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**INVITED REVIEW PAPER**

# Integration of thermochemical conversion processes for waste-to-energy: A review

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**Abstract**−As a strategy for mitigating climate change and waste problems, waste-to-energy has rapidly emerged. Thermochemical conversion is a widely used waste-to-energy process that involves the degradation of waste structure at high temperatures under oxygenic or anoxygenic atmosphere. Integration of different thermochemical conversion processes enhances the overall efficiency of energy recovery from waste substances. To maximize the enhancement of waste-to-energy efficiency, the selection of thermochemical conversion system configurations is critical. Understanding possible configurations of hybrid thermochemical waste conversion processes (e.g., pyrolysis, gasification, hydrothermal carbonization, and aqueous-phase reforming) is necessary for further development and propagation of the integrated hybrid thermochemical waste conversion processes. To this end, we provide a systematic review of existing hybrid thermochemical waste conversion systems that integrate different thermochemical conversion processes for waste-to-energy. The challenges and future research suggestions regarding integrated thermochemical waste conversion processes are also discussed.

Keywords: Energy Recovery, Hybrid System, Process Integration, Sustainable Energy, Waste Valorization

## INTRODUCTION

Globally, more than 2 billion tons of municipal solid waste (MSW) are annually generated, estimated to increase to >3 billion tons by 2050 [1]. In addition to the generation of large quantities, a paradigm shift from fossil energy toward renewable energy is essential to mitigate climate change by contributing to carbon neutrality [2]. Waste-to-energy is the key to both sustainable waste management [3] and renewable energy production [4], owing to the abundance of waste substances as the feedstock for energy recovery. Furthermore, waste-to-energy has enormous potential for flexibility and employment [5].

Thermochemical conversion is a promising approach to convert carbonaceous waste into gas, liquid, and solid fuels [6-8]. Gasification, reforming, pyrolysis, and hydrothermal carbonization are representative thermochemical waste conversion processes [9]. They are classified by target product phase (gas, liquid, or solid), oxidation atmosphere (partially oxidative or fully inert), and feedstock characteristics (dry or wet) [10-12]. Thermochemical waste conversion is particularly beneficial to decentralized electricity generation in developing countries [13-16]. Moreover, waste-to-energy based on thermochemical conversion contributes to fulfilling renewable portfolio standards in the US [17].

Single thermochemical waste conversion systems are commonly used for direct heating and gas, liquid, and solid fuel production [18-20]. However, all products cannot be fully re-used; thus, single thermochemical waste conversion systems are often unreliable and cost-ineffective [21]. Compared to single thermochemical systems, hybrid thermochemical waste conversion systems (e.g., a thermochemical conversion process integrated with another) enhance the effectiveness of waste-derived fuel usage, thereby increasing total carbon efficiency of the waste-to-energy and overall reliability of the process [22-28].

Even though thermochemical energy production in the form of fuels, electricity, and even co-products is an effective use of waste to substitute for fossil-based energy [29], hybrid systems that integrate different thermochemical waste conversion processes have received little attention. The present review supports wider practical applications of the hybrid waste-to-energy systems by providing a systematic overview of the hybrid thermochemical waste-to-energy systems. The challenges facing hybrid thermochemical waste-to-energy systems are discussed along with presenting recommendations for future research.

## THERMOCHEMICAL WASTE CONVERSION PROCESS

### 1. Gasification

Through gasification, carbonaceous waste substances are converted into gaseous mixtures composed of $H_2$, CO, and $CO_2$ under controlled oxygen, air, steam, or supercritical water at >700 °C [30, 31]. This process is called gasification, and the resultant gas mixtures are named syngas. The reactions typically occurring in gasifi-

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cation of solid carbon involve:

$C+0.5O_2 \rightarrow CO$
$CO+0.5O_2 \rightarrow CO_2$
$H_2+0.5O_2 \rightarrow H_2O$
$C+CO_2 \rightleftharpoons 2CO$
$C+H_2O \rightleftharpoons CO+H_2$
$C+2H_2 \rightleftharpoons CH_4$

Syngas is directly employed as a fuel for power generation [32] after proper purification removing ash and other impurities since its major portion (i.e., $H_2$ and CO) is flammable. Gasification has a high potential to improve the exergy efficiency (i.e., the effectiveness of a system relative to its performance in reversible conditions) of a combined heat and power (CHP) system [33]. Moreover, the production of electricity through gasification-based CHP can be environmentally friendlier than that through direct combustion. For instance, when producing 3.6 MJ electricity from timber through gasification, it can lead to low global warming potential of 0.07 kg $CO_2$ equivalent, acidification potential of 0.09 kg sulfur dioxide ($SO_2$) equivalent, and eutrophication potential of 0.36 kg nitrous oxide ($NO_2$) equivalent, compared with direct combustion [34]. Besides energy recovery, syngas can be upgraded to liquid hydrocarbons via Fischer-Tropsch process [35], hydrogen via water-gas shift reaction [36], and ethanol via fermentation [37].

### 2. Pyrolysis

In pyrolysis, waste feedstocks are anaerobically decomposed at a range of operative temperatures from 300 °C to 1,200 °C [12]. Pyrolysis is effective in the treatment of carbon-containing feedstocks having heterogeneous complex natures such as MSW and organic waste [38]. Pyrolysis of waste has various applications to produce $H_2$ [39, 40], biofuels [41], value-added chemicals [42,43], and catalytic materials [44]. Pyrolysis commonly produces three different pyrolysates: pyrolytic gas, pyrolytic oil, and char. A representative reaction for pyrolysis of cellulose $(C_6H_{10}O_5)_n$ can be expressed as:

$$3(C_6H_{10}O_5) \rightarrow 2CO+2CO_2+CH_4+H_2 \text{ (pyrolytic gas)} \\ +8H_2O+C_6H_8O \text{ (pyrolytic liquid)}+7C \text{ (char)}$$

Pyrolytic gas is a mixture of non-condensable gases including $H_2$, CO, $CO_2$, and $C_1$-$C_4$ hydrocarbons (e.g., alkanes and alkenes) [45]. Pyrolytic oil often contains water and more than hundreds of chemical species such as alcohols, organic acids, aldehydes, ketones, aromatics, phenols, and furans [46]. Char is a solid residue retained after pyrolysis, considered a renewable alternative to coal [47]. Major pyrolysate depends on temperature, heating rate, and feed and vapor residence time. For instance, fast pyrolysis (fast heating rate and short residence time) leads to a high yield of pyrolytic oil, while slow pyrolysis (slow heating rate and long residence time) leads to a high yield of char [48]. All three different pyrolysates can be used to generate power by combustion with post-pyrolysate upgrading (e.g., $CO_2$ separation from pyrolytic gas [45] and hydrodeoxygenation of pyrolytic oil [49]), so they are considered renewable energy sources.

### 3. Hydrothermal Carbonization

Hydrothermal carbonization transforms waste feedstocks having a high content of moisture (e.g., agricultural residue, manures, aquatic biomass, and sludge) into char at a temperature of 180-280 °C and a pressure of 2-6 MPa for 5-240 min [50]. Hydrothermal carbonization leads to char with a high energy density [51,52]. During hydrothermal carbonization, a variety of reactions occur to reduce the hydrogen and oxygen contents of the feedstock, involving aromatization, condensation, decarboxylation, dehydration, and hydrolysis [53,54]. This results in a coal-like product called hydrochar with byproducts such as process water containing organic species and inorganic salts and $CO_2$ [53]. Hydrochar made through hydrothermal carbonization of waste substances could be employed for the production of heat and electricity by combustion [55]. A recent study has shown that combustion of hydrochar derived from wet waste (e.g., bagasse) via hydrothermal carbonization can offer 170% higher electricity in comparison with conventional direct combustion process [56]. Hydrothermal carbonization is potentially applicable to dechlorination of chlorine-containing waste such as polyvinyl chloride (PVC) waste [57].

### 4. Aqueous-phase Reforming

Aqueous-phase reforming is a process that produces $H_2$ from oxygenated hydrocarbons by reacting with water at relatively mild conditions compared with steam reforming (i.e., 230-270 °C and autogenous pressure) [58]. The feedstocks for aqueous-phase reforming involve a large variety of oxygenated compounds derived from biomass and waste, such as cellulose [59,60], woody biomass [61], and wastewater streams [62]. A representative reaction pathway in aqueous-phase reforming over a metal catalyst involves C-C cleavage, rearrangement, and methanation [63]. A range of supported metal catalysts have been used to produce $H_2$ from oxygenated compounds through aqueous-phase reforming, as reviewed by many research groups [63-66]. The conversion of feedstock and selectivity toward $H_2$ for aqueous-phase reforming are highly dependent upon different factors, such as the kind of metal and support in the catalyst, characteristics of feedstock, process operation conditions (e.g., solution pH, temperature, pressure, and catalyst loading) [67].

## HYBRID THERMOCHEMICAL WASTE CONVERSION PROCESS

Different hybrid thermochemical waste conversion systems have been proposed that integrate thermochemical conversion processes mentioned in Section 2. The hybrid system configurations can be gasification-pyrolysis, hydrothermal carbonization-gasification, and hydrothermal carbonization-pyrolysis. All of them are discussed in the following subsections.

### 1. Gasification-pyrolysis Hybrid System

There are several hybrid processes consisting of gasification and pyrolysis. Table 1 lists various gasification-pyrolysis hybrid system configurations for waste-to-energy and summarizes the performance of each system configuration. In an earlier study, Moghadam et al. made an effort to recovering energy from agricultural waste through an integrated pyrolysis-gasification processes (Entry 1 in Table 1) [68]. The experimental work was conducted using coconut shell as the feedstock in the hybrid system. Reaction temperature, steam/biomass ratio, and equivalence ratio were considered for important experimental parameters. Under the optimal condition (pyrolysis temperature: 500 °C, gasification temperature: 950 °C, steam/biomass ratio=2.45, and equivalence ratio=0.23), $H_2$

**Table 1. Gasification-pyrolysis hybrid system for waste-to-energy**

| Entry | Feedstock | System configuration | System performance | Ref. |
|---|---|---|---|---|
| 1 | Coconut shell waste | Separate zones of pyrolysis and gasification in a reactor | • $H_2$ yield of 83.3 g $kg_{feed}^{-1}$<br>• Syngas yield of 485.9 g $kg_{feed}^{-1}$<br>• Lower heating value of product gases of 12.54 MJ $Nm^{-3}$ | [68] |
| 2 | Sewage sludge | Pyrolysis to produce char & gasification of the char | • Char yield of 51.9 wt% (HHV of 5.2 MJ $kg^{-1}$) obtained from the pyrolysis<br>• Highest char gasification efficiency of 64%<br>• Highest energy content of the resultant gas of 3.52 MJ $kg_{char}^{-1}$ | [69] |
| 3 | Lignite | Fluidized bed gasification & transport bed pyrolysis | • Syngas containing $CH_4$ of 10.8 vol%<br>• Liquid product containing light tar of 95 wt% | [73] |
| 4 | Victorian brown coal (as-mined) | Pyrolysis to produce char & gasification of the char | • $H_2$/CO molar ratio of 2 in syngas<br>• Maximum exergy efficiency of 62% with 20 wt% black coal loading | [74] |
| 5 | Pine sawdust (gasification) & $CH_4$ (pyrolysis) | CO production from pine sawdust via $CO_2$ partial gasification & $H_2$ production from $CH_4$ via catalytic pyrolysis on Ni/gasification char | • 92% $CO_2$ conversion (for gasification)<br>• 91% $CH_4$ conversion (for pyrolysis) | [75] |
| 6 | Algal waste, *Spirogyra* sp., *Rhizoclonium* sp., & *Chlorella vulgaris* | Gasification of pyrolytic products | • Highest $H_2$ yield of 6.5% (from *Chlorella vulgaris*)<br>• Highest molar $H_2$ fraction of 0.58 (from *Chlorella vulgaris*) | [76] |
| 7 | Peanut shell waste | Gasification of pyrolytic products | • Char production rate of ~30 kg $h^{-1}$<br>• $H_2$/CO ratio of ~2.3<br>• Optimal operating condition: T=650 °C, P=0.1 MPa, and air/biomass ratio=0.1 | [77] |
| 8 | Heavy oil | Gasification of coke to supply syngas to pyrolysis of heavy oil | • Increase in pyrolytic liquid yield<br>• Increase in the contents of alkanes, olefins, aromatics, oxygenates, and S- and N-containing compounds | [78] |

and syngas yields were 83 g $kg_{feed}^{-1}$ and 486 g $kg_{feed}^{-1}$, respectively, with a lower heating value (LHV) of 12.5 MJ $Nm^{-3}$ ($Nm^3$=normal cubic meter at 0 °C and 1 atm).

Gil-Lalaguna et al. presented a hybrid process composed of pyrolysis of sewage sludge and gasification of sewage sludge-derived char (Entry 2 in Table 1) [69-71]. The pyrolysis of sewage sludge at 530 °C in $N_2$ (4.5 $m^3$ $min^{-1}$) led to a char yield of 51.9 wt% with a higher heating value (HHV) of 5.2 MJ $kg^{-1}$. The highest char gasification efficiency (64%) and energy content of the resultant gas (3.52 MJ $kg_{char}^{-1}$) were achieved at 850 °C with an equivalent ratio of 0.32 and a steam/biomass mass ratio of 0.39. Energetic assessment of the hybrid process showed that an additional energy input is needed to perform the hybrid process. The additional energy may be supplied by combustion of pyrolytic oil of sewage sludge obtained in the pyrolysis stage only if the oil is properly upgraded to enhance its stability and reduce its nitrogen content. A similar hybrid system was also reported by Im-orb et al. for the co-production of syngas and liquid fuel from rice straw, which found that the integrated process operated at a high pyrolysis temperature leads to a high yield of syngas and pyrolytic oil with reduced waste heat [72].

An integrated fluidized bed comprising a transport bed pyrolyzer and a fluidized bed gasifier was developed by Chen et al. [73]. The hybrid process was beneficial for producing $CH_4$-rich syngas and high-quality liquid fuel. The $CH_4$ and liquid fuel production were highly associated with pressure and $Ca(OH)_2$ catalyst. The combination of high pressure and $Ca(OH)_2$ catalyst led to the $CH_4$-rich producer gas of 10.8 vol% with a $H_2$/CO ratio of 2.3. This was estimated to be suitable for making synthetic natural gas (i.e., $CH_4$). The obtained liquid fuel had a light tar content of 95 wt% (Entry 3 in Table 1).

Dai et al. introduced a hybrid process to integrate pyrolysis and entrained-flow gasification for the conversion of as-mined brown coal having 65 wt% moisture (Entry 4 in Table 1) [74]. The initial pyrolysis resulted in $H_2$-rich pyrolytic gas, pyrolytic oil, and char. The char was dried and then gasified with bituminous coal or $SiO_2$, yielding syngas. The syngas was cleaned and underwent water-gas shift reaction to obtain a $H_2$/CO molar ratio of 2. The cleaned syngas was then mixed with the $H_2$-rich pyrolytic gas to maximize energy density of the gaseous product. The exergy efficiency of the hybrid process was 4.5% higher than that of single gasification process. The pre-removal of feedstock moisture by 20% could enhance the exergy efficiency by 4%. The exergy efficiency was also increased to 62% with an addition of 20 wt% black coal.

A study done by Zhang research group [75] was aimed at syngas production by integrating the gasification of pine sawdust in the presence of $CO_2$ for the production of CO and the catalytic pyrolysis of $CH_4$ on a Ni catalyst supported on gasification char for the production of $H_2$ (Entry 5 in Table 1). The impacts of reaction temperature, $CO_2$ flow rate, catalyst loading, and residence time on the properties of the gasification char were explored. For the gasification, the $CO_2$ conversion was 92%. In particular, the gasification char-based catalyst allowed a stable $CH_4$ conversion of ~91% during the $CH_4$ pyrolysis at 850 °C most likely due to a high Ni reduction degree and high Ni dispersion on the catalyst surface.

Faraji and Saidi proposed to integrate pyrolysis and air gasification for the production of $H_2$-rich syngas from various algal biomass and waste feedstocks (e.g., algal waste, *Spirogyra* sp., *Rhizoclonium* sp., and *Chlorella vulgaris*) (Entry 6 in Table 1) [76]. The authors used a steady state equilibrium simulation model as a predictive tool to optimize the gasification performance. The optimal condition was air flow rate of 0.01 $m^3\ h^{-1}$, gasification temperature of 600 °C, and gasification pressure of 0.1 MPa, leading to the highest $H_2$ content in syngas. At comparable operation condition, *Chlorella vulgaris* resulted in a higher $H_2/CO$ ratio than other three feedstocks, while algal waste resulted in a lower $H_2/CO$ ratio than the others, equivalent to ~6.5% $H_2$ yield at ~1,000 °C.

More recently, the same research team (Faraji and Saidi) also reported a similar hybrid pyrolysis-gasification process that treats peanut shell waste (Entry 7 in Table 1) [77]. Pyrolysis of peanut shell waste made char that was used for catalyst support. The activation of the char was done with KOH, followed by pyrolysis at 650 °C to produce activated carbon support. The specific surface area of the char increased from 3.5 $m^2\ g^{-1}$ to ~360 $m^2\ g^{-1}$ with rising pyrolysis temperature from 300 °C to 500 °C. A simulation of the large-scale hybrid pyrolysis-gasification process was performed to optimize temperature, pressure, and air/biomass ratio to simultaneously enhance char yield and syngas quality. The optimal operating condition involved T=650 °C, P=0.1 MPa, and air/biomass ratio=0.1, resulting in a char production rate of ~30 kg $h^{-1}$ and a $H_2/CO$ ratio of ~2.3.

The Zhang research group suggested a hybrid process integrating pyrolysis of heavy oil and gasification of coke, aimed at realizing *in situ* coke gasification that provides syngas atmosphere for heavy oil pyrolysis to obtain high-quality liquid fuel (Entry 8 in Table 1) [78]. The integrated process was operated at 450 °C. The yield of heavy oil-derived pyrolytic liquid was higher under the syngas atmosphere than under typical $N_2$ atmosphere, while the yields of pyrolytic gas and coke were lower under the syngas atmosphere than under typical $N_2$ atmosphere. The proportions of $CO_2$, $CH_4$, and $C_2$-$C_5$ hydrocarbons in the pyrolytic gas were decreased in the syngas condition, but the proportions of alkanes, olefins, aromatics, oxygenates, and S- and N-containing compounds in pyrolytic liquid were increased. The results showed that the syngas hinders additional decomposition of condensable products.

### 2. Hydrothermal Carbonization-gasification System

Yan et al. recently proposed a hybrid energy recovery process consisting of hydrothermal carbonization and supercritical water gasification for the treatment of household kitchen waste [79]. In the hybrid thermochemical conversion process, the waste feedstock is first hydrothermally carbonized at 300 °C for 75 min, resulting in hydrochar with an energy content of 20.6 MJ $kg^{-1}$ and liquid byproduct. The liquid byproduct is then transformed into $H_2$-rich syngas (~3.9 $mol_{H2}\ kg_{feed}^{-1}$) via supercritical water gasification at 480 °C for 20 min. Fig. 1 describes the concept of the hybrid thermochemical conversion process. The hybrid system could lead to higher energy efficiency and return on energy investment than direct supercritical water gasification. The cost benefit ratio of the hybrid system was estimated to be ~1.9, which is an indication of its economic feasibility.

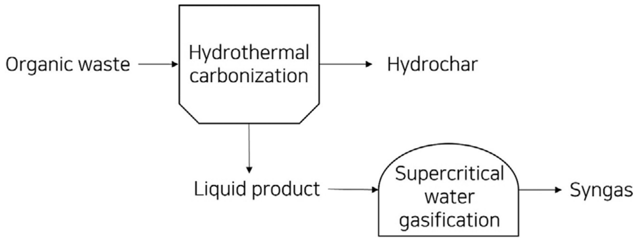

**Fig. 1. Schematic diagram of a hydrothermal carbonization-gasification hybrid waste-to-energy system.**

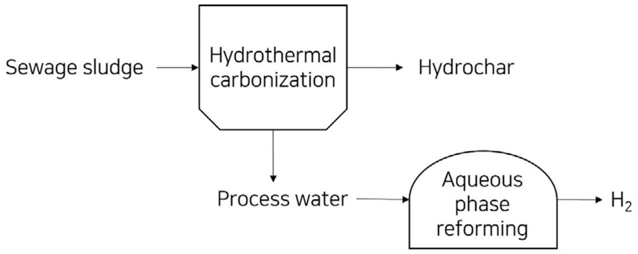

**Fig. 2. Schematic diagram of a hydrothermal carbonization-aqueous-phase reforming hybrid waste-to-energy system.**

### 3. Hydrothermal Carbonization-aqueous-phase Reforming System

A hybrid thermochemical waste conversion process composed of hydrothermal carbonization and aqueous-phase reforming has recently been suggested by Oliveira et al. [80]. The authors aimed at recovering energy from sewage sludge through the hybrid system, as schematically depicted in Fig. 2. Hydrothermal carbonization of sewage sludge was first performed at 170-230 °C for 60 min, which made hydrochar having an energy content of 20-24 MJ $kg^{-1}$, a fuel ratio of 0.2-0.5), and a comprehensive combustion index ($5.8\times10^{-7}$-$10^{-6}\ min^{-2}\ {}^{\circ}C^{-3}$) and process water (byproduct of the hydrochar production). Aqueous-phase reforming of the process water was performed at 220 °C and 2.5-2.9 MPa for 240 min in order to produce $H_2$. The aqueous-phase reforming of the process water led to up to 98.7 $mmol_{H2}\ g_{TOC}^{-1}$ on a carbon black-supported Pt-Rh bimetallic catalyst. The potential energy recovery from dry sewage sludge achieved with the hybrid system was calculated to be 17.3 MJ $kg^{-1}$, equivalent to 93.5% of gross energy of the sewage sludge feedstock.

## TECHNO-ECONOMIC VIABILITY OF HYBRID THERMOCHEMICAL WASTE CONVERSION PROCESS

Although there have very rarely been studies of economic analysis of the hybrid thermochemical waste-to-energy systems, few studies of modeling large-scale hybrid thermochemical waste-to-energy process are available, which deserve to be introduced in this section.

Rezaei and Mehrpooya conducted a process simulation of a hybrid thermochemical process integrating fast pyrolysis and co-gasification, which produces liquid fuels and subsequent hydrotreating [81]. Waste biomass is first transformed into pyrolytic oil, pyrolytic gas, and char via fast pyrolysis. The pyrolytic products are then employed in biorefinery and gasification. The process simulation results indicated that the feed stream of 1 kg $s^{-1}$ produces pyrolytic liquid of ~0.7 kg $s^{-1}$, pyrolytic gas of 0.16 kg $s^{-1}$, and char of 0.17 kg $s^{-1}$. In addition, approximately 5.6 $MW_e$ could be generated through steam cycle. Excess heat of gasification was exploited to produce additional heat supplied to the integrated process. Syngas evolved from the gasification unit was fed into a steam reforming unit to make $H_2$ for the hydrotreating. The resultant yields of gaseous, liquid, and solid fuels were 16.4% 68.9%, and 14.7%, respectively. The energy efficiency of the entire process was determined at ~61.8% with greenhouse gas saving rate of up to 57.6%. As a result, maximum energy recovery from waste biomass through the hybrid system reached 69.8 MW. The economic analysis results showed that the hybrid thermochemical waste-to-energy system (daily feeding: 717 tons) has a total capital cost of 53.7 million USD, total yearly operating cost of 19 million USD, and product value of 7.2 USD per gallon.

Detchusananard et al. developed a hybrid pyrolysis-gasification process that uses empty fruit bunch to produce biofuels via a computer simulation process modelling with a heat exchanger network design to improve overall energy efficiency of the integrated process [82]. The process condition was set to be a steam/biochar mass ratio of 2.7, a gasification temperature of 900 °C, a steam/syngas mass ratio of 3, and a water-gas shift reaction temperature of 240 °C, resulting in $H_2$ (140 kg $h^{-1}$), other gases (290 kg $h^{-1}$), gasoline-range chemicals (657 kg $h^{-1}$), naphtha-range chemicals (729 kg $h^{-1}$), kerosene-range chemicals (298 kg $h^{-1}$), and diesel-range chemicals (811 kg $h^{-1}$). The minimum cold and hot utilities were estimated to be ~5,250 MJ $h^{-1}$ and ~21,600 MJ $h^{-1}$, respectively. Key indicators of economic performance of the hybrid system (e.g., net present value, payback period, and internal rate of return) were also analyzed. The economic analysis showed that the hybrid system that transforms empty fruit bunch into biofuels is potentially economically viable as net present value is ~250 million USD, payback period is about 6 years, and internal rate of return is 22%.

## SUMMARY AND OUTLOOK

Hybrid thermochemical waste-to-energy processes have recently been proposed by several research groups. These systems have great potential as highly effective and feasible solutions to waste management and climate change mitigation. The following points might be considered for further developments of the hybrid thermochemical waste-to-energy systems.

The conversion efficiency of hybrid thermochemical waste-to-energy processes is significantly influenced by waste feedstock characteristics (e.g., elemental composition, the contents of moisture, ash, and other impurities, and biodegradability). Nevertheless, various factors, such as industrial structure, municipality, waste management regulations, and economic situation, affect the waste characteristics [83]. Therefore, hybrid thermochemical waste-to-energy processes are difficult to instantly fulfill changing energy demands. The collection and transportation of waste to waste-to-energy plants are also important for continuous operation of the hybrid systems. Hence, the waste collection and transportation systems should be fully established, associated with local environments and situations. It would be a necessary part of future research to solve the power fluctuation problems in grid-connected hybrid waste-to-energy systems.

High contents of moisture and ash of waste feedstocks (e.g., >10 wt%) may lead to high tar production requiring additional cleaning steps [84] and cause slugging in gasifier [85]. As this problem is particularly related to continuous feeding, more studies on the pretreatment of a range of waste feedstocks are needed to promote the installation of hybrid thermochemical waste-to-energy processes as an active waste treatment approach. In addition, comparative analysis of various hybrid thermochemical waste-to-energy process configurations needs to be conducted in order to elucidate how to select hybrid system configurations according to the kinds of waste substances. Techno-economic analyses of the different configurations need to be carried out to assess the possibility of scale up of the hybrid thermochemical waste-to-energy processes.

Some cases have shown that liquid and char produced from pyrolysis are transformed to gasification system for following gasification reaction. However, transformation systems of intermediate products into the next reactor have not yet been demonstrated in the earlier studies. For practical use of the hybrid systems, the transformation of intermediate products into the next reactor needs to be fully developed.

Despite potential sustainability of the hybrid thermochemical waste-to-energy systems, the industrialization of the systems cannot be achieved without social awareness. Governmental, non-governmental, and social organizations persuading people to employ the hybrid waste-to-energy technologies might play a substantial role in promoting the application of hybrid thermochemical waste-to-energy systems [86]. Furthermore, the pressing needs for eco-friendly industrial processes to achieve carbon neutrality will eventually improve the viability of hybrid thermochemical waste-to-energy systems.

Overall, this paper gives an extensive review of hybrid systems integrating two different thermochemical waste conversion processes (e.g., gasification–pyrolysis, hydrothermal carbonization-gasification, and hydrothermal carbonization-aqueous-phase reforming). Current technical accomplishments in hybrid thermochemical waste-to-energy system designs are summarized and discussed. Even though hybrid thermochemical waste-to-energy systems have shown promise, the number of available literatures is limited. Therefore, continuous efforts need to be made to further enhance the effectiveness and feasibility of hybrid thermochemical waste-to-energy systems.

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## CONFLICTS OF INTEREST

There are no conflicts to declare.

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