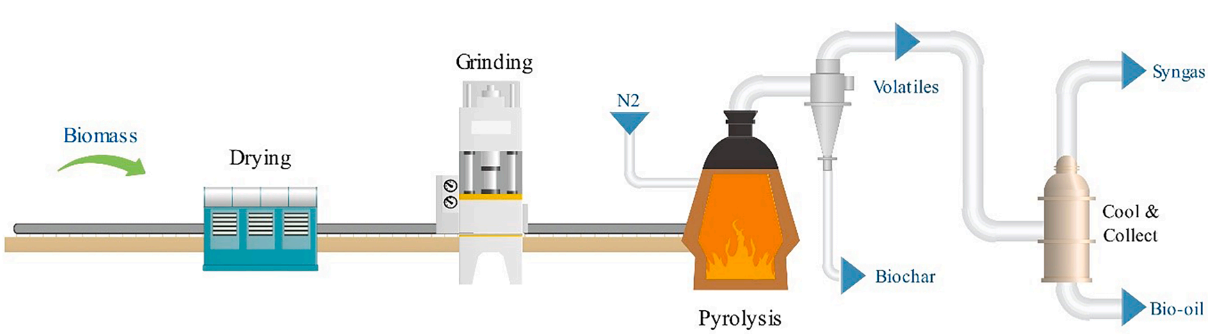


Fig. 3. A simplified process flowsheet of pyrolysis.

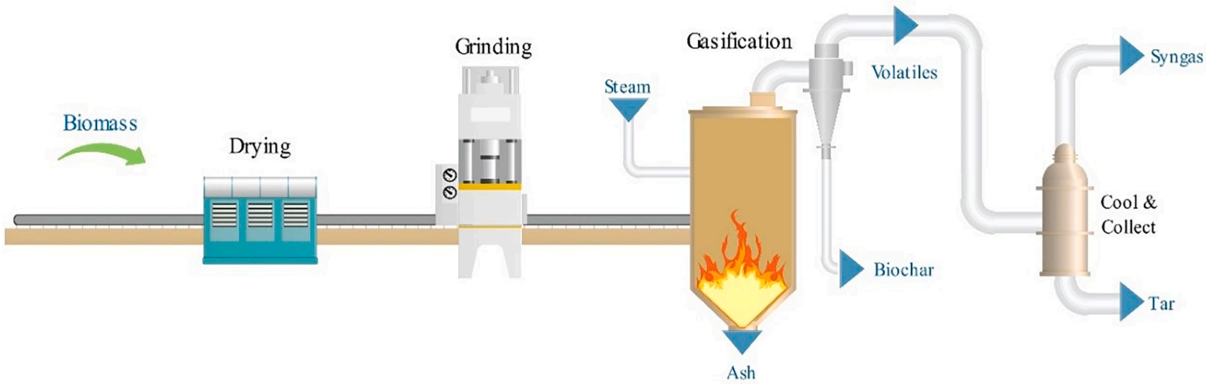


Fig. 4. A simplified process flowsheet of gasification.

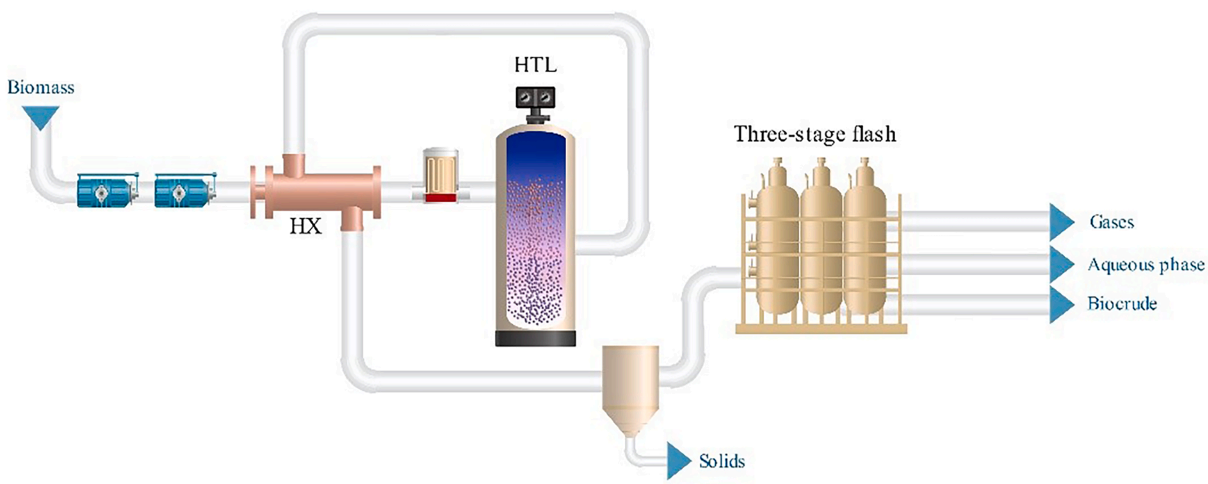


Fig. 5. A simplified process flowsheet of hydrothermal liquefaction.

Table 4
Optimisation variables.

Definitions	
K :	Processing pathway
J :	product category
I :	biomass category
Parameters	
C_{jki}	Cost to generate product "j" from biomass "i" via pathway "k"
P_{ijk}	Market price of product "j" from biomass "i" via pathway "k"
E_{jki}	Emissions related to generation of product "j" from biomass "i" via pathway "k"
Decision Variable	
x_{jki}	$\begin{cases} 1, & \text{if technology } k \text{ will be used to produce product } j \text{ from waste } i \\ 0, & \text{otherwise} \end{cases}$

desert conditions, they are tamed to ferry passengers and cargo. Due to this reason, they are referred to as the *'ship of the deserts'*. They are also domesticated for their meat and milk. There are around 35 million camel heads all over the world (FAOSTAT, 2017). The Arabian Peninsula comprising of Saudi Arabia, Qatar, Oman, Kuwait, Bahrain, United Arab Emirates and Yemen is the home for about 1.7 million Camel heads (FAOSTAT, 2017). A well-grown camel excretes 2.6 kg per day of manure. Hence, there exists a huge generation potential of camel dung in the region (Lensch, 1999). Besides, the camel manure has excellent potential to be used as fuel because it biodegrades at a faster rate because of the presence of diversified microflora present in the rumens of the camel. Furthermore, the dung contains only limited moisture, and it can be used as fuel as such. As the manure is rich in nutrients it can be used as a soil supplement as well. Al-Rumaihi et al. (2021) demonstrated that the came manure can be valorized to produce biochar. In a further study, Mohammad Alherbawi et al. (2021) reported that the manure can be used to produce drop-in fuel through liquefaction.

Municipal solid waste is an inexorable by-product that is produced due to the activity of humans. Municipal wastes are wastes that are generated from households, industries, offices, commercial buildings, and public institutions. The municipal solid waste is a grave concern as the waste keeps on mounting day-by-day. Well over 1300 million tonnes of municipal solid waste are generated every year (Campuzano and González-Martínez, 2016). The figure is expected to reach 2200 million tonnes in 2025 (Ranieri et al., 2018). The notorious aspect of the MSW is its varying composition, which varies from community to community, region to region, across countries and even periodically. This varying composition is owing to the varied culture, socioeconomic status, and lifestyle the people. The conventional methods of municipal solid wastes such as open dumping, landfilling, and incineration are no more encouraged due to their ill-effect on the environment. Notwithstanding, they have a high organic content composition (46 %), which needs to be exploited (Campuzano and González-Martínez, 2016). Owing to their rich organic composition, it can serve as a prospective source of energy.

At present, food waste is the largest globally generated waste (Niu et al., 2017). Food waste refers to unconsumed food that is wasted by food processing industries (wastes generated while processing), suppliers and retailers (wastes produced due to poor transportation and storage), restaurants (wastes produced-during preparation, due

Table 5
Raw data for the economic and environmental assessment.

Items	Economic parameter
Interest rate (i)	20 (%year)
Plant Lifespan n)	20 (years)
Plant construction time	3 (years)
Operators required	6 (1/shift)
Operators wages	20 \$/operator/h
Supervisors required	1
Supervisors wages	35 (\$/supervisor/h)
Plant operation time	350 (days/y)
Feedstock cost	0.03 (\$/kg)
Water cost	0.22 (\$/m^3
Nitrogen cost	0.6 (\$/kg)
Bio-char selling price	0.2 (\$/kg)
Syngas selling price	0.11 (\$/m^3)
Bio-oil selling price	0.16 (\$/L)
Items	**Economic formula**
Capital expenses (CAPEX)	FPC + WPC
Fixed project capital (FPC)	Equipment + instrumentation + civil / electric + management
Working project capital (WPC)	5% × FPC/period
Operating expenses (OPEX)	Raw material + operating costs + labour costs + maintenance + management + overhead
Labour costs	Salaries and wages
Overhead	0.5 × labour
Operating costs	0.25 × labour
Management	0.08 × operating costs
Profit (annual cash flow)	Annual sales –annualised cost
Items	**Environmental formula**
CO_2 emission/h (streams)	CO_2 mass flow rate × GWP of CO_2
CO_2 emission/h (utilities)	Utilities' energy × emission factor × efficiency factor

to-leftover, expiry), and end-users (wastes produced- due to leftover). Over 1.3 billion tonnes of waste is discarded every year worldwide (FAO, 2018). Food waste should not be considered as a waste of a commodity, rather it should be measured as a waste of resources, such as land, water, manpower, and energy. Food waste of such magnitude is equivalent to 30 % of the world's agricultural land, 20 % of global freshwater consumption, 8 % of the world's greenhouse gas emissions, and 38 % of the total energy involved in the food supply chain (FAO, 2018). Food waste decomposes at a very rapid pace due to its rich biodegradable organics and high-water content (75–85 %) (Moon et al., 2009). The natural decomposition of food waste produces CH_4 a greenhouse gas, which can harm the environment adversely. On the other hand, as food wastes are rich in organic components, proteins, and oil, *etc.*, they can be used as a potential source of energy. Alnouss et al. (2021) demonstrated that food waste, such as fruit waste can be pyrolysed to generate biochar. In continuation to the above study, Pradhan et al. (2020) reported that vegetable food waste can also be valorised to produce biochar.

The solid/semi-solid by-product of water and wastewater treatment process is termed as 'sludge'. Sludge typically contains 0.25 to 12 % of solids (by weight), however, it largely depends on the treatment methods it undergoes (Garg, 2010). Due to increasing numbers of water and wastewater treatment plants, the production rate of sludge is also increasing and hence it is considered as a potential threat to the environment. It has been estimated that the sludge production rate is varying between 0.1 to 30.8 kg per person per year (Kumar and Mohan, 2018). Due to its increased production rate, its disposal is becoming increasing complicated and expensive day-by-day. The traditional methods of sludge disposal, such as landfilling and incineration are not at all encouraged these days, because of their negative impacts on the environment. Hence, some alternate disposal methods are explored. Sludge is rich in organic content and it comprises of chemicals suchas proteins, carbohydrates, sugars, detergents, phenols, and lipids. It is interesting to note that sludge also comprises of many nutrients, which are essential for the plant growth. The sludge also entails humus like material, which can improve the fertility of the soil and augment the water adsorption capacity of the soil (Demirbas et al., 2016). This infers that they are suited for pyrolysis through which biochar can be generated. As sludge is rich in carbohydrates, they can be used to produce biogas as well. Alherbawi et al. (2021) demonstrated that sludge can be used as a feedstock in the liquefaction process to produce biocrude oil. The reported environmental impacts of the selected wastes are presented in Table 1. Hence, there is an impetus to explore alternative routes for utilizing these wastes focusing mainly on generating energy, fuels, and chemicals.

1.2.2. *Thermochemical conversion processes*

The choice of the aforementioned WTE technologies for treating wastes depends on various factors such as availability of waste sources,

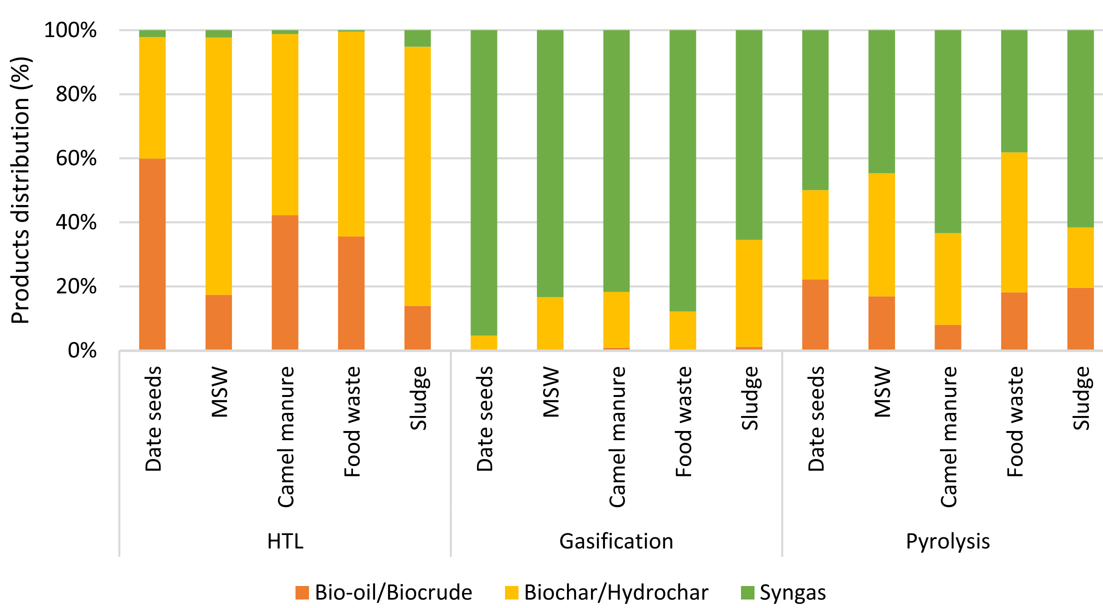


Fig. 6. Products distribution of different technologies and biomass resources.

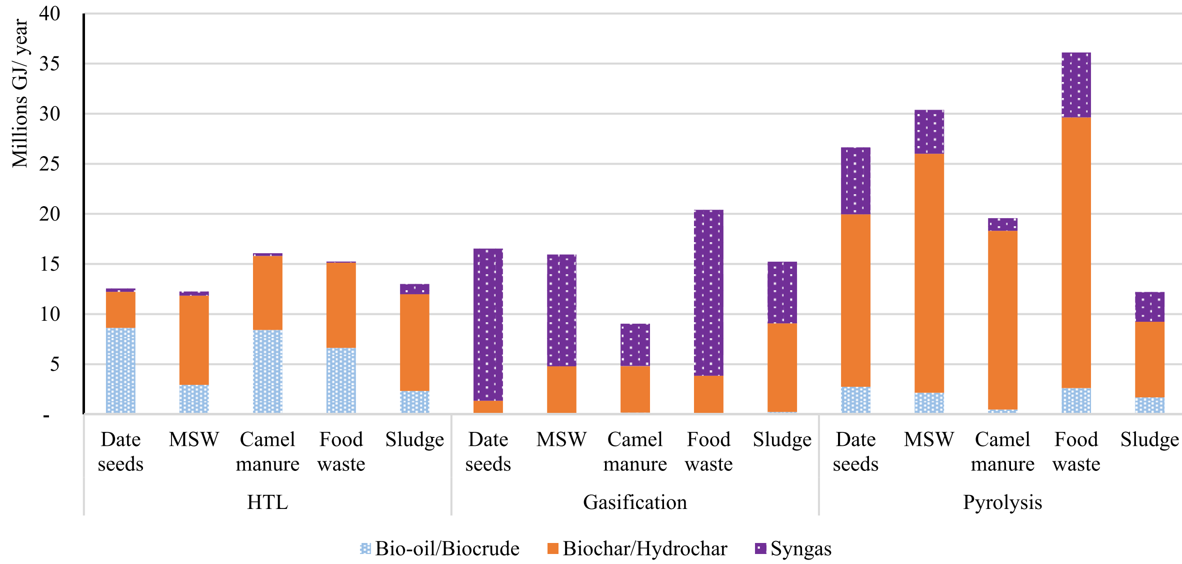


Fig. 7. Energy yield of different technologies and biomass resources.

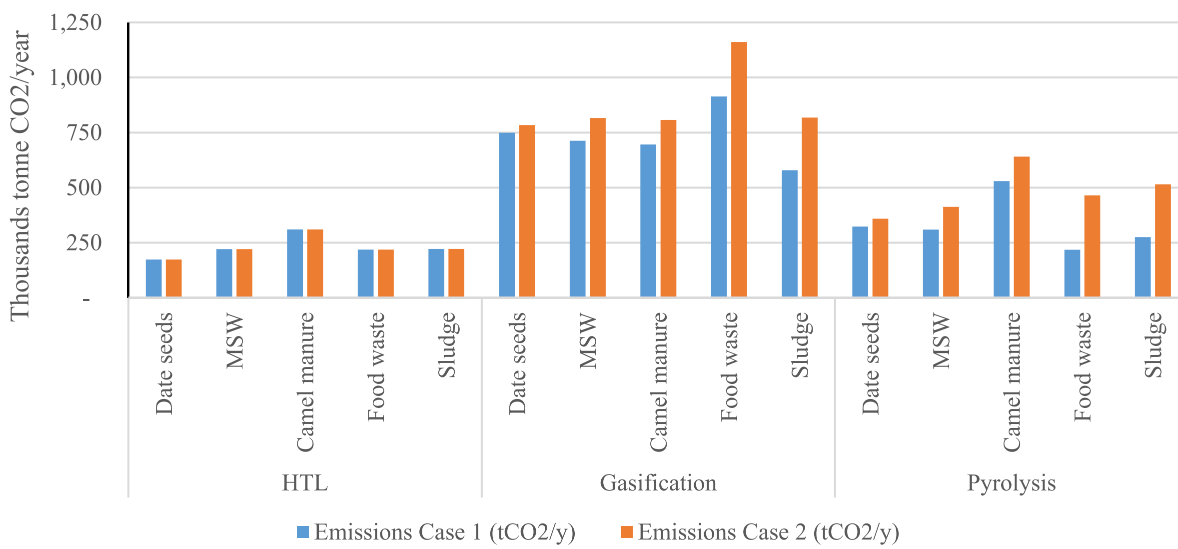


Fig. 8. Emissions associated to different technologies and biomass resources.

the demand of a product, availability of other resources, i.e. money, water, electricity, manpower, and topography and environmental regulations of a country/place, *etc.* (Soltani et al., 2016). The waste types and the varying composition of wastes also plays a key role in the selection of the most suitable WTE scheme.

1.2.2.1. Pyrolysis. Pyrolysis is the phenomenon of converting any organic material into convenient solid (char), liquid (biooil), and gaseous (syngas) fuels by the application of heat (300–600 °C) under an inert atmosphere (Xiao and Yang, 2013). In pyrolysis, the biomass' pseudo components named: hemicellulose, cellulose, and lignin (Gupta et al., 2016), are thermally broken-down at temperature ranges of 220–315 °C, 314–400 °C and 160–900 °C, respectively, yielding multiple solid, gas and liquid products with different compositions (Amin et al., 2016). The process is of great interest as the composition of char, biooil, and syngas can be varied easily by controlling few critical operating parameters such as temperature, heating rate, residence time, *etc.*

1.2.2.2. Gasification. Gasification is a mature technology for the valorisation of biomass into value-added products (i.e., combustible gas). It is a process to transform carbonaceous materials at elevated temperature levels into synthesis gas (syngas) with the aid of a gasifying agent (*i. e.*, oxygen, air, steam) (Lepage et al., 2021). Apart from syngas, the process also generates a liquid fuel (bio-oil) and a solid biochar, although in smaller quantities. The process is carried out at high temperatures (700–1100 °C) under the influence of gasifying agents such as air, O_2, steam, CO_2, and any mixture of these. Gasification processes are classified based on reactor operating conditions, which vary from mild operating conditions (425–650 °C) to moderate and extreme temperatures of (900–1050 °C) and (1250–1600 °C), respectively. In addition to the variation of operating pressure from 1 bar to high-pressure systems. The different operating modes impact the oxygen consumption in the different reactions, as well as the products compositions and the H_2:CO ratio (Shahbaz et al., 2021).

1.2.2.3. Hydrothermal liquefaction (HTL). HTL is the process of converting a relatively wet organic material into biocrude oil using pressurized hot water (50–200 bar) at medium temperatures between 250 and 400 °C (Mohammad Alherbawi et al., 2021). The process primarily produces liquid products (bio-oil and aqueous phase), but it also

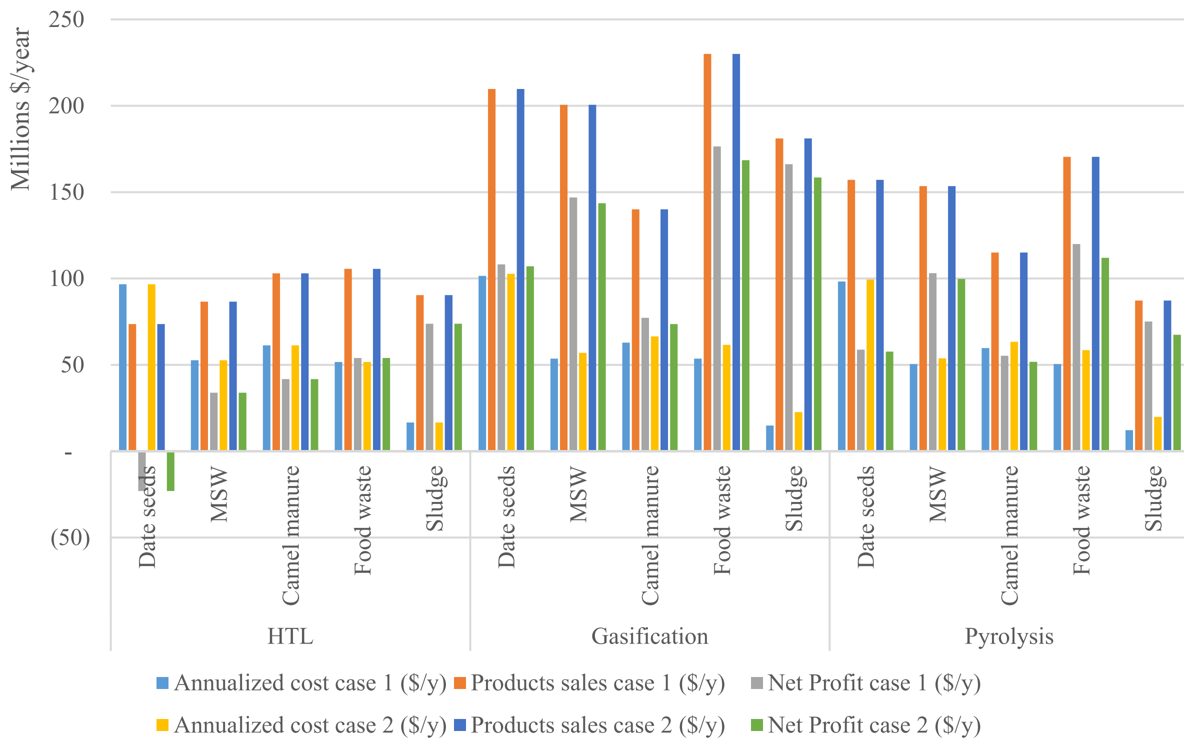


Fig. 9. Key economic parameters of different technologies and biomass resources.

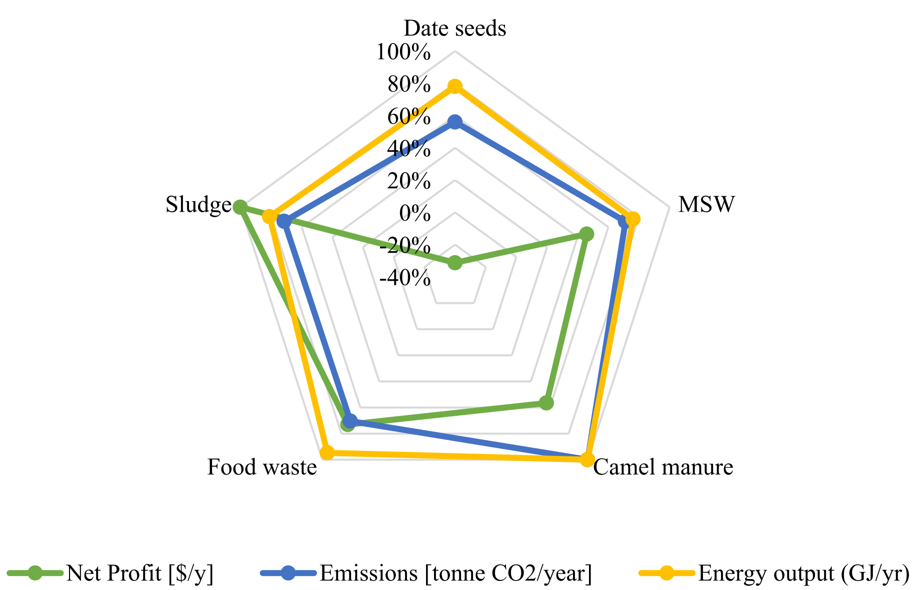


Fig. 10. Evaluation of various feedstocks performance in HTL process.

produces significant amounts of char and syngas. It is typically preferred for feedstock with a high moisture content because the water in the feedstock can be used more effectively as a medium for the reactions. This method can handle feedstock with up to 95 % moisture content. As a result, this process is better suited for feedstock such as food waste, sewage sludge, and microalgae, amongst other things. Another advantage of the process is that, unlike pyrolysis and gasification, it does not require pre-drying of feedstock. Temperature, pressure, residence time, feedstock type, solvent type, and catalyst are some critical parameters that influence the HTL process yield. The temperature is the most important parameter influencing product yield amongst these. The nature and composition of the feedstock also have an impact on the product yield (Alherbawi et al., 2020). Aside from the aforementioned parameters, the type of catalyst and its composition may also have an impact on product yield.

The merits and demerits of the aforementioned processes are presented in Table 2 (El-Haggar, 2007; Uma Rani et al., 2020; Wei et al., 2020; Xu et al., 2018).

1.3. *Technology selection*

It is imperative for all stakeholders to choose the most appropriate WTE technology considering all the societal, environmental, economic, and technical factors. The assessment and the selection of the optimal

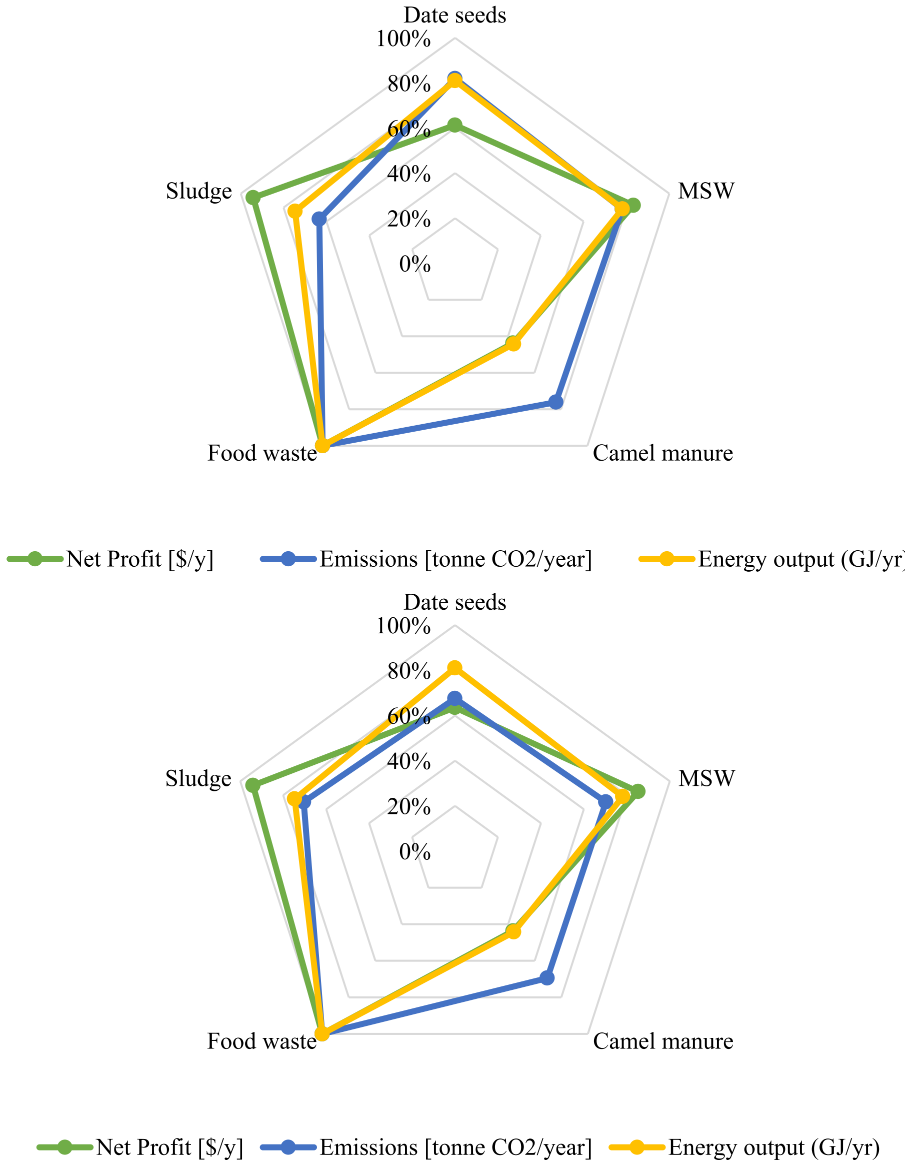


Fig. 11. a: Evaluation of various feedstocks performance in gasification process reference to case 1.
Figure 11a: Evaluation of various feedstocks performance in gasification process reference to case 2.

waste type and WTE technology is a complex process as it is closely linked with socio-economic and environmental factors, hence an appropriate solution for the above challenge has to be arrived at based on multi-criteria decision-making (MCDM) (AlNouss et al., 2018).

The concept of MCDM has become an important entity in the framework of sustainable energy planning (Coelho et al., 2017). Many MCDM practices have been applied in the decision-making process of various commercial, energy, and environment businesses. For example, Yap and Nixon (2015) employed the analytic hierarchy process (AHP) model to identify the most suited WTE technology in the UK and India. It was reported that gasification is the most appropriate WTE technology for treating wastes in UK while anaerobic digestion is the most suitable technique for India. Jovanovic et al. (2016) applied a simple additive weighting method (SAW) along with a technique for order of preference by similarity to an ideal solution (TOPSIS) to select an appropriate municipal waste management approach that is best suited for the city of Kragujevac in Serbia. It was identified that collective application of waste recycling, biochemical treatment techniques, landfilling, and incineration could be the ideal solution for managing wastes in Kragujevac. Rahman et al. (2017) also used the AHP model to ascertain a most suited WTE method amongst the pyrolysis, anaerobic digestion, and plastic gasification technologies for the city of Dhaka, Bangladesh. It was concluded that plastic gasification could be the most ideal technique for valorising wastes in Dhaka. A similar study using the AHP model was conducted by Qazi et al. (2018) to find an optimal WTE technology for utilising wastes in the Sultanate of Oman. The study revealed that anaerobic digestion could be most ideal for the country. It was further disclosed that next to anaerobic digestion, fermentation and incineration could also be more appropriate. The same AHP model was also applied by Tsydenova et al. (2018) to decipher the best waste management practice in Mexico. The study concluded that reusing recycle waste materials, compositing of organics, and thermochemical treatment of remaining wastes could be the best approach for converting wastes in the country. Siregar et al. (2018) employed the same AHP model to assess the best and worst WTE for Bantar Gebang landfill located in the Bekasi city of Indonesia. The study disclosed that anaerobic digestion could be the best-suited technique while incineration could be the least suited technology for the landfill. Wang et al. (2018) applied a hybrid model integrating inter valued fuzzy decision-making trail evaluation laboratory (DEMATEL) and grey relational analysis

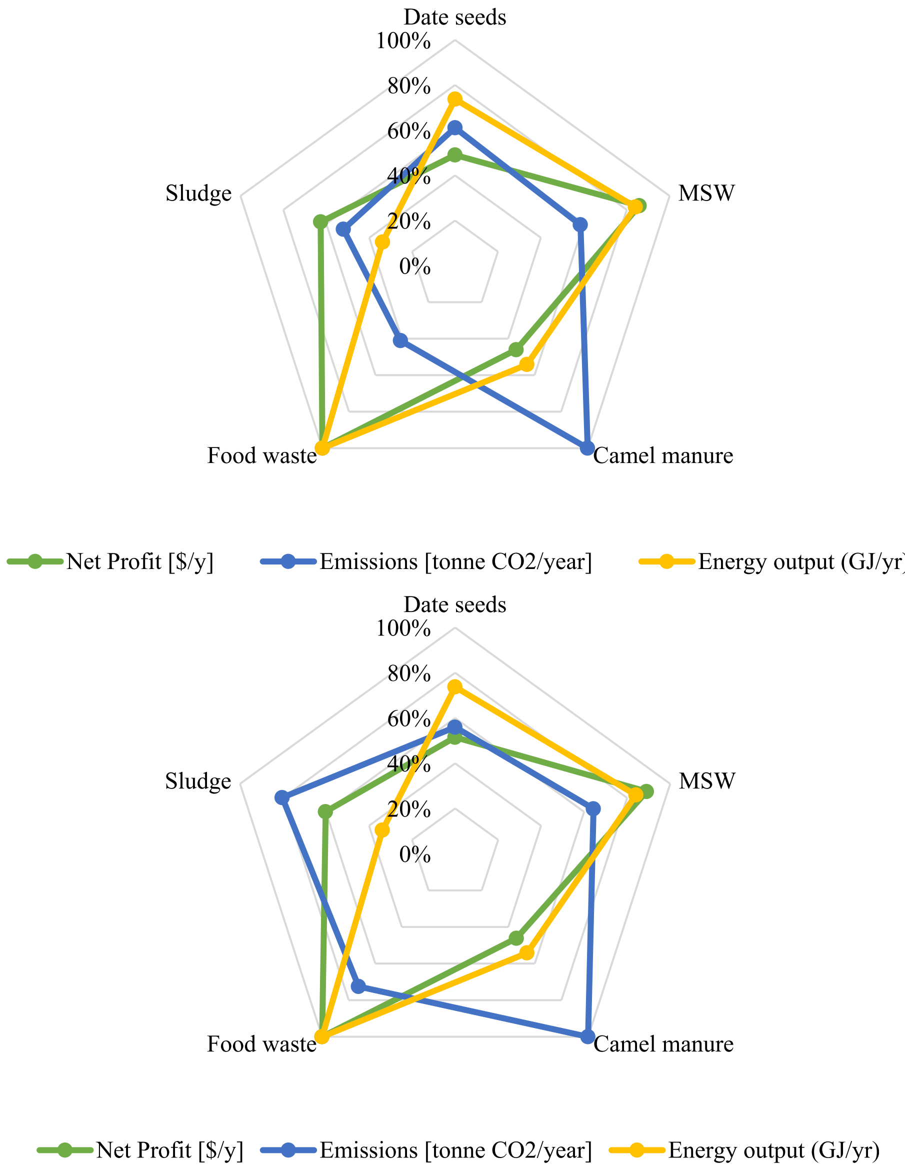


Fig. 12. a: Evaluation of various feedstocks performance in pyrolysis process reference to case 1.
Figure 12b: Evaluation of various feedstocks performance in pyrolysis process reference to case 2.

(GRA) to find a few appropriate methods for treating wastes in Chongqing municipality of China. The study reported that anaerobic digestion could be the best scenario for handling wastes in the municipality followed by gasification, conventional incineration and landfill.

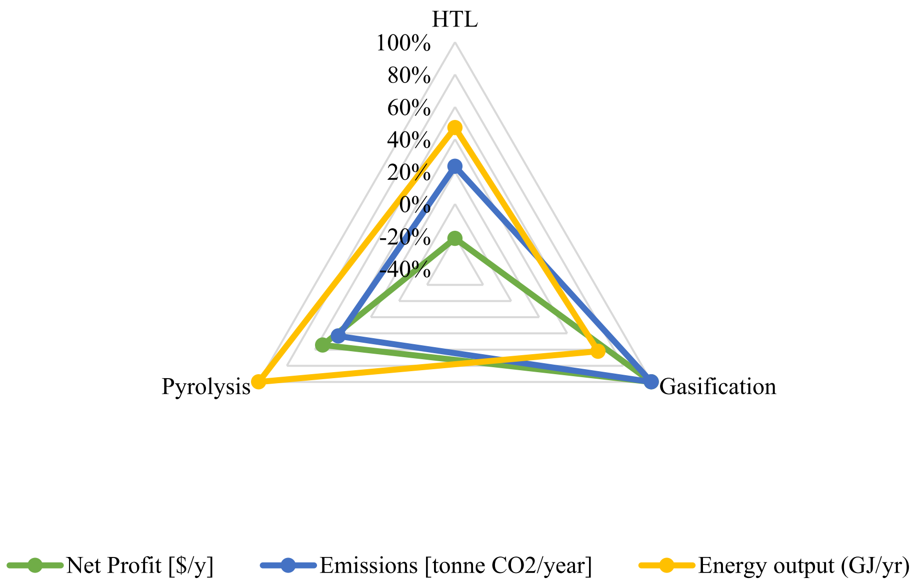
With rising energy costs, uncertainty about future fossil fuel sources, and concerns about the environmental consequences of atmospheric emissions, efficient energy management has become a topic of great interest in both the public and private sectors. Although there is much promise in the valorization techniques for generating energy and value-added commodities, it has not been commercially successful. Furthermore, in order for the techniques to be commercially viable and environmentally friendly, an integrated framework for the identification of the optimal processing pathways to convert the different biomass resources into valuable energy products is required. In light of the existing gaps, an integrated framework has been developed in this current study to explore optimal technological routes while taking economic and environmental factors into account. Outcomes of this study will support stakeholders who are involved in the decision-making process for framing waste management strategies.

2. Methodology

As indicated earlier, five waste types (date seed, camel manure, MSW, food waste, and sewage sludge) and four WTE conversion technologies (pyrolysis, gasification, and HTL) are evaluated. The waste types, WTE conversion pathways and products considered in the study are presented in Fig. 2. The pathways are evaluated under environmental and economic indicators that are utilised in a multi-objective optimization problem to determine:(1) the best WTE pathway for each waste type, and (2) the best waste type for each WTE pathway.

2.1. Process development

Aspen Plus (V.10) software is deployed for the development of the three thermochemical conversion processes. Steady-state and isothermal process are assumed in all models. Besides, feedstocks are defined in aspen according to their proximate and elemental characteristics presented in Table 3 and considering Qatar's built environment characteristics (AlNouss et al., 2020). The optimisation framework is developed to select the optimal processing route to valorise each waste



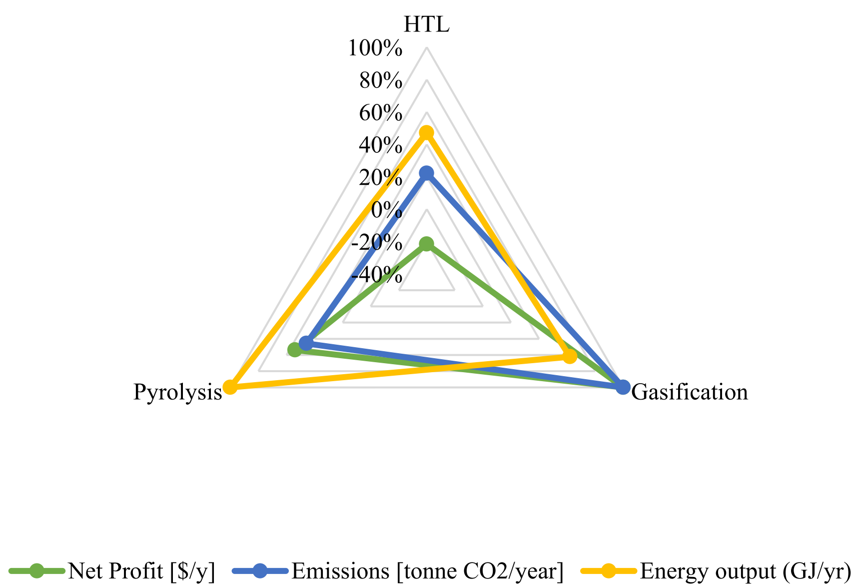


Fig. 13. a: Evaluation of various technologies using date stones as feedstock reference to case 1.
Figure 13b: Evaluation of various technologies using date stones as feedstock reference to case 2.

category and convert it into value-added products (*i.e.* syngas, biochar/hydrochar, and bio-oil/biocrude).

2.1.1. *Pyrolysis*

In this study, the pyrolysis process is modelled considering a kinetic-free equilibrium. A simplified process flow diagram of the process is illustrated in Fig. 3. The biomass feedstocks are first defined according to their elemental composition as non-conventional components. However, these components are then broken-down at 500 °C in "RGibbs" reactor into the corresponding conventional compounds. The outflow products are fed into a cyclone to recover the solid fractions, whereas heat is recovered from the volatile stream to condensate the low boiling point compounds to form an oil product (bio-oil). Furthermore, the recovered solids are fed into a second solid separator to obtain an ash-free char (Elkhalifa et al., 2019).

2.1.2. *Gasification*

A simplified gasification flow diagram is illustrated in Fig. 4. The Peng-Robinson model was chosen for the evaluation of fluid properties, assuming nonpolar and real components. The biomass inputs are first introduced as non-conventional compounds considering their characteristics listed in Table 3. They were defined as non-conventional components, whereby, they are then transformed into their equivalent conventional compounds with the aid of a Fortran-based calculation. A solid separator is used to collect the ash prior to pumping the stream into the system. Steam is applied as an agent at a ratio of 0.75, relative to biomass. The key processing stage is simulated using an "RGibbs", which restricts the equilibrium by minimizing the Gibbs' free energy. The process is conducted at an operating temperature of 850 °C. The validity of the model is tested against existing published models.

2.1.3. *Liquefaction*

A simplified HTL flowsheet is presented in Fig. 5. The process is modelled using non-random two liquid property package (NRTL). The biomass feedstocks properties are evaluated based on charcoal's correlations of density and enthalpy. The feedstocks are then fed to a hydrolysis reactor, while pressurized water is pumped into the system to create a slurry. At this stage, non-conventional components are broken down into the relevant components using a Fortran-based calculation.

The outflow stream is then fed into an "RGibbs" reactor representing

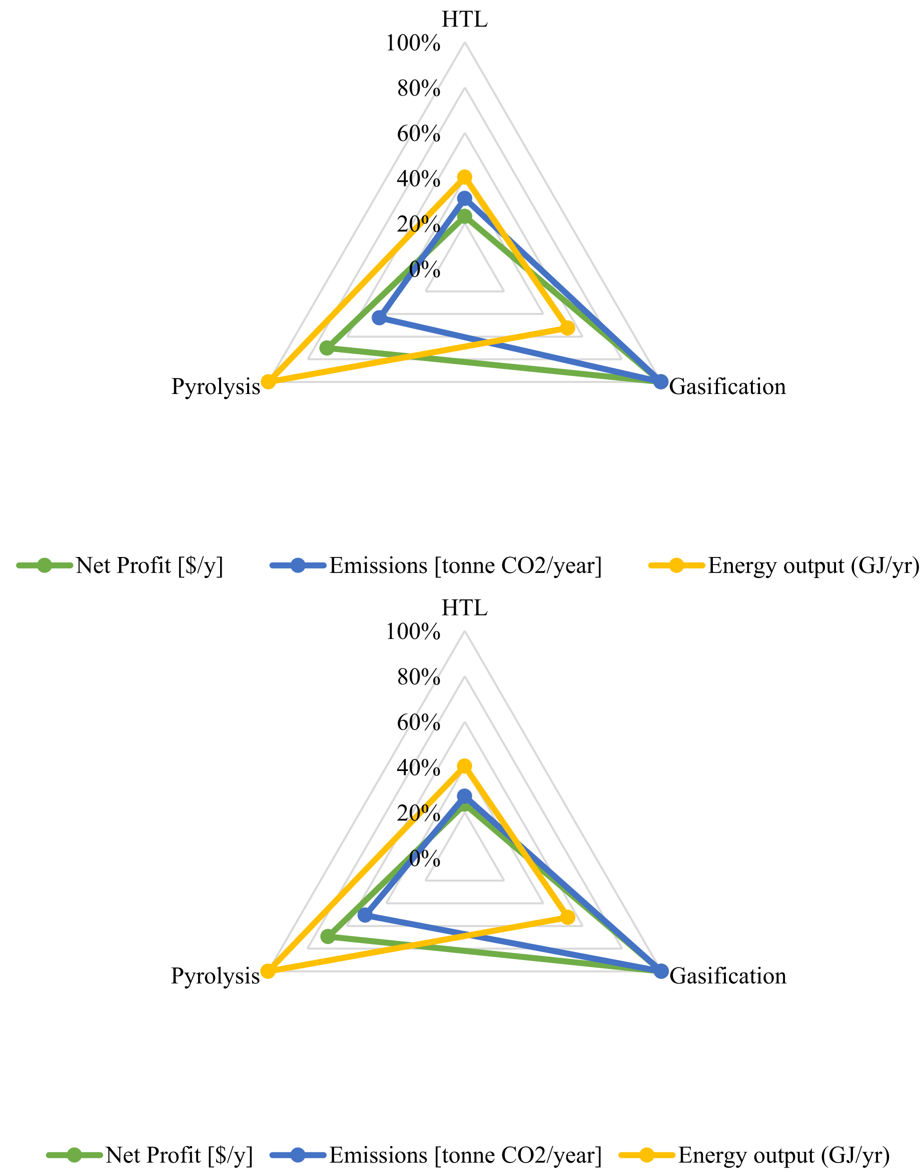


Fig. 14. a: Evaluation of various technologies using MSW as feedstock reference to case 1.
Figure 14b: Evaluation of various technologies using MSW as feedstock reference to case 2.

the key HTL stage. At this reactor block, potential outflow is defined according to earlier experimental works (Magdeldin et al., 2018; Panisko et al., 2015). The process is conducted at 300 °C and 150 bar. By the end of the process, all solid fractions are collected by a solid separator before partly cooling down the stream to separate the gaseous products. Finally, the remaining stream is transferred to a flash drum to obtain gas, biocrude and aqueous phases. The validity of the model is tested against existing experimental studies (Shuping et al., 2010).

The drying stage is an important step to prepare the feedstock for the reaction units, particularly in pyrolysis and gasification technologies. Therefore, two cases have been considered in this study; the first case assumes all feedstock are entering as dried biomass and no requirement for pre-drying, and the second case assumes drying stage for pyrolysis and gasification technologies to bring feedstock to 8 % moisture content.

2.2. Optimization techniques

The problem in hand is solved using two optimization techniques: a single-objective optimization using integer programming, and a multi-objective optimization as elaborated in the following sub-sections:

2.2.1. Integer programming

The first optimization model was developed as an integer programming formulation with two objectives that are solved sequentially. Firstly, an economic objective is introduced to maximise the biomass-based technology profit ($/year). Meanwhile, the second objective is defined as an environmental objective, aiming at minimising the total emissions associated to different biomass-technology combinations (CO_2e/year). The integer problem is subjected to a logical constraint to ensure selecting a single technology for each biomass category. The optimization variables have been presented in Table 4.

Objective function:

$$Economic: \ \max \sum_{I=1}^{i} \sum_{K=1}^{k} \sum_{J=1}^{j} \left[\left(P_{ijk} x_{jki} \right) - \left(C_{jki} x_{jki} \right) \right] \tag{1}$$

$$Environmental: \ \min \sum_{I=1}^{i} \sum_{K=1}^{k} \sum_{J=1}^{j} \left(E_{jki} x_{jki} \right) \tag{2}$$

Subject to:

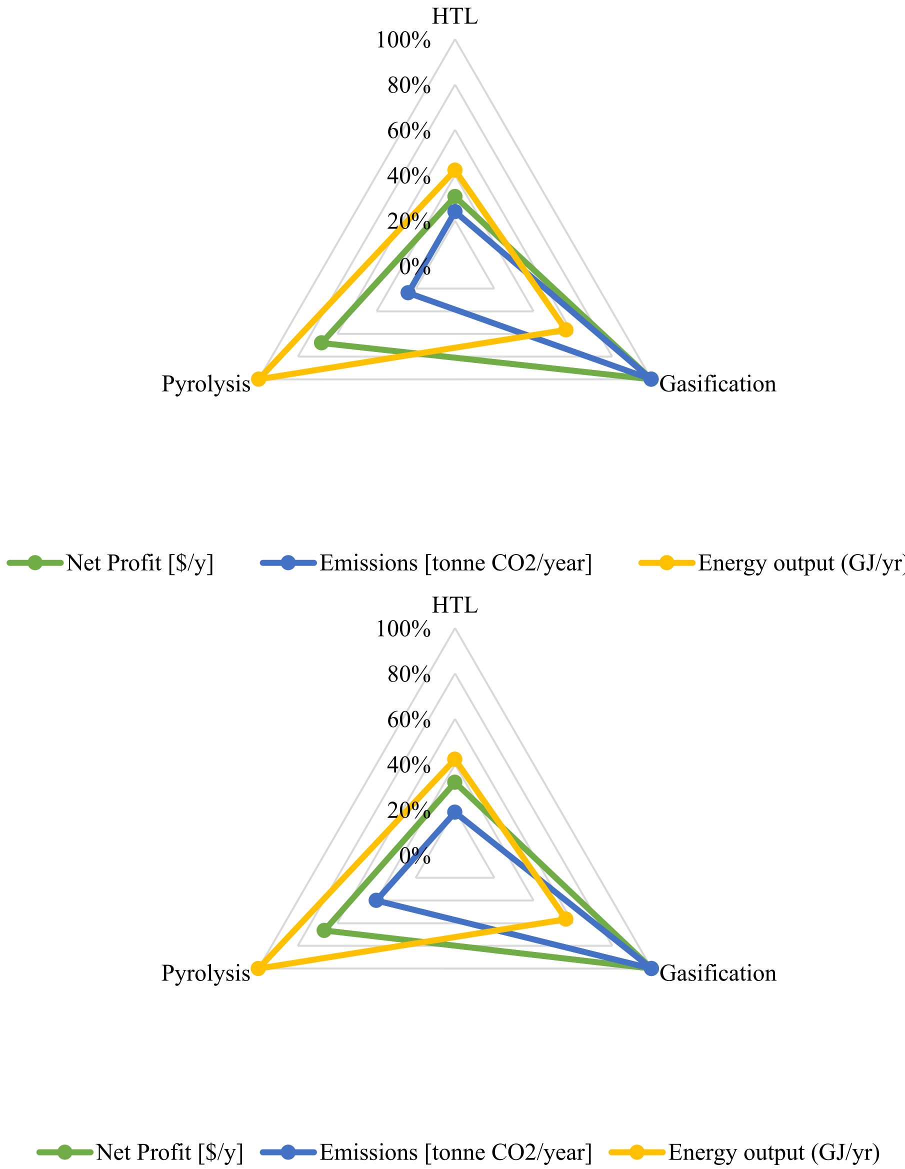


Fig. 15. a: Evaluation of various technologies using food waste as feedstock reference to case 1.
Figure 15b: Evaluation of various technologies using food waste as feedstock reference to case 2.

$$\sum_{K=1}^{k} x_{jki} \leq 1 \; \forall \; I = 1,2,\ldots,i; J = 1,2,\ldots,j \tag{3}$$

2.2.2. Multi-objective optimization

The second optimization scenario considers three objectives, which are solved collectively using the MATLAB's genetic algorithm approach. The model illustrated through Eqs. (4)–(6) aims at maximizing processes net energy generation and economic profit, while minimizing the associated GHG emissions. In this scenario, the products category is not considered, where a fixed product distribution is assumed for each processing technology.

$$Energy: \; max \sum_{k=1}^{3} \sum_{i=1}^{5} Y_k X_i G_{ik} \tag{4}$$

$$Profit: \; max \sum_{k=1}^{3} \sum_{i=1}^{5} Y_k X_i P_{ik} \tag{5}$$

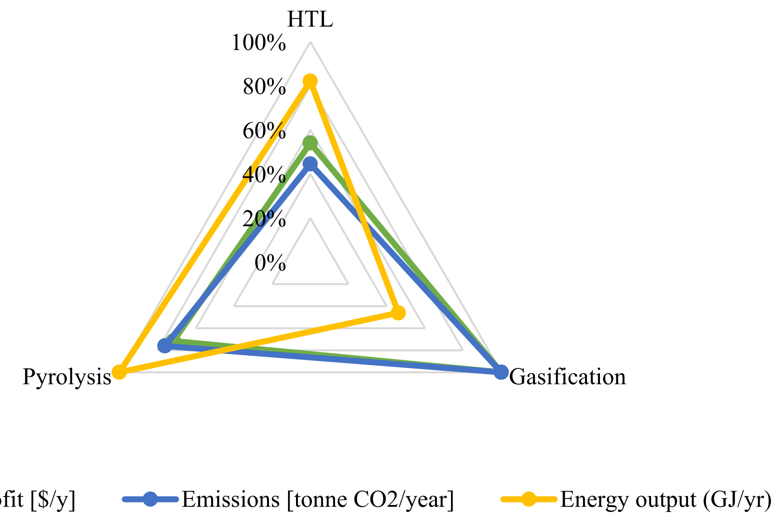
$$Emissions: \; min \sum_{k=1}^{3} \sum_{i=1}^{5} Y_k X_i E_{ik} \tag{6}$$

Were, "k" is processing pathway, "i" is biomass category, "Y_k" is the share of processing pathway k, while "X_i" is the share of biomass i. "G_{ik}", "P_{ik}", "E_{ik}" are the net energy, profit, and emissions, respectively, which are obtained through pathway k and using biomass i.

Subject to:

$$\sum_{i=1}^{5} X_i = 1, \; \sum_{j=1}^{3} Y_k = 1, \; X_i, \; Y_k \; \geq 0$$

The basis of optimization problem (for both techniques) are the results of the conducted techno-economic and environmental assessment on the 15 simulation cases of hydrothermal, gasification and pyrolysis methods. Table 5 summarises the raw data used in the techno-economic and environmental assessment. The assessment has been conducted using built-in capabilities of Aspen Plus software and the activated analysis of economic analysis and emission quantification.



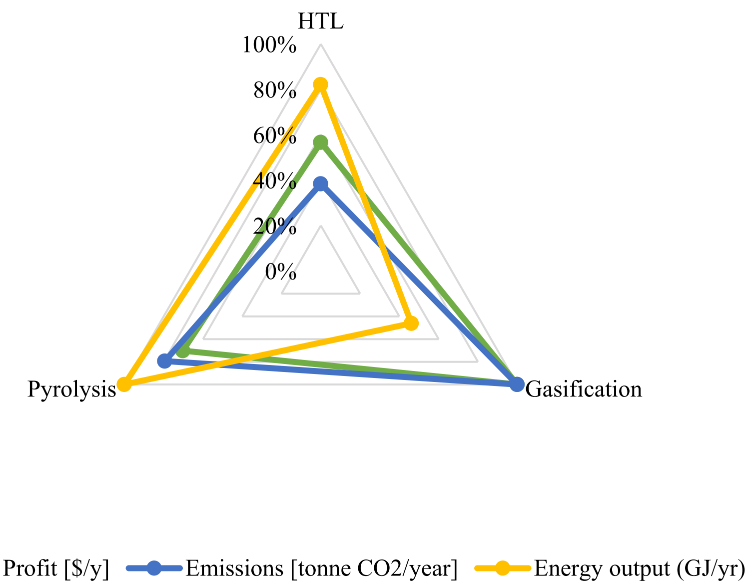


Fig. 16. a: Evaluation of various technologies using camel manure as feedstock reference to case 1.
Figure 16b: Evaluation of various technologies using camel manure as feedstock reference to case 2.

3. Results and discussion

A total of 15 simulation runs have been conducted to evaluate the performance of three thermochemical processing pathways in accommodating five different biomass resources. The products distribution, energy output and associated emissions achieved in each run are utilised in the selection of the optimal technology for each feed. The following subsections shed the light on the obtained results.

3.1. Products and energy distribution

Syngas is the key product of gasification process, with a varying syngas share from the overall useful products from as low as 82 % for camel manure, up to 95 % for date seeds feed as illustrated in Fig. 6. Whereas no bio-oil is produced in gasification at high temperature levels (above 1000 °C), whereby, all volatiles are converted into gases at this stage. Apparently, the volatile matter (VM) content of biomass plays a crucial rule in syngas yield, where date seeds have the highest VM content of ~84 % as compared to other biomass used in this study. However, HTL demonstrated a high biocrude yield of ~60 % for date seeds, while the biocrude yield reaches the lowest level when sludge and MSW are used as feedstock at only 14 % and 17 % yield out of useful products, respectively. Though, very little useful syngas is generated in HTL process, whereby the gas phase is dominated by carbon dioxide with a composition reaches around 90 %. Evidently, the high ash and fixed carbon results in higher solids production at the expense of biocrude yield. Nevertheless, pyrolysis resulted in moderate products' distribution, with syngas achieving the highest yield at 63 % using camel manure. Besides, biochar and bio-oil are maximized at 44 % and 22 % when food waste and date seeds are used as feedstocks, respectively. Like HTL process, higher char yield in pyrolysis is associated to fixed carbon content, which seems to apply to all thermochemical processes that operate at moderate temperature levels (300–600 °C), within which the fixed carbon content remains mostly in a solid state. The product distribution and energy output does not differ between the two drying stages since drying is assumed as a pre-stage for the reaction and product distribution stages.

The energy output of each technology using various feedstocks is illustrated in Fig. 7. Pyrolysis achieved the highest energy output, which is associated to the high char yield, especially when food waste is utilised in the process, followed by MSW. Char composition is dominated by carbon content; therefore, it demonstrates highest heating value per unit mass. The overall lowest energy output is obtained when camel manure is gasified, which could be associated to the low carbon and

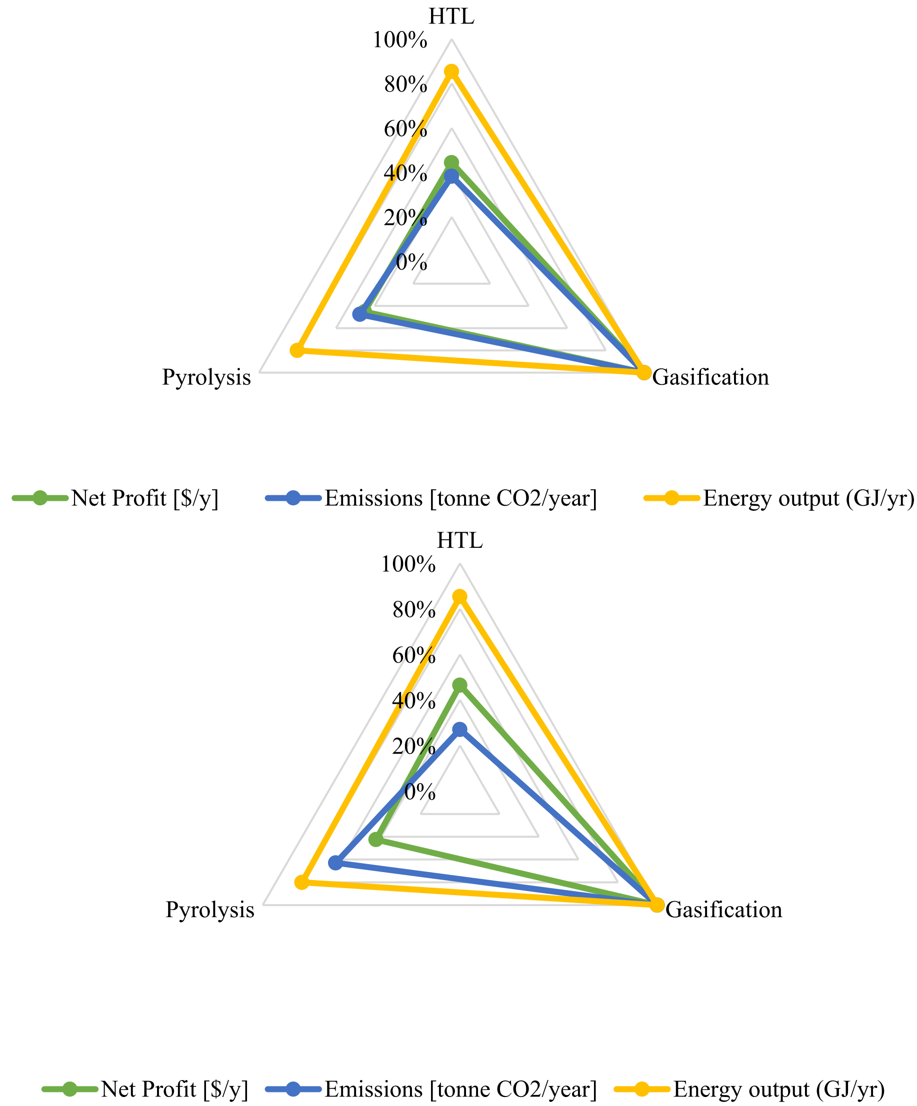


Fig. 17. a: Evaluation of various technologies using sewage sludge as feedstock reference to case 1.
Figure 17b: Evaluation of various technologies using sewage sludge as feedstock reference to case 2.

hydrogen contents of manure (27 % and 1 % respectively). The composition of manure is dominated by oxygen, which could result into excess carbon dioxide generation upon gasification. Nevertheless, HTL achieved a relatively low energy output as compared to pyrolysis, which is explained by the higher yield of oxygenated products (*i.e.*, biocrude) and the high share of generated carbon dioxide.

3.2. Process associated emissions

The emissions associated to biomass processing technologies is mainly a function of biomass composition, operating conditions, and energy consumption. Fig. 8 illustrates the variation in emissions released for different technologies and feedstocks, in addition to variation in emissions between the two drying cases since the pre-drying stage is associated with some additional emissions. Gasification is responsible for the highest global warming potential relative to other technologies, particularly while considering the pre-drying requirement. The high operating temperature of gasification considering natural gas as a mean for heating is behind the high associated emissions. Besides, amongst the different feedstocks, food waste contributed to higher emissions through gasification process due to its high carbon content. Whereby most of the carbon content (including fixed carbon) is gasified at high temperature. While in both, pyrolysis and HTL, the camel manure resulted into the highest emissions level, which is believed to be due to the high oxygen content of manure as compared to other feeds. Pyrolysis is still achieving higher emissions than HTL as it is conducted at higher temperature levels and requires a drying stage, which consumes a significant amount of energy.

3.3. Technologies' economics

The overall economic parameters of different biomass processing technologies are presented in Fig. 9. Gasification has achieved highest products sales, and therefore, highest annual profit. Whereby, minimal organic matter is wasted throughout the process since minimal carbon dioxide is generated as a product as compared to other technologies. While the use of steam as a gasifying agent has enhanced the syngas yield through the incorporation of steam in water-gas-shift (WGS) reactions. In addition, the HTL process achieved the lowest product sales, which is mainly due to the loss of biocrude into the aqueous phase, as well as the generation of a relatively high carbon dioxide amount. The results indicated that low-moisture feedstocks such as date stones may not be feasible to be utilised in HTL process, where a significant water amount is required to create the HTL slurry. In addition, the pre-drying

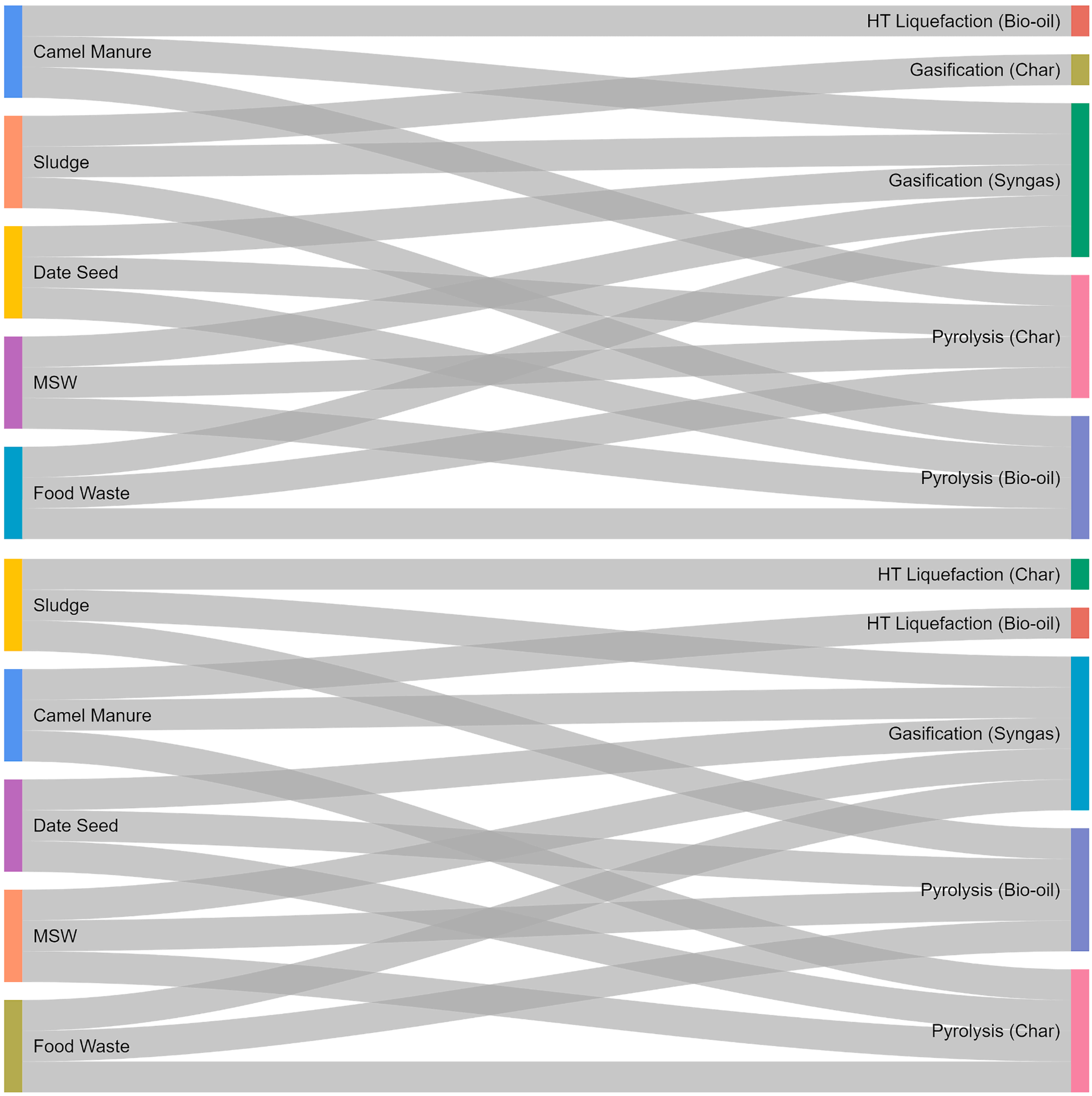


Fig. 18. a: Biomass and technology combination based on economic criteria and considering case 1.
Figure 18b: Biomass and technology combination based on economic criteria and considering case 2.

stage in case 2 has increased the annualized cost of the process which lowered the overall net profit.

3.4. Multiple biomass evaluation

A rapid appraisal of the different biomass performances is plotted by spider diagrams presented in Figs. 10, 11 and 12 for HTL, gasification and pyrolysis, respectively. The optimal biomass for HTL process considering the annual profit is found to be sewage sludge, followed by food waste. However, when the energy generation is concerned, the optimal biomass becomes camel manure, followed by food waste. Whereas considering the lowest associated emissions, date seeds are selected followed by food waste. It can be generalised that the high moisture containing biomass resources are the best feedstocks for HTL process.

In addition, the optimal biomass for gasification process is food waste considering economic and energy generation criteria in both drying cases. Although camel manure is the least preferred biomass for gasification from the technical and economic perspectives, it achieved a relative good score in terms of environmental performance. Nevertheless, food waste and MSW are also selected as best performing biomass resources for pyrolysis process, satisfying almost all three criteria in both drying cases. However, sludge is still exhibiting the best environmental performance in pyrolysis considering drying case 1 while it increases considering drying case 2. Nevertheless, date seeds exhibited a good technical and environmental performance in pyrolysis and gasification, however, its high cost undermines the process economics.

3.5. Multiple technology evaluation

In addition to evaluating the performance of multiple biomass resources for each technology, the optimal technology for each biomass is defined based on multiple criteria in this subsection and illustrated in Figs. 13–17. Considering the economic criteria, all five biomass resources are best utilised in gasification process, followed by pyrolysis. Whereby, gasification is a relatively more mature technology as

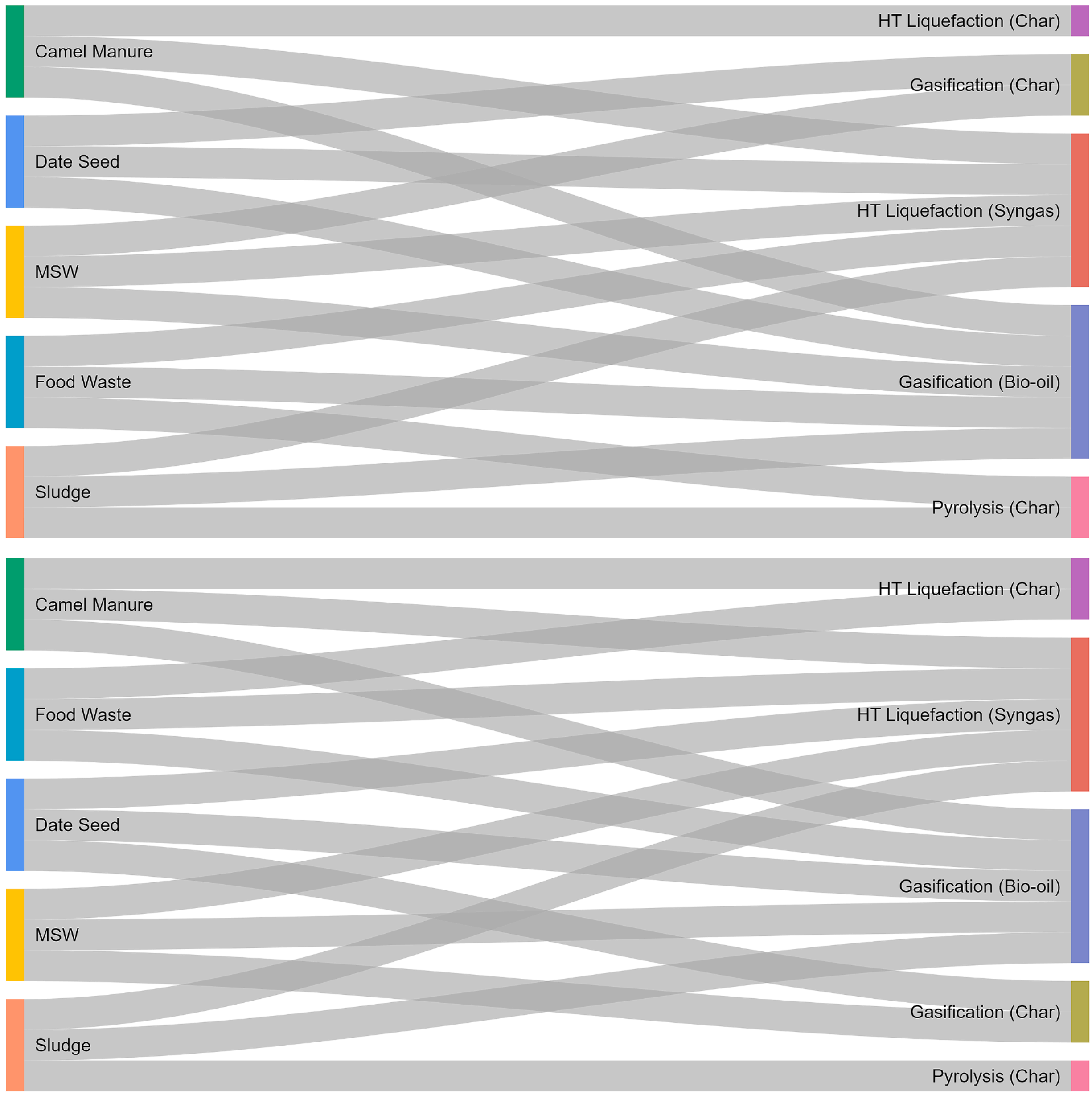


Fig. 19. a: Biomass and technology combination based on environmental criteria and considering case 1.
Figure 19b: Biomass and technology combination based on environmental criteria and considering case 2.

compared to HTL and pyrolysis. However, as far as energy output is concerned, pyrolysis is selected as an optimal pathway for the utilisation of all studied biomass resources, except for sludge. Whereby, sludge is selected to be processed in gasification to generate the highest possible amount of energy. Whereas from an environmental perspective, HTL process is selected as an optimal processing pathway for all studied biomass resources, followed by pyrolysis. That is mainly due to drying requirement for gasification and pyrolysis and their high operating temperature. The drying requirement is best differentiated between the two illustrated cases of pre-drying stage where in case 2 that considers the pre-drying requirement, the emissions increase and the net profit decreases compared to case 1 without pre-drying consideration.

3.6. Optimal multi-technology selection

The optimal biomass-technology combinations considering the economic objective (maximum profit) are illustrated in Fig. 18. The solutions of cases 1 and 2 indicate gasification is the optimal technology to process all biomass feedstock into syngas, while char and bio-oil are best produced via pyrolysis for all feedstock except some differences in sludge and camel manure cases. The main difference between the two cases is mainly due to the consideration of pre-drying stage which for instance moved the optimality of char production from gasification to HTL in the case of sludge.

When the environmental objective is considered (Fig. 19.), HTL turned out to be the best technology for the production of syngas and gasification is the best technology for the production of bio-oil for all studied wastes in cases 1 and 2, while char production is scattered over the three technologies. Hence, gasification is excluded from the production of syngas as it is associated to higher emissions release as compared to HTL. The main difference between the two drying is in the food waste case where the optimality of char production moved from pyrolysis to HTL. The obtained solutions draw conclusions on optimal biomass-technology combination regardless to the products composition and quality, therefore, further analysis shall be conducted to evaluate the products quality of different processing technologies in future

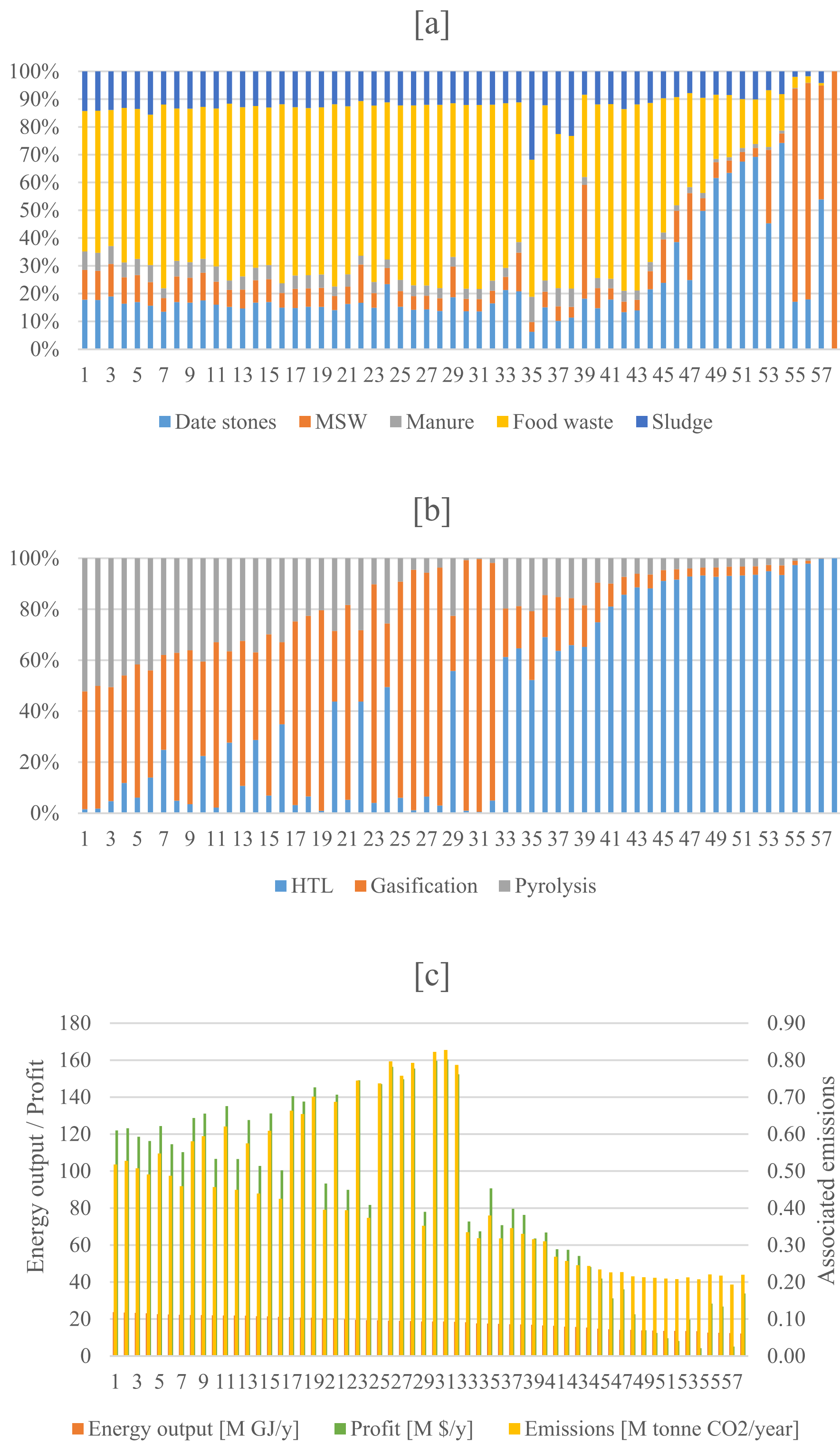


Fig. 20. Genetic algorithm's solution: (a) optimal biomass blend (%), (b) optimal technology share (%), and (c) Associated optimal solutions for Case 1.

studies.

3.7. Multi-objective biomass-technology selection

The genetic algorithm model generated 58 solutions for Case 1, and 77 solutions for Case 2 as illustrated in Figs. 20 and 21, respectively. All solutions are considered optimal since the given objectives maybe contradicting, where achieving an objective may lead to a diversion from other objectives. Throughout the optimizing process, the solver leans partly towards one of the objective in each iteration and performs a trade-off between the objectives, thus, yielding multiple solutions that are believed to partly meet all objectives.

Reaching a single solution in multiple objective optimization problems is not a straightforward task. However, the dominant solution can be observed from the charts in Figs. 20 and 21. For Case 1, it can be deduced that the food waste is dominating biomass blending solutions, with an average of 49 %, followed by date stones (22 %), and MSW (13 %), as illustrated in Fig. 22a. Whereas, HTL process is dominating the

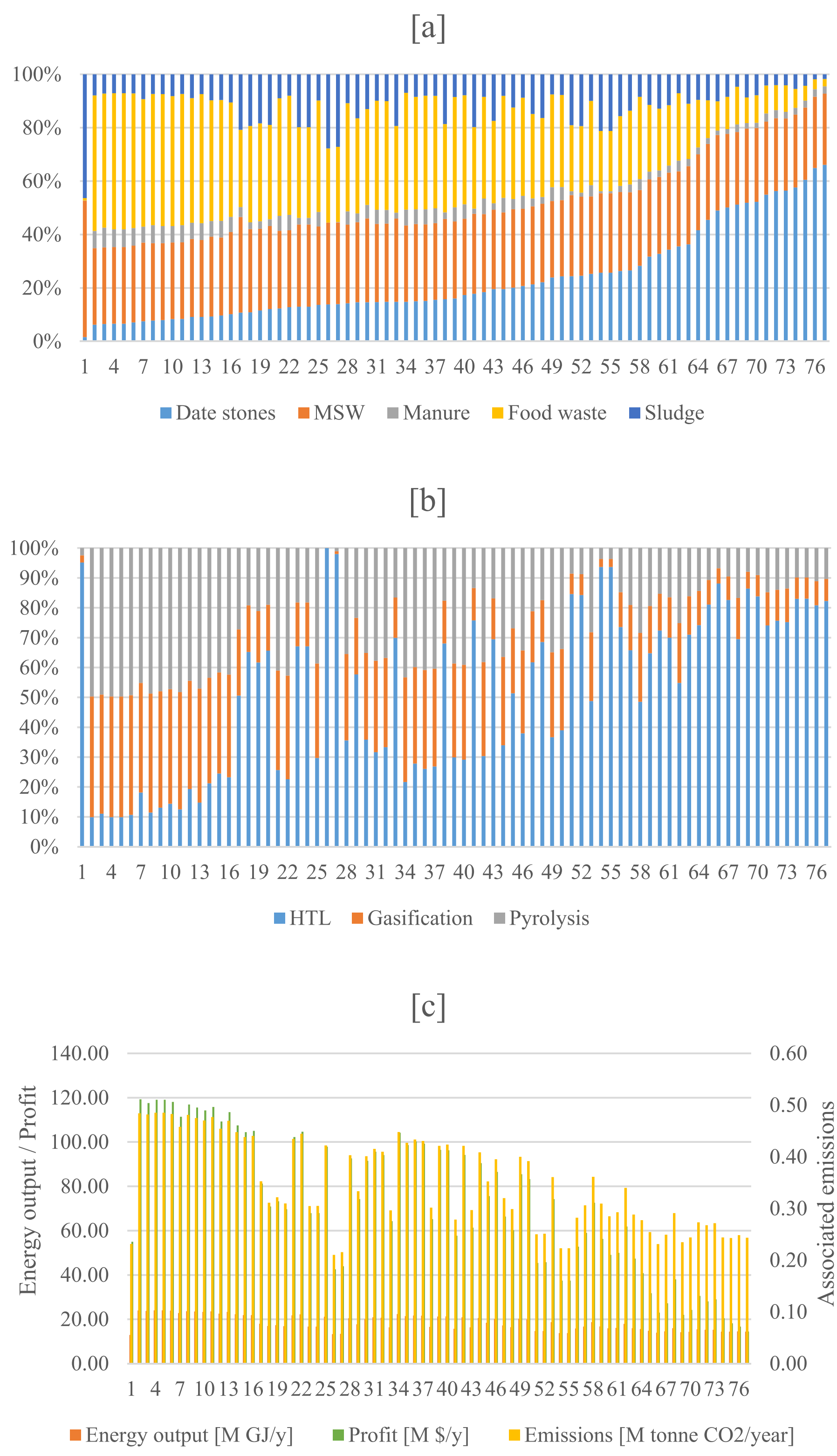


Fig. 21. Genetic algorithm's solution: (a) optimal biomass blend (%), (b) optimal technology share (%), and (c) Associated optimal solutions for Case 2.

technology share solutions, with an average of 45 %, followed by gasification (37 %), and finally pyrolysis (18 %), as presented in Fig. 22b. The HTL in this scenario has been dominantly selected due to the considerably lower associated emissions, with moderate energy generation and returns as compared to other technologies. Whereas, gasification significantly achieved a better economic performance, therefore, occupied the second place in the optimal solutions.

However, for Case 2, where drying of feedstock is required, food waste is still the dominant biomass at (32 %), followed by MSW (29 %). While HTL is also dominating the technology share solutions, with an average od (52 %), followed by pyrolysis (27 %), and finally gasification (21 %) as illustrated in Fig. 22c and d.

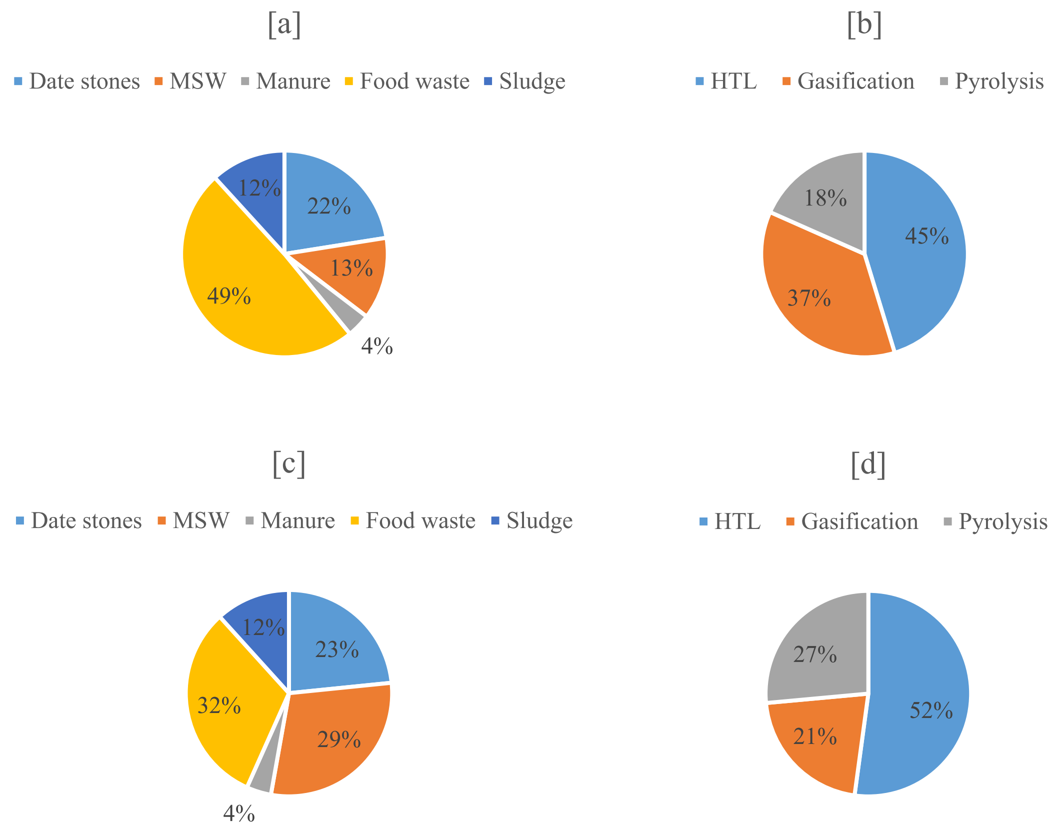


Fig. 22. Dominant solutions considering the three objectives collectively: (a) and (b) for Case 1, (c) and (d) for Case 2.

4. Conclusion

Given the development of multiple technologies capable of treating different biomass resources, it is critical to develop decision frameworks that identify the optimal processing pathway for each feedstock considering multiple criteria. Thus, the goal of this research is to develop an integrated approach for predicting the most efficient way to convert biomass waste into value-added products. In this study, five different types of waste in Qatar are considered: date seed, camel manure, MSW, food waste, and wastewater sludge.

An optimization framework for three processing pathways; pyrolysis, gasification, and HTL – has been modelled. Using the results obtained for the different feedstocks processing in different pathways, a multiple objective optimisation model has been developed to select optimal combination that include technology pathways and the energy products for different biomass types. The optimisation model maximizes net profit and energy output, while minimizing total associated emissions.

The model recommended gasification to achieve a higher profit, while pyrolysis is selected to achieve the highest possible energy generation. Meanwhile, HTL exhibited the best environmental performance with lowest associated emissions. In addition, high moisture containing biomass are selected as optimal biomass resources (*i.e.*, manure, sludge, and food waste). However, food waste and MSW are selected as best performing biomass resources for both, gasification, and pyrolysis.

Future work may comprise the development of an optimisation solver that can accommodate both environmental and economic objectives simultaneously through the application of trade-off concept. Furthermore, additional constraints maybe considered to fulfil different criteria including water and energy consumption in these processes, as well as a greater emphasis on the quality of the products generated by the various conversion pathways. The research presented in this paper illustrates the effectiveness of an integrated approach in waste to energy decision making and provides useful information to policymakers and potential investors for optimizing waste-to-energy investment, particularly in Qatar, however the methodology could be applied to any country in the world.

Code availability

Not applicable.

Availability of data and material

Not applicable.

CRediT authorship contribution statement

Ahmed AlNouss: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Mohammad Alherbawi:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Prakash Parthasarathy:** Formal analysis, Validation, Writing – original draft. **Naela Al-Thani:** Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Gordon McKay:** Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing. **Tareq Al-Ansari:** Conceptualization, Methodology, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.compchemeng.2024.108595.

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