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3 **Catalytic steam reforming of biomass tar: Prospects and challenges**
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1
2 **Abstract**
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4 Tar is unavoidable by-product during biomass gasification process. Catalytic steam
5 reforming of tar to syngas is a promising way for the removal of tar from the gas
6 products. However, the key issue for this way is catalyst development. To date, the
7 developed catalysts always have advantages and disadvantages: nickel-based catalysts
8 have high activity, but they are easily deactivated by coking; noble metal based catalysts
9 have high catalytic activity, long-term stability and high carbon deposition resistance,
10 but they are expensive; other transition metal catalysts such as Fe, Co and Cu exhibit a
11 good performance, but they are also deactivated easily by carbon deposition in the case
12 of high heavy-tar content in the tar; alkali metal catalysts also have high catalytic
13 activity for tar reforming, but they are easy to be evaporated with the generated gases;
14 natural catalysts have been widely applied for the steam reforming of tar due to its
15 inexpensive, abundant and disposable, but their catalytic activities are lower than those
16 man-made ones, and especially have low mechanical strength, making them not suitable
17 to be used in fluidized bed reactor; zeolite is suggested to be a good catalyst support due
18 to its high thermal/hydrothermal stability, high resistance to sulfur compounds, and easy
19 to be regenerated; biomass char has been used as the catalyst or catalyst support in the
20 steam reforming of tar due to its low cost and its natural production inside the biomass
21 gasifier; even biomass ash now is considered to be a good catalyst for tar removal. In
22 this review, to get better understanding of the mechanism of catalytic steam reforming
23 of tar derived from biomass, tar formation, tar properties and catalytic reaction
24 mechanism are also introduced, and prospects and challenges are summarized.

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56 **Keywords:** Biomass; tar; gasification; catalyst; steam reforming; activity; stability;
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58 challenge.
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1 Introduction

1.1 Biomass resources

Nowadays, energy, environment and economy (3E) issues are three common concerns that should be considered simultaneously. Due to the growth of the world's population, worldwide energy demand is increasing rapidly. To date, fossil fuels are the major energy resources for the world energy requirement. However, they cause global warming and air pollution due to the emission of greenhouse gas and toxic gases and particles. To solve the 3E issues simultaneously, the utilization of new energy resources such as solar, wind, tide, geothermal and biomass, which are abundant, low carbon emission and environmentally friendly, is becoming more and more important. Among these new energy resources, it should be noted that only biomass is the real renewable energy source which can provide stable power as fossil fuels. For instances, the use of solar energy is limited in the day time; the use of geothermal energy may let toxic chemicals under the earth erupt to the atmosphere and the use of wind energy needs strong and stable wind, and simultaneously generate noise problem. According to the World Energy Outlook 2011, biomass is the fourth world-wide energy resource after coal, petroleum and natural gas (Table 1) and could provide about 14% of the world's energy consumption [1]. Moreover, compared with fossil fuels, the use of biomass as fuel is a carbon neutral process since the produced carbon dioxide from biomass utilization process can be captured via photosynthesis during the growth of biomass. Thus, the utilization of biomass energy can result in both the reduction of greenhouse gas emission and the replacement of non-renewable energy resources [2-6].

Table 1. World primary energy demand (Mtoe) [8].

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2 Biomass can be defined as any organic **materials derived** from plants or animals
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4 which **can be divided into two main** groups: (1) Virgin biomass (2) Waste (Fig. 1) [2].
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8 9 **1.2 Biomass energy conversion**

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11 Biomass is the renewable source of carbon which can be converted to solid, liquid
12 and gaseous products through various conversion processes. **To date, as shown in Fig.2,**
13 there are 4 main **routes**, i.e., direct combustion, physical conversion, biochemical and
14 thermochemical conversions, to convert biomass into various energy such as heat, solid,
15 liquid and gaseous fuels. For biochemical conversions, the biomass is converted into
16 liquid (ethanol, acetone and butanol, **hydrogen**) or gaseous fuels (methane) by aerobic
17 fermentation or anaerobic fermentation while for thermochemical conversions, the
18 biomass can be converted by four main **ways**: (1) torrefaction; (2) direct liquefaction;
19 (3) pyrolysis and (4) gasification. **Thermochemical** conversion technologies have some
20 advantages over biochemical conversion ones. The feedstock for biochemical processes
21 is very **limited** (rich in starch or sugar) whereas **that for the thermochemical processes**
22 **can include anything.** Moreover, **thermochemical conversion rate processes is much**
23 **faster than biochemical one** [7].
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47 **Fig. 1.** Major groups of biomass and their sub classifications [1,2,7].
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53 **Fig. 2.** Four possible routes for biomass energy conversion [1-9].
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58 **1.3 Biomass gasification**

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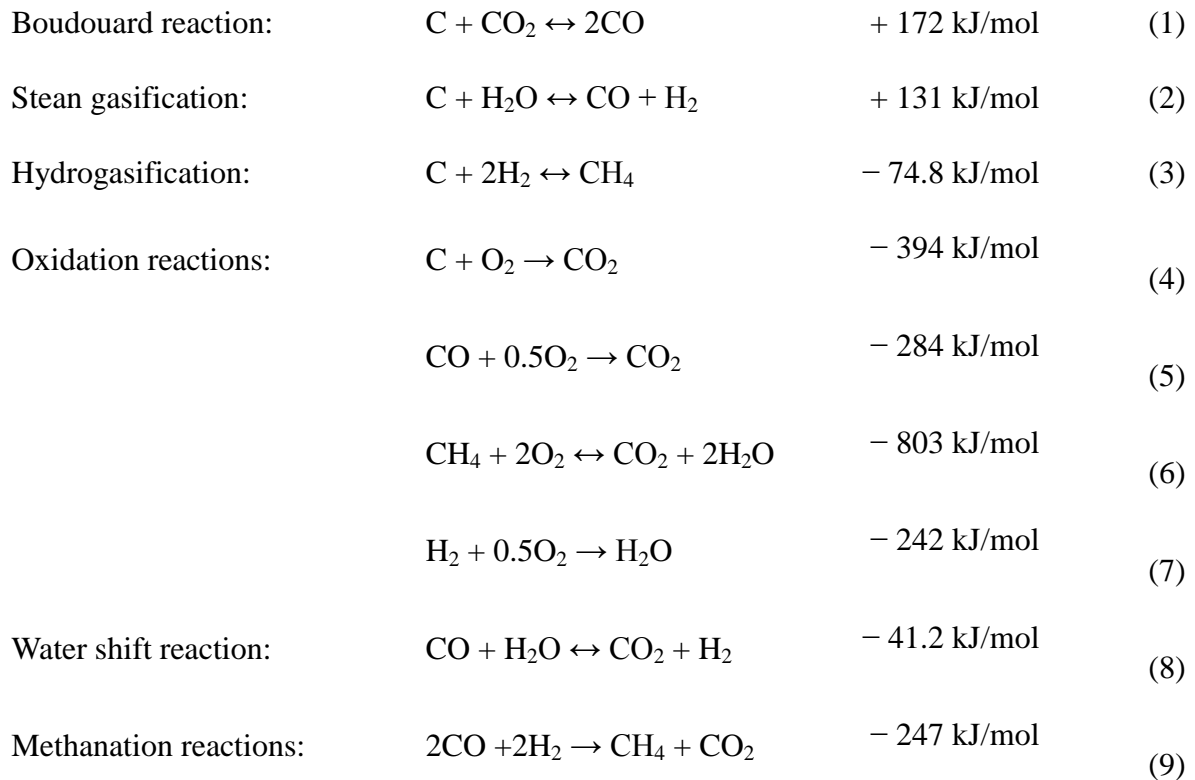
Among all thermochemical conversion technologies, gasification is a promising way to convert biomass energy **into gas fuels**, called syngas (synthesis gas), which can be widely used for electrical power generation (fuel cells, gas turbine or engine), or as feedstock for the synthesis of liquid fuels and various chemicals [10-12]. Therefore, biomass gasification has attracted the most attention from both industrial and academic researchers due to its advantages. Biomass gasification is a thermochemical conversion process in which carbonaceous substances in biomass are converted into combustible gaseous products in the presence of a gasifying agent (air, steam, oxygen, CO₂ or a mixture of these) at high temperatures (**generally over 700 °C to date**). The main products of biomass gasification are H₂, CO, CO₂, CH₄, H₂O, solid carbonaceous residues, ashes, and tars (oils) [12-14]. **Biomass gasification process usually undergoes 4 steps as illustrated in Fig.3:**

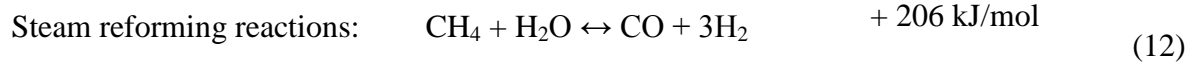
- ***Drying and Heating of biomass:* This step occurs from the start until a temperature of around 200 °C. For gasification, the optimum moisture content in the biomass should be below 15%, and thus, more moisture in the biomass should be evaporated at first by heating.**
- ***Pyrolysis:* This step occurs at the temperature ranged from 150 to 900 °C. Hemicellulose, cellulose and lignin in biomass will be decomposed in order into gases with small molecules and volatiles with various molecular weights and char (a solid residue mainly containing carbon). Some volatiles become to liquid after cooled down to room temperature, which is called tar, a black, viscous and corrosive liquid composed of heavy organic and inorganic molecules.**

- *Oxidation or partial combustion:* This step occurs at a temperature over 700 °C. The products of the pyrolysis are partially or completely oxidized with oxygen in air to form CO, CO₂, and H₂O. The oxidation reactions are exothermic which provides heat for the subsequent gasification reactions.
- *Reduction or gasification:* This step occurs at temperatures over 800 °C, in which the char reacts with gasifying agents such as oxygen and steam, and the final products mainly include H₂, CO, CO₂ and CH₄.

Fig. 3. Main processes during biomass gasification.

The main reactions that occur during biomass gasification can be summarized as follows [13]:





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18 In these gasification reactions, one important factor to significantly influence on
19 the quantity and quality of the products is the gasifying agent. The use of different
20 gasifying agents results in different reactivity and gas compositions. Various gasifying
21 agents such as air, oxygen, steam, carbon dioxide or their mixtures can be used. The
22 choice of them depends on the desired product gas composition and energy
23 consumption [14, 15]. Air is the most used gasifying agent owing to its near-zero cost,
24 but the obtained syngas has low heating value due to the dilute effect of the large
25 amount of nitrogen in air. Pure oxygen can produce syngas with higher quality, but the
26 operating cost is high due to energy requirement for the oxygen production [16]. In
27 contrast, steam gasification of biomass can increase the heating value of syngas. In
28 recent years, steam gasification of biomass attracts more and more attentions because it
29 produces a gaseous fuel with relatively higher hydrogen content which can be used in
30 fuel cells and hydrogen engines. However, the composition and properties of the
31 products from the steam gasification of biomass depend on several parameters. Thus, to
32 obtain the desired product gas, the gasification operating conditions need to be
33 optimized.

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Biomass consists of cellulose and hemicellulose, lignin and minerals (ash) [17].
These components affect the product composition from the steam gasification of

1 biomass. Many researchers carried out gasification of different types of biomass.
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3
4 Hanaoka et al. [18] studied the gasification of two types of biomass: aquatic biomass
5 (gulfweed) and terrestrial biomass (cedar), which have different chemical compositions
6 and ash content, and found that gulfweed obtained a higher conversion to gas compared
7 to that of cedar. This is due to the higher ash content in gulfweed (11.8 wt.%) and
8 residual alkaline metals in char promoted pyrolysis and char gasification. In our
9 previous study[19], three types of biomass, i.e., brown seaweed, Japanese cedar, apple
10 branch containing different concentrations of alkali and alkaline earth species, and the
11 mix of both of them were gasified with steam in a fixed-bed reactor under atmospheric
12 pressure. The results also indicated that higher gas production yields (especially for H₂
13 and CO₂) were obtained for brown seaweed than other two types of biomass since the
14 brown seaweed contains much higher ash content and larger amount of alkali and
15 alkaline earth species than terrestrial biomass. Although some compositions in ash can
16 promote the gasification rate, the extremely high amount of ash may cause some
17 disadvantages. Yang et al. [20] co-gasified woody biomass and microalgae in a
18 fluidized bed and found that the high ash content in microalgae (9 wt.%) caused
19 sintering and agglomeration during gasification so that the cogasification was
20 unfavorable for syngas production. Asadullah et al. [21] performed gasification of
21 different biomass in a dual-bed gasifier system and concluded that the carbon
22 conversion to gas and the yields of useful gases such as CO, H₂ and CH₄ were
23 dependent on the characteristics of each type of biomass. Lapuerta et al. [22] reported
24 that K₂O content in biomass ash can play an important role on the gasification
25 performance, since its catalytic effect improved the energy content of produced gas.
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58 Gasification temperature is also a significant operating parameter, which has great
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2 effect on the gaseous composition and carbon conversion throughout the oxidation and
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4 gasification reactions [23]. Yan et al. [24] studied the effect of bed temperature on
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6 hydrogen yield and syngas composition. With the increasing of the bed temperature
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8 from 600 to 850 °C, the carbon conversion efficiency was obviously increased from
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10 13.16 to 95.78% and the dry gas yield increased from 0.19 to 2.44 Nm³/kg. Moreover,
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12 H₂ content was increased significantly from 29.54 to 52.41%. Min et al. [25]
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14 investigated the effect of bed temperature (500-850 °C) on tar content and found that
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16 the tar **yield was** decreased with the increasing of temperature. Erkiaga et al. [26]
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18 gasified pinewood sawdust in the bed temperature range of 800-900 °C, and observed
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20 that the increase in the temperature led to the increasing of H₂ content **and the**
21
22 **decreasing of tar and char yields**. Berrueco et al. [27] investigated the gasification
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24 properties of two types of biomass (Norwegian spruce and Norwegian forest residues)
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26 at 750-850 °C and found that the increase of temperature resulted in higher gas **yield,**
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28 **higher** char gasification rate and lower tar formation. From these results, it can conclude
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30 that the gasification temperature is the dominant parameter which influences both the
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32 amount and **compositions of products**. Higher gasification temperature produces **a**
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34 **syngas** rich in hydrogen and carbon monoxide but with small amounts of methane **and**
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36 **heavy hydrocarbons**. This is because the higher temperature enhances the endothermic
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38 **steam** gasification reactions and Boudouard reaction. Moreover, higher temperature can
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40 effectively decompose and convert the tar into lighter gaseous products.
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52 Steam flow rate is another important parameter **to influence** both product gas
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54 compositions and energy input in **the** steam gasification of biomass [1,28]. Generally,
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56 the steam flow rate **is expressed** in term of steam to biomass ratio (S/B), which is
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58 defined as the flow rate of the steam fed into the gasifier divided by the biomass flow
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1
2 rate. Many researchers have reported that the introduction of a sufficient steam amount
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4 leads to the increase of gas yield, especially the increase of hydrogen yield. Xiao et al.
5
6 [29] studied the catalytic steam gasification of biomass in fluidized bed at low
7
8 temperature. The effects of catalyst performance, reaction temperature and steam
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10 amount on gas yield, gas composition and carbon conversion efficiency were
11
12 investigated. They found that the carbon conversion, the selectivity of H₂ and the energy
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14 output were improved by the introduction of steam. The product gas contains lower CH₄
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16 and CO contents due to steam reforming of CH₄ and the water-gas shift of CO.
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18 However, the H₂ yield was increased from 13.9 to 21.3 mmolg⁻¹-d.a.f., which is very
19
20 close to the optimum value of 22.0 mmolg⁻¹-d.a.f. at the equilibrium state. Luo et al.
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22 [30] investigated the effect of S/B in the range of 0-2.80 on the gasification performance,
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24 and observed that the introduction of steam improved the dry gas yield and carbon
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26 conversion efficiency but the excessive steam decreased hydrogen content and finally
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28 degraded fuel gas quality. They reported that the optimum S/B was 2.10 in which the
29
30 hydrogen content reaches the maximum, up to 52.7%. Meng et al. [31] also investigated
31
32 the effect of S/B on product gas distribution and tar formation. The results revealed that
33
34 with the increasing of S/B from 1.13 to 1.45 at 770 °C, the total tar content was
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36 decreased from 10.2 to 7.2 g/Nm³. They also reported that with the increase in S/B, the
37
38 concentrations of CO, CH₄, C₂H₄ and C₂H₂ gradually decreased, while the
39
40 concentration of H₂ increased due to the partial oxidation and steam reforming reactions.
41
42 Lv et al. [32] studied the effects of operating conditions on gas composition and carbon
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44 conversion efficiency. In their experiments, the S/B was varied from 0 to 4.04. Their
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46 results revealed that the introduction of steam improved the gas quality. With the
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48 increase of S/B from 1.35 to 2.70, the contents of CO, CH₄ and C₂H₂ decreased
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2 gradually, whereas CO₂ and H₂ content increased. From these results, one can conclude
3
4 that the introduction of steam in gasification process can provide a gaseous product with
5
6 high content of H₂. Moreover, the increase of steam flow rate can decrease char and tar
7
8 yields since the introduction of steam favors water-gas shift reaction, steam gasification
9
10 of char, and steam reforming of tar. However, the use of excess steam may cause some
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12 disadvantages including high water quantity in the produced gas, which leads to more
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14 energy consumption in separation of steam out of the gas product.
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22 *1.4 Tar issue*

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24 Tar formation is one of the major problems during biomass gasification, which can
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26 cause the following 3 problems [12]:
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- 28 ● Condensation and subsequent plugging of downstream equipment
- 29 ● Formation of tar aerosols
- 30 ● Polymerization into more complex structures

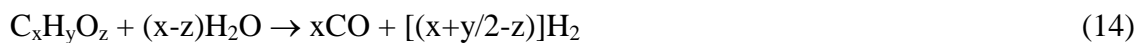
31
32 High concentration of tar can lead to unacceptable levels of maintenance for engines
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34 and turbines. Especially, tar is harmful to our health because of its carcinogenic
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36 character. Tar can be defined as a complex mixture of condensable hydrocarbons, which
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38 includes single ring to 5-ring aromatic compounds along with other oxygen-containing
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40 hydrocarbons and complex polycyclic aromatic hydrocarbon (PAH) [33].
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49 There are many possible techniques for tar removal. In general, tar removal
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51 methods can be classified into physical method using ceramic candle filters or wet
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53 scrubber, and thermochemical conversion method using high temperature or using
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55 catalyst to convert tar into syngas. In comparison to the physical method which only
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57 physically removes tar from gas product, the latter one has received much attention
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1
2 because tar can be converted into useful gas product, and increase the overall efficiency
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4 of the gasification process [34]. Thermal cracking of tar at high temperature to
5
6 decompose the large organic molecules to smaller non-condensable gases without
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8 catalyst is not attractive because it requires energy and produces soot [35]. In contrast,
9
10 catalytic conversion of tar can reduce the reaction temperature and more effectively
11
12 convert tar to useful gases.
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17 Two main approaches are considered for catalytic tar conversion [36]. One is
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19 mixing catalyst with the biomass feedstock and in this case, tar can be converted inside
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21 the gasifier. The other approach uses a separated reactor located at the downstream of
22
23 the gasifier and converts tar outside the gasifier. Although the latter one has high
24
25 effectiveness to remove tar, it is either costly or complex for those small and medium
26
27 scale systems [37,38].
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32 To date, it is proved that steam reforming of tar, which can be expressed in Eq.
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34 (14), is a very attractive technique for tar removal since it can remove tar more
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36 effectively and simultaneously convert tar into useful gases (H₂, CH₄, and CO) [39-41].
37
38 Especially, in this process, the produced CO can react further with the excess steam via
39
40 water-gas shift (WGS) reaction as shown in Eq. (15) to produce more useful gas like H₂
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42 [42].
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57 The basically catalytic mechanism of the steam reforming of tar is the
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1
2 dehydrogenation of hydrocarbon components in tar on the active sites of catalyst
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4 whereas the carbon could be formed on the same sites. However, the deposited carbon
5
6 could further reacts with steam to generate additional CO and maintains the catalyst
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8 activity [43]. Generally, the catalyst with high activity and stability is required for the
9
10 efficient steam reforming of tar.
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14 In this review, to get better understanding of the mechanism of catalytic steam
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16 reforming of tar derived from biomass, tar formation, tar properties and catalytic
17
18 reaction mechanism are introduced. The objective of this review is to summarize
19
20 various typical catalysts that have been used in recent research works for the steam
21
22 reforming of tar. The advantages and disadvantages of each type catalyst will be
23
24 evaluated. It is expected to give a guidance for the development of novel catalysts with
25
26 high activity, long-term stability and/or excellent reusability, and low-cost for a
27
28 practical tar reforming process.
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37 **2. Steam reforming of biomass tar**

38 ***2.1 Tar formation and properties***

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42 Tars are generally formed in the pyrolysis step due to the decomposition of
43
44 lignocellulosic biomass. The main components in this step are mostly oxygenated
45
46 hydrocarbons. With the increase in the reaction temperature, the oxygenated
47
48 hydrocarbons can be converted to light hydrocarbons, aromatics and olefins, which are
49
50 then converted to higher hydrocarbons and larger polycyclic aromatic hydrocarbons.
51
52 The schematic of tar formation as a function of temperature is shown in Fig. 4. It can be
53
54 seen that the organic compounds become more stable with the increase in temperature.
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59 Therefore, temperature is the key factor for tar distribution.
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5 **Fig. 4** Tar maturation scheme (Modified from Elliott 1988) [44].
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10 Tar can be classified by various ways. For instances, based on its appearance, tar
11 can be divided as primary, secondary and tertiary tars as shown in Table 2. Based on
12 molecular weight, tar can be divided into 5 classes as shown in Table 3. Tar problem is
13 not mainly concerned with the tar quantity, but with the properties and the compositions
14 of tar [33].
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25 **Table 2.** Tar classification based on its appearance [45,98,119].
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29 **Table 3.** Tar classification based on molecular weight of tar compounds [33,98].
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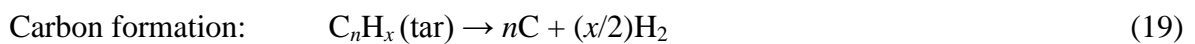
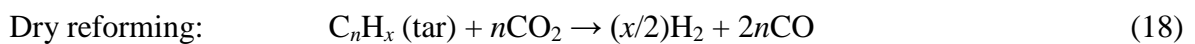
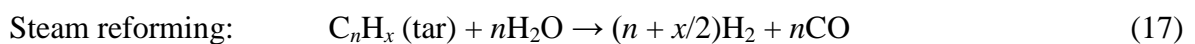
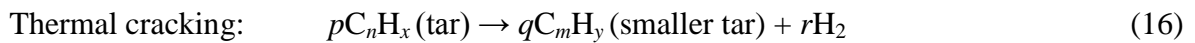
35 The typical composition of biomass tar is shown in Fig. 5. However, the amount
36 and composition of tar produced in biomass gasification depends on many factors such
37 as type of biomass feedstock, gasifier type and gasifying agent, and operating
38 conditions such as temperature and pressure. Yu et al. [46] studied tar formation
39 characteristics for the gasification of major biomass components (i.e., cellulose,
40 hemicellulose and lignin) and revealed that lignin has higher tar yields and results in the
41 formation of more stable components in tar than others but the tar composition shifts
42 toward higher-molecular-weight substances such as PAHs at higher temperature. Meng
43 et al. [31] reported that with the increasing of temperature the total produced tar
44 decreases. Moreover, the temperature affects not only tar formation yield but also the tar
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2 properties. Han and Kim [11] reported that with the increase in the temperature more
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4 class 1 and 2 tars are decomposed but more class 3 and 5 tars are formed. For the
5
6 gasifying agent, the additions of steam and oxygen can greatly reduce the tar yield [47].
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13 **Fig. 5.** Typical composition of biomass tars [48, 120].
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18 **2.2. Catalytic steam reforming of tar**

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21 As stated above, among tar removal techniques, catalytic steam reforming is the
22
23 most attractive technique since the presence of catalyst can remove tar more effectively
24
25 and simultaneously convert tar into useful gas (H₂, CH₄, and CO) at lower temperature
26
27 than non-catalytic tar conversion. During catalytic steam reforming, many reactions take
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29 place simultaneously and the product distribution is a result of the competition among
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31 them. Those reactions can be summarized as follows [1, 33]:
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46 and reactions (1)-(13).

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49 **It is expected that all tar can be converted** by steam into simpler and lighter
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51 molecules like H₂ and CO. In case of excess steam, the produced CO could react further
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53 with steam, producing more H₂. Many researchers studied the tar removal by catalytic
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55 steam reforming [38, 49-54]. For instances, Kim et al. [50] investigated the catalytic
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57 conversion of tar under inert and steam reforming conditions and found that catalytic
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1
2 steam reforming of tar exhibited lower tar yield and less coke deposition on catalyst
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4 surface than the inert condition. Miyazawa et al. [51] investigated the catalytic
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6 performances of various supported Ni catalysts for the steam reforming of tar derived
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8 from cedar and found that no tar was observed when using Ni/Al₂O₃, Ni/ZrO₂ or
9
10 Ni/TiO₂ as the catalyst at a reaction temperature of 650 °C. Li et al. [52] also reported
11
12 that the steam reforming of biomass tar over BaAl₁₂O₁₉-supported Co catalyst
13
14 effectively removed almost all tar at relatively low temperature of 550 °C.
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22 **2.3. Mechanism of catalytic steam reforming of tar**

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24 Due to the complexity of real tar, most researchers used the model tar compounds
25
26 such as benzene, toluene, or naphthalene to study the catalytic mechanism [55-60]. For
27
28 instances, Bampenrat et al. [55] studied steam reforming of naphthalene over nickel
29
30 supported on Ce_{0.75}Zr_{0.25-x}Mn_xO₂ mixed oxide catalysts and found that the complete
31
32 naphthalene conversion can be remained for at least 6 h on stream. Ferella et al. [57]
33
34 also studied the steam reforming of naphthalene as a model tar over ZrO₂- and
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36 Al₂O₃-supported catalysts and found that Al₂O₃-supported active metal catalysts were
37
38 more active than zirconia ones, achieving 90-100% of naphthalene conversion even at
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40 500 °C. Zhao et al. [58] used toluene as model tar compound to study the catalytic
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42 performance of Ni/cordierite catalyst and found that the conversion of toluene increased
43
44 with temperature, reaching 94.1% at 900 °C. Park et al. [59] investigated steam
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46 reforming of benzene over various nickel supported metal oxide catalysts and reported
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48 that 15 wt.% Ni/CeO₂(75%)-ZrO₂(25%) showed the highest catalytic performance with
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50 a 87% of benzene conversion.
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59 Jess [61] studied the mechanisms and kinetics of thermal conversions of aromatic
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1
2 hydrocarbons derived from solid fuels, using naphthalene, toluene and benzene as the
3
4 model compounds and proposed the simplified reaction scheme in the presence of
5
6 hydrogen and steam as shown in Fig. 6. He concluded that benzene should be the key
7
8 component of thermal decomposition of aromatic hydrocarbons. Carbonaceous residue
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10 (soot) formed is principally from the large hydrocarbon molecules such as naphthalene.
11
12 He also indicated that the soot and organic cracking products can be completely
13
14 converted to CO and H₂ in the presence of steam at a high temperature of 1400 °C.
15
16 Rama et al. [62] studied the catalytic activity and stability of oxidation pretreated
17
18 Ni-containing alloy tube catalysts in the steam reforming of model compounds of
19
20 tetradecane, toluene and naphthalene, and found that during thermal cracking,
21
22 straight-chained hydrocarbons easily convert to shorter and simpler hydrocarbons
23
24 whereas aromatic hydrocarbons dominantly change to benzene which is easy to form
25
26 carbon. As a result, the higher amount of carbon was formed in the case of naphthalene
27
28 when compared to toluene due to its 2-ringed structure. The coke formation during
29
30 cracking is the main factor for the catalyst deactivation since it could encapsulate the
31
32 active sites of the catalyst. Chen et al. [63] also reported that the coke deposited on the
33
34 catalyst is mainly from polycyclic aromatic hydrocarbons (PAHs), which could undergo
35
36 series of reactions of dehydrogenation, cyclization, and condensation, and result in the
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38 formation of larger polyaromatic molecules and coke. However, the coke formation
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40 during cracking can be avoided by increasing the temperature.
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54 **Fig. 6.** Simplified reaction scheme of thermal conversion of aromatic hydrocarbons in
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56 the presence of hydrogen and steam (Modified from Jess 1996) [61].
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2 In our previous studies[38,39, 64-66], various catalysts were developed for the
3 steam reforming of tar in the biomass gasification process. In order to describe about its
4 mechanism, all tar components are considered as one group (tar mixture) and the
5 proposed mechanism of catalytic steam reforming of biomass derived tar is shown in
6 Fig. 7. The volatiles produced in the pyrolysis step are passed over the catalyst layer.
7 Tar molecules are broken down to lighter molecules and reformed to useful gaseous
8 fuels (CO and H₂) on the active sites of catalysts via several simultaneous reactions
9 (thermal cracking, steam reforming, dry reforming, carbon formation, water-gas shift,
10 etc.). In the same time, tar molecules are also decomposed and formed free radicals
11 which can further generate coking on the catalyst surface via polymerization reactions.
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29 **Fig. 7.** Mechanism of catalytic steam reforming of biomass derived tar supposed in our
30 study (M_xO_y represents metal oxide catalyst) [121].
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36 **3. The prospects of catalytic reforming of tar**

37 There are several types of catalysts that have potential for catalytic reforming of tar.
38 The catalyst may be selected according the following criteria based on its properties
39 [67]:
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- 46 ● Effectiveness for tar reforming
- 47 ● Activity in the reforming of heavy hydrocarbon and aromatic compounds.
- 48 ● Ability to provide a suitable syngas ratio for special purpose.
- 49 ● Resistance to deactivation due to coking, sintering and impurity fouling.
- 50 ● Stability and reusability.
- 51 ● Mechanical strength.

- Cost and availability.

3.1. Nickel-based catalysts

Ni-based catalysts are used extensively for biomass tar conversion because of their high tar destruction activity, along with the added activity for methane reforming and water-gas shift [51,59,68-70]. Some studies also showed that Ni-based catalysts had the ability for the reversing ammonia reaction, thus it is also possible to reduce NO_x emission during biomass gasification and tar reforming [43].

Ni is generally supported on various materials. To date, Ni/Al₂O₃, Ni/olivine, Ni/ZrO₂, Ni/TiO₂, Ni/CeO₂, and Ni/MgO have been extensively studied by many researchers. However, the main limitation of nickel-based catalysts is the rapid deactivation, caused by carbon formation on the catalyst surface. Świerczyński *et al.* [10] studied the activity of Ni/olivine catalyst for tar reforming using toluene as a model tar compound, and its resistance to deactivation by carbon deposition in a fixed bed reactor. They found that Ni/olivine catalyst exhibited higher activity, higher selectivity to H₂ and CO, and lower carbon deposition when compared to olivine alone. The reason of this stability can be explained by the strong metal-support interactions (Ni-/Fe/MgO/olivine system), which provide resistance against carbon formation.

Recently, some researchers tried to add the second metal additive to improve the stability as well as activity of supported nickel catalysts. Zhang *et al.* [71] studied the steam reforming of tar over Ni/olivine catalysts doped with CeO₂, and found that the doping of CeO₂ had particular effectiveness in terms of both catalytic activity and coking resistance. The promoting effect of cerium oxide on the nickel catalyst is probably through a redox mechanism. The lower valence state of cerium might adsorb

1
2 water and dissociate it, the resulting species of -O or -OH could transfer to the nickel
3
4 and react with surface carbon species to form CO, CO₂ and H₂. Some researchers
5
6 investigated the synergistic effect of the combination of two active elements of Ni and
7
8 Co and indicated that Ni was more suitable than Co in the steam reforming of
9
10 hydrocarbons [49, 72,73]. However, supported Co catalysts were utilized for the steam
11
12 reforming of oxygenates such as ethanol, and methanol, and it is found that Co was
13
14 more effective to the steam reforming of oxygenates than Ni [74-76]. All these results
15
16 showed that the performances of Ni-Co/Al₂O₃ catalysts with the optimum composition
17
18 were much higher than the corresponding monometallic Ni and Co catalysts in terms of
19
20 the catalytic activity, the resistance to coke formation and catalyst life in the steam
21
22 reforming of biomass tar. This is due to the synergy between Ni and Co atoms on the
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24 Ni-Co alloy surface.
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34 **3.2. Non-nickel transition metal catalysts**

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36 Non-nickel metal catalysts such as Rh, Ru, Pd, Pt, Co, Fe, etc. have been
37
38 developed for the steam reforming of biomass tar. Several literatures reported that noble
39
40 metal catalysts such as Ru, Rh, and Pt have very high catalytic activity with high sulfur
41
42 resistance and long term stability in the steam reforming of tar [77,78]. Tomoshige et al.
43
44 [79] studied the catalytic activity of noble metal catalysts supported on CeO₂/SiO₂ for
45
46 the steam reforming of tar and compared with Ni-based catalysts. It is found that Rh/
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48 CeO₂/SiO₂ catalyst had better performance than the commercial Ni catalysts. Among the
49
50 noble metals, Rh was found to be significantly more active than others with a selectivity
51
52 order of Rh > Pt > Pd > Ru = Ni. Recently, Ru was supported on 12SrO-7Al₂O₃, which
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54 can incorporate active oxygen ions into the nanocage, and applied for the steam
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1 reforming of dodecane and toluene. As a result, Ru/12SrO-7Al₂O₃ showed superior
2 catalytic performance with a high coking resistance [80,81]. To reduce cost and improve
3 reforming economics by using these noble metals, low loadings (for instance, <1 wt%)
4 of them on some special materials were also found to have high catalytic performances
5 at low temperatures, which can be considered as potential industrial catalysts for the tar
6 steam reforming[82,83]. Even so, noble metals are still expensive when comparing with
7 other catalysts.
8
9

10 Besides noble catalysts, other metal catalysts like Co, Fe, Zn, and Cu have also
11 been investigated in the steam reforming of tar, and some of them showed higher
12 catalytic activity than Ni catalyst [12, 52, 84, 85]. For instances, Furusawa and
13 Tsutsumi [12] reported that Co loaded MgO showed better tar reforming performance
14 and higher catalytic activity than Ni loaded MgO. Li et al. [52] reported that Co
15 supported on BaAl₁₂O₁₉ (BA) showed high activity and high reusability in the steam
16 reforming of tar due to the high dispersion of Co particles on BA. To improve the
17 performance in steam reforming of tar, bimetallic or trimetallic catalysts were also
18 investigated [34,86,87]. Noichi et al. [34] studied the effects of addition of copper
19 species to the iron-based mixed metal oxides such as iron-alumina (Fe-Al) and
20 iron-zirconia (Fe-Zr) catalysts on the catalytic activity in steam reforming of
21 naphthalene as model biomass tar. They found that the addition of Cu increased the
22 activity and stability of the Fe-Al catalyst because the well dispersed copper in the
23 compound oxide facilitated the reduction of iron oxide to metallic iron and prevent the
24 catalytic deactivation. Wang et al. [87] modified the Co/Al₂O₃ with Fe and investigated
25 the performance of Co-Fe/Al₂O₃ catalysts in the steam reforming of tar and found that
26 the addition of Fe to Co/Al₂O₃ at the optimum amount enhanced the catalytic
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2 performance in terms of the catalytic activity and the suppression of coke deposition.
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7 **3.3. Alkali catalysts**

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9 Alkali metals are the metal belonging to group 1A of the periodic table such as
10 lithium (Li), sodium (Na), potassium (K). Many studies proved that alkali metal
11 catalysts are very effective in steam reforming of tar and can improve the quality of
12 gaseous product [88-90]. However, the major disadvantage of these catalysts is their
13 evaporation during the reaction and difficult recovery. Kuchonthara et al. [89] studied
14 the catalytic activity of K_2CO_3 on the steam gasification of lignin and found that K_2CO_3
15 had a good catalytic activity for tar decomposition during pyrolysis and steam
16 gasification. Particularly, almost all components in biomass were completely converted
17 at 800 °C. On the other hand, the alkali species contained in biomass always plays
18 catalytic role in the thermal conversion process and the released alkali species may also
19 act as catalyst for the steam reforming of tar in the gasification process. Hognon et al.
20 [90] studied the influence of inorganic elements in the biomass itself on the steam
21 gasification of biomass, and confirmed that the difference of the reactivity of various
22 biomass depends on the inorganic elements in them. The high reactivity was observed
23 for the biomass samples contained high amount of potassium, which is known to act as
24 catalyst in char gasification as well as tar reforming. Some researchers studied
25 co-gasification of coal and biomass [91-93], and found that the total gas yield in
26 co-gasification was higher than those expected based on the results of gasification of
27 coal or biomass alone. This is due to the synergy effects which are related to the
28 catalytic activity of some of ash components, e.g. alkali and alkali earth metals, in the
29 biomass. Moreover, the use of ashes as catalysts gives some advantages such as
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2 avoiding the problem of the handling of ash wastes [94].
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7 **3.4. Natural catalysts**

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9 Natural minerals such as dolomite, olivine, and shells can be used as catalysts
10 directly or with some pretreatment such as calcination. These natural catalysts are
11 inexpensive and abundant and show considerable activity for the reforming of tar [25,
12 39, 42, 95-105]. Hu et al. [99] found that both olivine and dolomite were active for the
13 steam reforming of tar into H₂-rich gas. Furthermore, the catalytic activity of these
14 catalysts can be improved by calcining them at 900 °C for 4 h. Among all the catalysts
15 tested, the calcined dolomite was the most effective catalyst for increasing H₂ content in
16 the gaseous product. However, dolomite became very friable after calcination, making
17 them not suitable to be used in the fluidized bed gasifier. Roche et al. [100] applied
18 dolomite for air-steam gasification of sewage sludge, and found that H₂ content
19 increased while tar content decreased, reaching a tar removal efficiency up to 71%.
20 Besides dolomite, some research groups investigated olivine as a tar reforming catalyst
21 [92,101-104]. Constantinou et al. [96] reported that calcined olivine had good
22 performance for tar reduction and its activity was comparable to the calcined dolomite.
23 Moreover, some researchers mentioned that the catalytic activity of olivine can be
24 further improved by the addition of some metals. Michel et al. [103] compared the
25 catalytic activity of olivine with olivine supported nickel for the steam reforming of tar,
26 and found that the Ni/olivine had much higher ability for the tar reforming than olivine
27 alone. Virginie et al. [104] reported that toluene conversion and hydrogen production
28 when using Fe/olivine catalyst were approximately 3 times higher than the case using
29 olivine alone. Yang et al. [105] attempted to improve the catalytic activity of olivine by
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2 modification of olivine with calcium aluminate cement and found that porosity of
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4 catalysts **increased** above 30% and the obtained catalyst exhibited **higher** catalytic
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6 activity and stability due to the pore structure and the well dispersion of Ni particles on
7
8 the catalyst. Moreover, the advantage of olivine catalyst over dolomite catalyst is its
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10 high attrition resistance, which is more suitable to be used in fluidized bed gasifier.
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17 **3.5. Zeolite catalysts**

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19 Zeolites are crystalline silicates and aluminosilicates linked through oxygen atoms,
20
21 producing a three-dimensional network containing channels and cavities of molecular
22
23 dimensions [106]. Zeolites have been widely used in heterogeneous catalysis because of
24
25 their well-defined pore **structure** and extremely high surface area and surface acidity.
26
27 The modification of zeolites with dispersed metals can **obtain** catalysts for
28
29 hydrogenation and ring-breaking of aromatic hydrocarbons. Such catalysts showed
30
31 relatively high tolerance for sulfur compounds in the clean-up of gasification effluents
32
33 [107]. In the case of tar reduction, various kinds of zeolites, especially the commercial
34
35 catalysts, were tested by some researchers [65,108-112]. Dou et al. [111] studied the
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37 catalytic cracking of tar component over five kinds of catalysts, i.e., Y-zeolite, NiMo
38
39 catalyst, silica, alumina and lime, and found that Y-zeolite and NiMo catalysts were the
40
41 most effective catalysts, which removed almost 100% tar at 550 °C **but no deactivation**
42
43 **was** observed over 10 h test. Some researchers revealed that the catalytic activity of
44
45 zeolite **depends** on the pore size and acidity. Buchireddy et al. [112] studied the catalytic
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47 activity of zeolites with varying pore size and acidity and nickel supported zeolites for
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49 tar reforming. Their results indicated that Y-zeolite had better catalytic activity due to
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51 its larger pore size when compared with ZSM-5. **Moreover**, the catalytic activity of
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2 zeolites increased with the increase in the acidity. It is found that the impregnation of
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4 nickel on zeolites improved the activity significantly. The advantages of zeolites are
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6 related to their acidity, better thermal/hydrothermal stability, better resistance to
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8 nitrogen and sulfur compounds, and easy to be regenerated. However, the main
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10 disadvantages of these catalysts are the rapid deactivation resulted from coke formation
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12 [38].
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19 **3.6. Carbon-supported catalysts**

21 **Activated carbons (AC) and char** derived from biomass and coal have been widely
22
23 used as catalyst supports for the conversion of hydrocarbons and tar cracking due to
24
25 their highly porous textural structures [6,107]. Their catalytic activities for tar
26
27 elimination are related to the pore size, the surface area, and the ash or mineral content
28
29 in them. The attractiveness of char as a catalyst is its low cost and its natural production
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31 [38]. The performance of char and char-supported catalysts for tar conversion can be
32
33 found in several literatures [36,115-118]. El-Rub et al. [36] studied the potential of
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35 using biomass char as a catalyst for tar reduction and compared with other known
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37 catalysts, i.e., calcined dolomite, olivine, spent fluid catalytic cracking (FCC) catalyst,
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39 biomass ash and commercial nickel catalyst. The results indicated that biomass chars
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41 had the highest naphthalene conversion with an order of nickel > commercial biomass
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43 char > biomass char > biomass ash > FCC > dolomite > olivine > silica sand. Min et al.
44
45 [117] also studied the catalytic activity of char and char-supported catalysts in steam
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47 reforming of tar. Their results showed that the char-supported iron/nickel catalysts
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49 exhibited much higher activity than the char itself. The similar result was also found by
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51 Zhang et al. [116]. They investigated the effectiveness of tar reforming using biomass
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2 char, iron supported biomass char and iron supported brown coal char. The results
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4 indicated that biomass char supported iron catalyst had much higher activity than coal
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6 char supported iron catalysts. They concluded that the activity should be related to the
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8 structure in char support. Bhandari et al. [118] investigated the catalytic performances
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10 of three synthesized catalysts including biochar, activated carbon and acidic surface
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12 activated carbon, and found that all three catalysts were effective in tar removal with
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14 removal efficiencies of 69-92%. Especially, activated carbon catalysts had higher
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16 toluene removal efficiency because of their higher surface area, larger pore diameter
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18 and larger pore volume compared to biochar catalysts.
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26 **4. Conclusions and remarks**

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28 As reviewed above, the developed catalysts with advantages and disadvantages
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30 that can be summarized as the following. Nickel-based catalysts have been used
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32 extensively for the steam reforming of tar due to their high activity, but the main
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34 disadvantage of these catalysts is the rapid deactivation by carbon formation on the
35
36 surface of catalyst. Although noble metal based catalysts have high catalytic activity,
37
38 long-term stability and high carbon deposition resistance, they are expensive. Beside
39
40 noble metal based catalysts, other transition metal catalysts such as Fe, Co and Cu also
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42 exhibit a good performance in the steam reforming of tar. However, they are deactivated
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44 easily by carbon deposition in the case of high heavy-tar content in the produced tar.
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46 Alkali metal catalysts also have high catalytic activity in the steam reforming of tar.
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48 Especially, alkali species contained in biomass can also act as a catalyst for tar
49
50 reforming, making the utilization of biomass ash as the catalyst is becoming interesting
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52 since it can reduce the problem of ash-handling during biomass gasification. Natural
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2 catalysts have also been widely applied for the steam reforming of tar due to its
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4 inexpensive, abundant and disposable. Sometimes their catalytic activities are lower
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6 than those man-made ones, but they are much cheaper than the latter. Another main
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8 problem of these catalysts is their low mechanical strength, making them not suitable to
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10 be used in fluidized bed reactor. Zeolite can be a good catalyst support in the steam
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12 reforming of tar due to its high thermal/hydrothermal stability, high resistance to sulfur
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14 compounds, and easy to be regenerated. Besides zeolite, biomass char have also been
15
16 used as a catalyst or catalyst support in the steam reforming of tar. The advantages of
17
18 biomass char are its low cost and its natural production inside the biomass gasifier.
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20 Moreover, the minerals contained in biomass can also enhance the catalytic activity of
21
22 biomass char.
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28
29 On the other hand, since the compositions of biomass-derived tar are very complex,
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31 during catalytic tar reforming process, a matrix of complex reactions among different
32
33 compositions and gases will occur. The relationship between different reactions is
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35 difficult to be known so that it is almost impossible to predict the mechanism of the
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37 catalytic process exactly. Various man-made catalysts such as metal supported catalysts
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39 have been successfully developed for the decomposition of model tars such as benzene,
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41 toluene, phenol and naphthalene. However, most of them are still unsuitable for a real
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43 tar reforming. Moreover, for a practical biomass gasification process, in order to reform
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45 the complex tars, using low-cost and disposable catalysts still attracts special attention.
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51 In the future work, the following points should be considered in order to realize
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53 complete conversion of tar into syngas:
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56 (1) *Steam reforming of heavy tar* To date, the mechanism on the steam reforming
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58 of heavy tar on the catalyst is still not clear. In general, coking on the catalyst
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2 is more easily occurred in the case of heavy tar. Hence, it is necessary to study
3
4 the coking mechanism using some model compounds of heavy tars.
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6 Furthermore, the effect of tar components on the steam reforming of heavy tar
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8 should be considered. As stated above, tar is a complex matter. Hence, the pH
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10 value of tar, the minerals in the tar, and the light compounds in the tar could
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12 affect the steam reforming of heavy tar.
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18 (2) *Novel catalyst development* Coking on the catalyst surface is almost the main
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20 reason for any catalyst deactivation in the steam reforming of tar. Therefore,
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22 structure and composition design of catalyst based on the coking mechanism
23
24 analysis is required for novel catalyst development. Structure design could
25
26 help different components with different molecular structures in the tar to find
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28 a suitable active site for its complete conversion. Due to the complex of the tar,
29
30 one composition in a catalyst could not be suitable for the conversion of all
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32 molecules in the tar, and thus, it is necessary to develop composite catalysts
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34 with several compositions for the reforming of real tar. On the other hand,
35
36 besides coking, some impurities such as S, P, N, Si, and other minerals in the
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38 real tar also have negative effects on the catalyst deactivation. Basic
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40 researches on these is still not enough. More experiments on the effect of
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42 these impurities should be considered. Furthermore, in order to decrease the
43
44 energy consumption in the reforming of tar, it is necessary to develop
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46 catalysts with high activity at lower temperature. If the developed catalysts
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48 can work well at lower temperatures, waste heat with a temperature of
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50 400-600 °C in the factory can be effectively used. For practical application,
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52 the catalyst strength should also be considered since many catalysts are fragile
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2 and cannot be used in fluidized bed reactors.
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5 (3) *Scale-up issues* To date, catalyst development is generally performed in the
6 laboratory scale. Not so many data can be found from larger scale or pilot
7 experiments by using these catalysts. In the lab scale, these catalysts may
8 show good catalytic properties for the reforming of model tar or even for real
9 tar. However, in larger scale reactors, the factors on the activity of catalyst
10 become very complex. Some important factors such as gas flow rate,
11 temperature and pressure variations, catalyst broken, the impurities such as
12 HCl, HCN, NO_x, SO_x and fly ash in the gas line must be considered.
13 Otherwise, any good catalysts obtained in the laboratory cannot be used in a
14 practical process.
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29 (4) *Catalyst regeneration technology* In a practical process, a chemical looping
30 system design for continuous tar removal with simultaneous catalyst
31 regeneration is always considered. In general, the catalyst even with high
32 activity in a small scale experiment could be deactivated in a practical system
33 due to the complexity of the tar compositions and operation conditions.
34 Although some natural low-cost catalysts can be discarded after deactivated,
35 how to regenerate the catalyst rapidly is still an important issue for the catalyst
36 development, especially for those man-made **catalysts** with relatively high
37 manufacture cost.
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53 **If all of the above issues can be resolved well, tar problem in biomass gasification**
54 **will be well solved and effective utilization of the by-produced tar could be really**
55 **realized. This will promote application of biomass energy in our daily life.**
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48 **Figure captions**

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51 **Fig. 1.** Major groups of biomass and their sub classifications [2,7].
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54 **Fig. 2.** Four possible routes for biomass energy conversion [1-9].
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57 **Fig. 3.** Main processes during biomass gasification.
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2 **Fig. 4** Tar maturation scheme (Modified from Elliott 1988) [44].
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5 **Fig. 5.** Typical composition of biomass tars [48, 120].
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7 **Fig. 6.** Simplified reaction scheme of thermal conversion of aromatic hydrocarbons in
8 the presence of hydrogen and steam (Modified from Jess 1996) [61].
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10 **Fig. 7.** Mechanism of catalytic steam reforming of biomass derived tar supposed in our
11 study (M_xO_y represents metal oxide catalyst)[121].
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20 21 **Table captions**

22
23 **Table 1.** World primary energy demand (Mtoe) [8].
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25 **Table 2.** Tar classification based on its appearance [45,98,119].
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27 **Table 3.** Tar classification based on molecular weight of tar compounds [33,98].
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29 **Table 4.** Typical catalysts for tar reforming reported in the literature.
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Figure-1

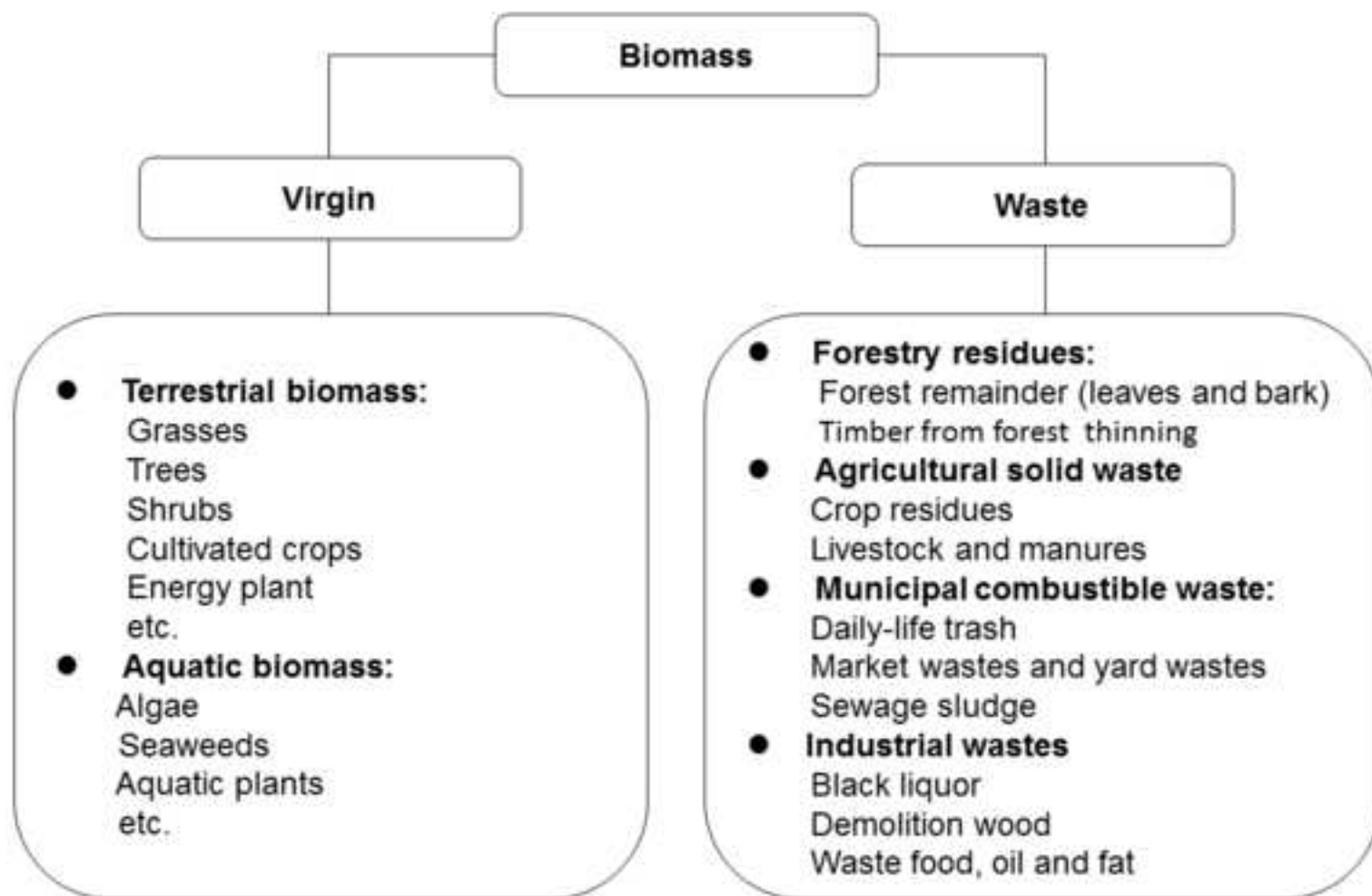


Figure-2

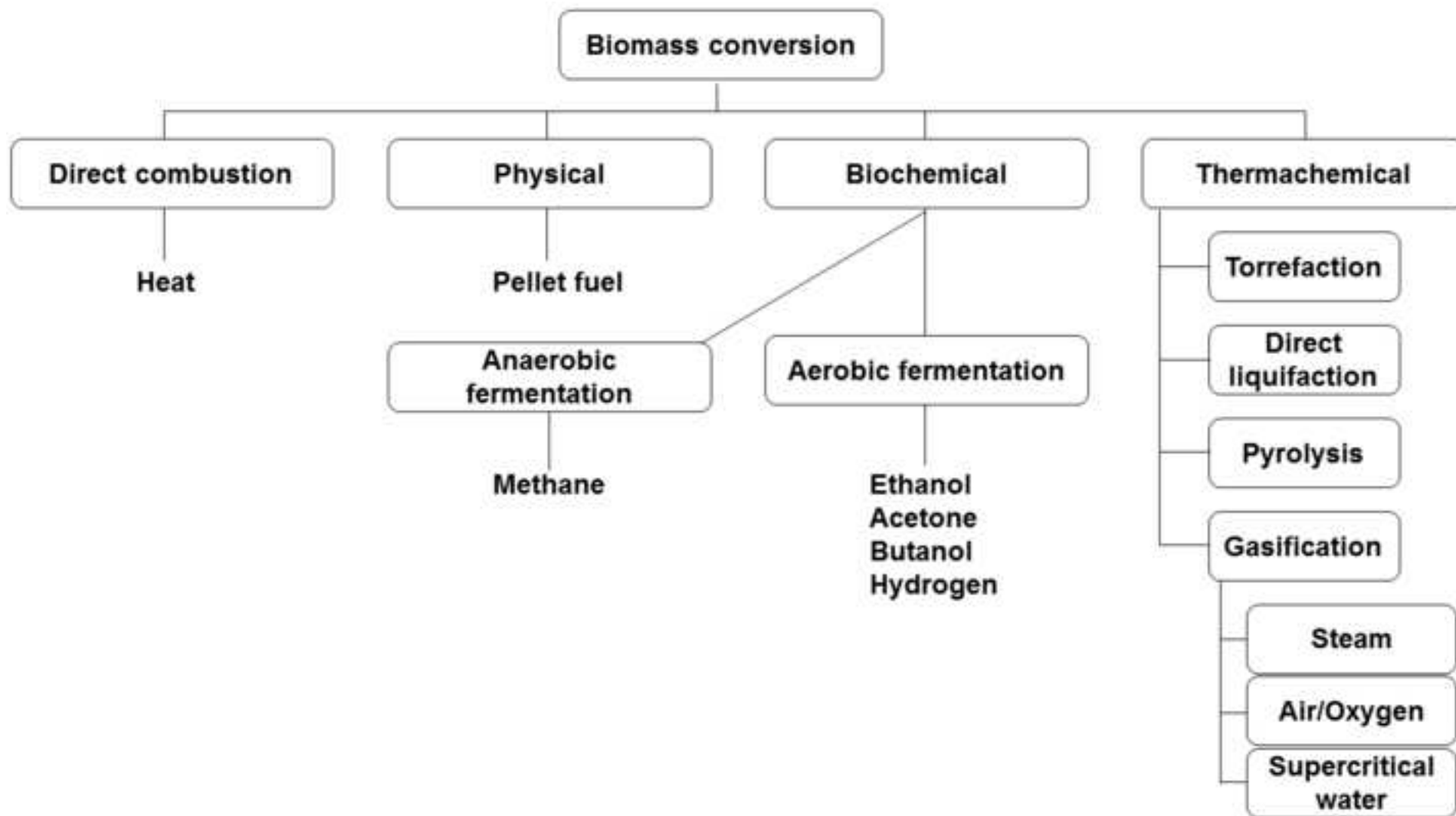


Figure-3

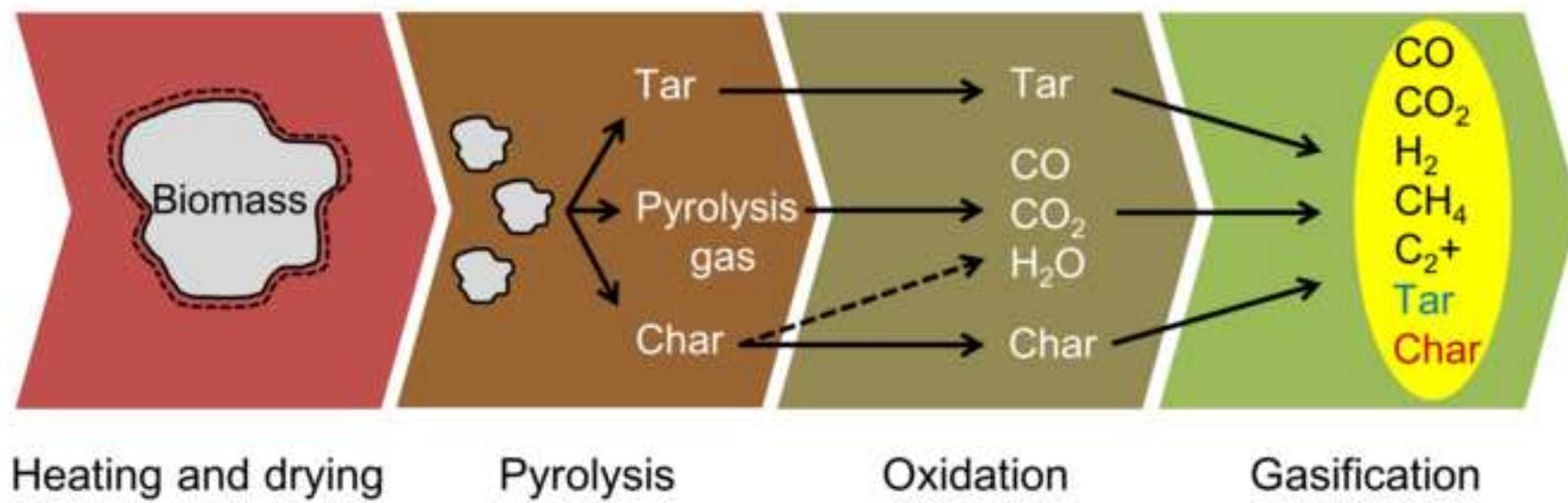


Figure-4

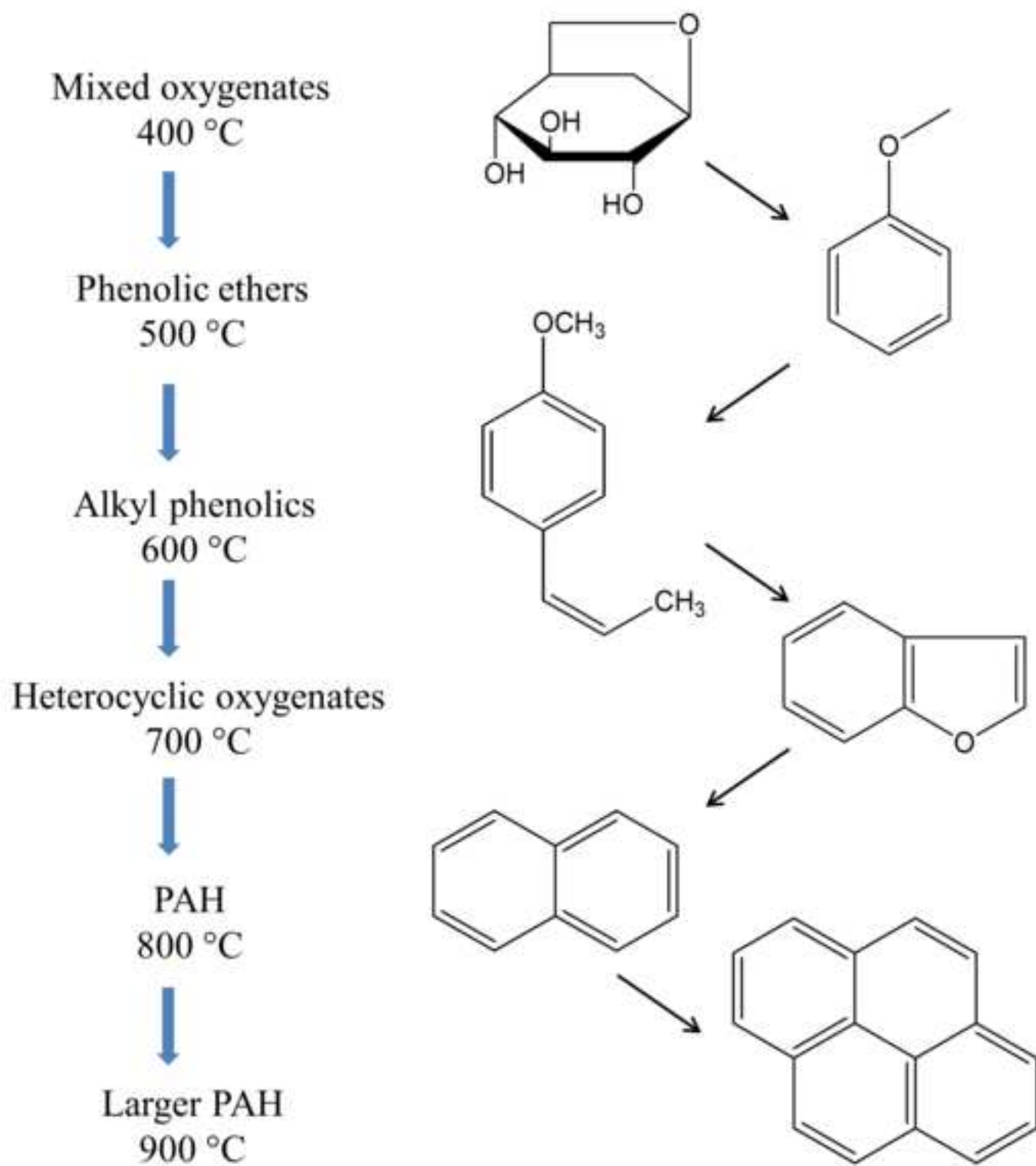


Figure-5

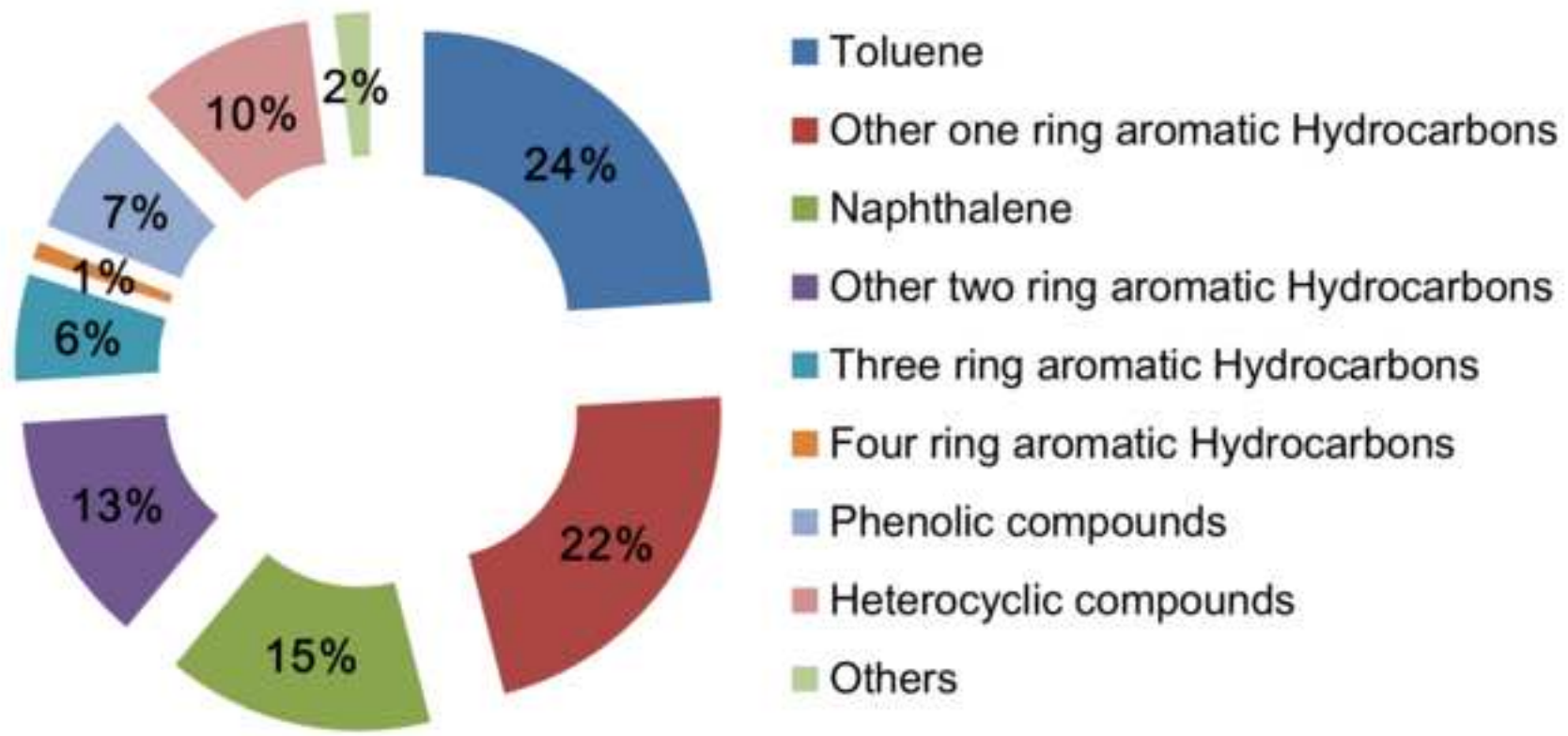


Figure-6

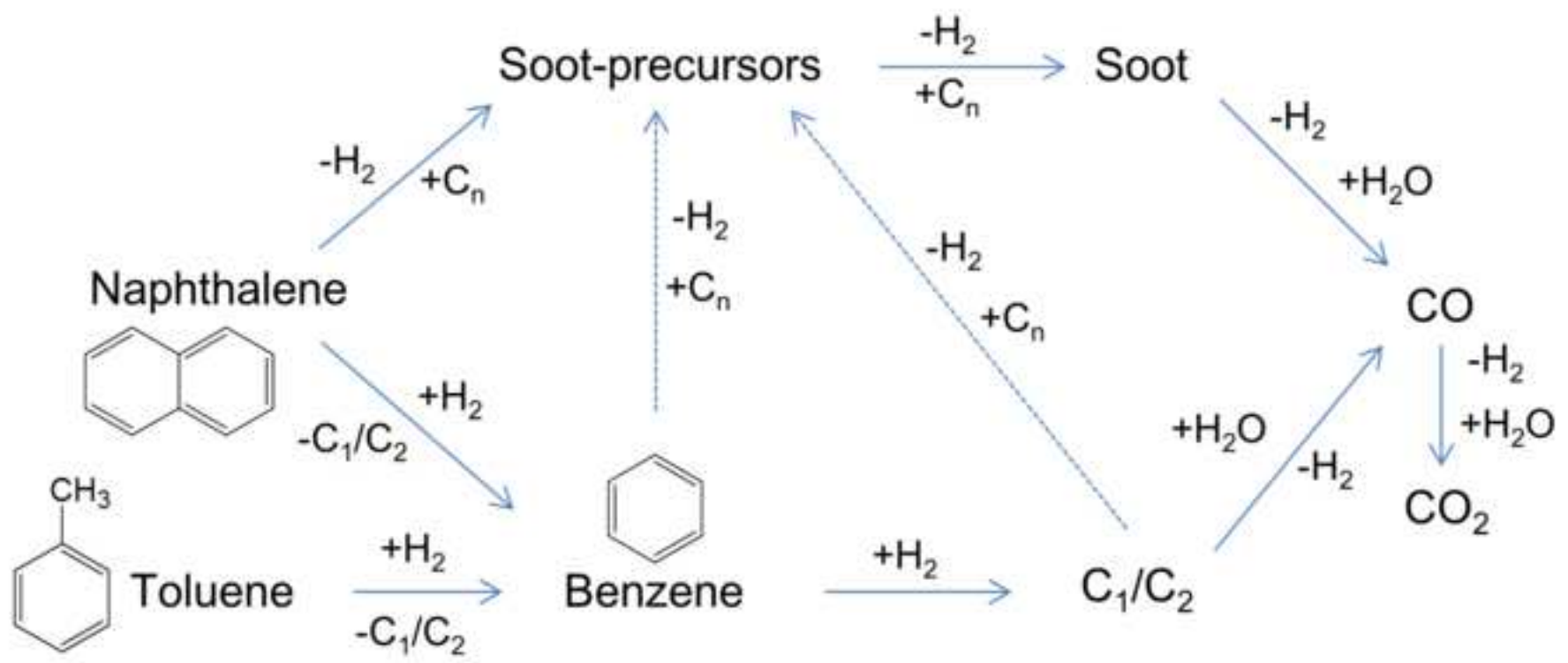
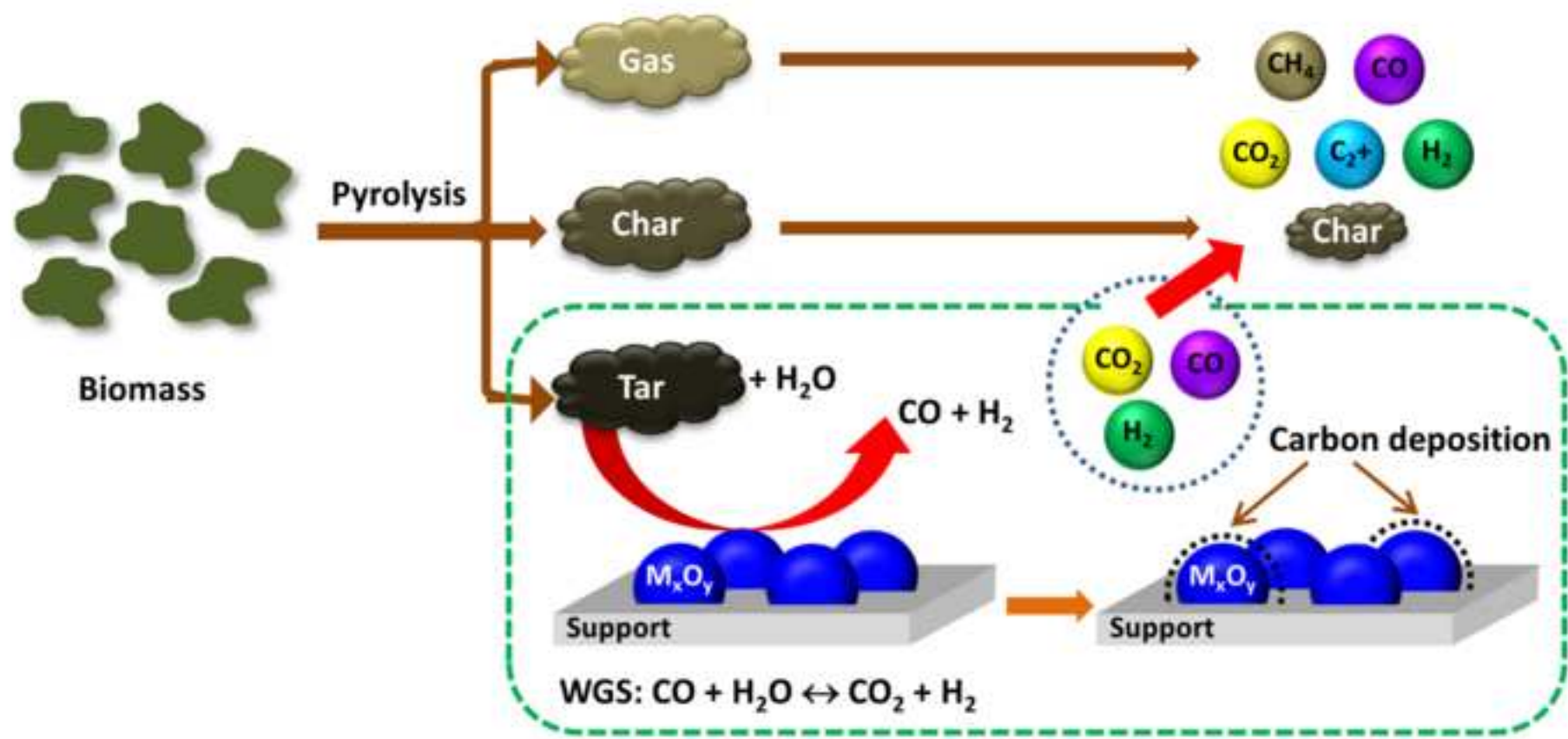


Figure-7



Tables

Table 1. World primary energy demand by fuel (Mtoe) [8].

	1980	2009	2015	2020	2030	2035	2009-2035 ^a
Coal	1792	3294	3944	4083	4099	4101	0.8%
Oil	3097	3987	4322	4384	4546	4645	0.6%
Gas	1234	2539	2945	3214	3698	3928	1.7%
Nuclear	186	703	796	929	1128	1212	2.1%
Hydro	148	280	334	377	450	475	2.1%
Biomass and waste	749	1230	1375	1495	1761	1911	1.7%
Other renewables	12	99	197	287	524	690	7.8%
Total	7219	12132	13913	14769	16206	16961	1.3%

^a Compound average annual growth rate.

Table 2. Tar classification based on its appearance [45,98,119].

Tar class	Property
Primary	Low molecular weight oxygenated hydrocarbons such as levoglucosan, furfural and hydroxyacetaldehyde, produced at 400-700 °C
Secondary	Phenolic and olefin compounds such phenol, cresol and xylene, produced at around 700-850 °C
Tertiary	Complex aromatic compounds such as benzene, naphthalene, pyrene and toluene, produced at around 850-1000 °C

Table 3. Tar classification based on molecular weight of tar compounds [33,98].

Tar class	Property
Class 1	GC undetectable heaviest tars which condense at high temperature and very low concentration
Class 2	Heterocyclic aromatic compounds which are high water solubility such as pyridine, phenol, cresols, quinoline, isoquinoline and dibenzophenol
Class 3	Light hydrocarbon aromatic compounds (1 ring) which do not cause a problem regarding condensability and solubility such as toluene, ethylbenzene, xylenes, styrene
Class 4	Light polyaromatic hydrocarbon compounds (2-3 rings) which condense at low temperature even at very low concentration such as indene, naphthalene, methylnaphthalene, biphenyl, acenaphthalene, fluorene, phenanthrene, anthracene
Class 5	Heavy polyaromatic hydrocarbon compounds (4-7 rings) which condense at high temperature at low concentration such as fluoranthene, pyrene, chrysene, perylene, coronene

Table 4. Typical catalysts for tar reforming reported in the literature.

Catalyst	Tar	Properties	Ref
Ni/olivine	Toluene	The presence of Ni–Fe alloys and basic MgO oxide in olivine are beneficial for limiting carbon formation	[10]
Ni/olivine-CeO ₂	Benzene Toluene	3.0% NiO/olivine doped with 1.0% CeO ₂ is the most promising catalyst based on catalytic activity and its resistance to coking.	[71]
Ni-Co alloy	Acetic acid	At the molar ratios of 0.25:1 (Ni:Co), the catalyst showed the best performances for acetic acid steam reforming	[75]
Ni-Co/HT	Ethanol	The best catalytic performance is obtained with the 30Co–10Ni catalyst, in which Co and Ni are intimately mixed and dispersed in hydrotalcite (HT)-like materials	[76]
Ru/12SrO-7Al ₂ O ₃	Kerosene	Ru/SrO–Al ₂ O ₃ catalysts with 12SrO-7Al ₂ O ₃ phase exhibit superior catalytic activities compared to a commercial Ru/Al ₂ O ₃ catalyst, despite low Ru loading and Ru dispersion.	[80]
	Toluene		[81]
Rh/Ce _{0.14} Zr _{0.81} Mg _{0.05} O ₂	Phenol	A 0.5 wt% Rh/Ce _{0.14} Zr _{0.81} Mg _{0.05} O ₂ catalyst developed led to a significantly better performance towards steam reforming of phenol	[83]
Co/MgO	Phenol	12 wt.% Co/MgO catalyst has higher activity than any kinds of Ni/MgO catalysts	[12]
Co–Fe/Al ₂ O ₃	Biomass tar Toluene	Co–Fe/Al ₂ O ₃ catalysts with the optimum composition (Fe/Co = 0.25) is much higher than corresponding monometallic Co and Fe catalysts in the steam reforming of tar from the pyrolysis of cedar wood	
K ₂ CO ₃	Biomass tar	Almost all components in biomass are completely converted at 800 °C	[89]
Calcined scallop shell	Biomass tar	Calcined scallop shell (CS) as well as iron- or nickel-loaded CS shows good catalytic activity for tar reforming	[39] [42]
Y-zeolite	Naphthalene	Y-zeolite and nickel-supported Y-zeolite have high catalytic activity for naphthalene conversion	[111] [112]
Biomass char	Biomass tar	The char-supported iron/nickel catalysts have high activity for the reforming of tar	[116] [117] [118]