Renewable and Sustainable Energy Reviews 90 (2018) 636–649

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Potential commercialisation of biocoke production in Malaysia—A best evidence review

Adila Maisyarah Mansor[a,b], Wai Lip Theo[a,b], Jeng Shiun Lim[a,b,*], Farid Nasir Ani[c], Haslenda Hashim[a,b], Wai Shin Ho[a,b]

[a] Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia
[b] Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia
[c] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia

ARTICLE INFO

Keywords:
Biocoke
Agricultural biomass
Municipal Solid Waste (MSW)
Pyrolysis
Fuel
Metallurgical industry
Renewable energy

ABSTRACT

Global depletion of fossil fuels, growing awareness on the effects of carbon emissions and greenhouse gases and, the need for renewable energy, has increased the attention towards biocoke research and active engagement with various research groups and industrial players. Biocoke production and utilisation is crucial as it contributes to the efficient management of agricultural residue and municipal solid waste. The technologies involved in the biocoke production and the viability of Malaysia's agricultural waste as a feedstock was described in this paper. In addition, the paper provided background information about the biocoke characteristics and the feedstocks that dictate quality. Comparisons of commercial coal coke and biocoke production technologies that may be applicable to Malaysia were also addressed. Moreover, the paper demonstrated the challenges towards Malaysia's biocoke commercialisation despite its viability from biomass feedstocks characteristics, availability, and evidence of calorific value estimations.

1. Introduction

Global issues pertaining to fossil fuel depletion, energy price fluctuations, energy security, the carbon footprint of the energy industry and, climate change have demanded the attention towards renewable energy. Efforts to synthesise and utilise renewable energy was reported in Germany [1], Australia [2], Chile [3], China [4], Romania [5], Mexico [6], India [7], Small Island Developing States (SIDS) [8], and developing countries [9]. While some of these countries are progressively developing their expertise in wind [10] and solar power [11], biomass is one of the renewable energy resources with established conversion technologies and proven track record [12–15] of success.

Concerns about the significant carbon footprint in the steel-making industry have to lead to innovation in biomass-based fuel and reducing agents [16]. For example, Malaysia's metallurgical industries recorded steel production of 7.5 million tonnes in 2004 [17], which contributed to the increased industrial carbon dioxide emissions trend as reproduced from Shahid et.al [18] as shown in Fig. 1.

There have been many reports on the increased use of biocoke in the steel-making and metallurgy processes, however, its full utilisation is still not practical [19]. This might be due to its application was enabled by partial substitution of top coke with biocoke and partial replacement of pulverised coal with biocoke through injection [20]. Extensive reviews of the biocoke synthesis and utilisation in metallurgical industries were conducted by M.Wei [21] and Suopajarvi [22]. This paper provided a comprehensive review of the current biocoke production technologies and the comparative viability of Malaysia's agricultural waste as diverse biocoke resources and feedstocks. In addition, this paper also addressed the challenges of biocoke application in Malaysia in terms of commercialisation barriers and competition with the commercial solid fuels for its full-scale implementation.

2. Biocoke feedstock

Biocoke, as a sustainable biomass-derived carbonaceous solid fuel, is characterised by low sulphur content, high feedstock availability and has an economically efficient production process [23]. Hence, the characteristics are attributed to biocoke's production route of a biomass pyrolysis [24], which is an irreversible process in which organic materials undergo thermochemical decomposition at an elevated temperature with the absence of oxygen [24]. Moreover, biocoke could also be formed by upgrading the pyrolysis oils from spent wheat grain and

* Corresponding author.
E-mail addresses: jslim@cheme.utm.my, jslim@utm.my (J.S. Lim).

https://doi.org/10.1016/j.rser.2018.03.008
Received 10 February 2017; Received in revised form 20 November 2017; Accepted 9 March 2018
1364-0321/

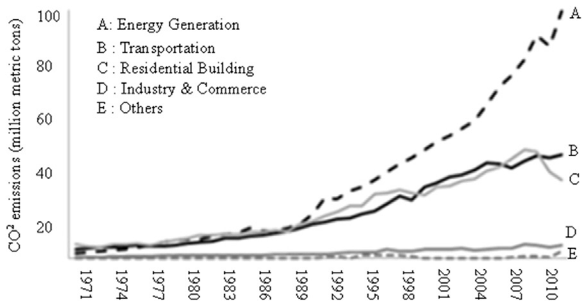

Fig. 1. Trends in carbon dioxide emissions from various sectors in Malaysia from 1971 to 2010 [18].

rapeseed meal biomasses using Thermo-T process which is similar to vis-breaking technology [24]. Furthermore, since biocoke is either fully or partially made up of photosynthetic plant matters, its low sulphur content implies minimum pollutant emissions [25]. Biocoke is efficient in greenhouse gas (GHG) emission mitigation by enabling arbon-neutral combustion [26] and, can defer biomass decomposition in a landfill [27]. Biocoke production cost was 31% lower than the biomass briquette synthesis yet, had a higher product selling price [28]. When biocoke's high bulk density is enhanced with biomass briquette [29], the resulting compound enabled low-cost fuel storage, handling and transportation [29].

Biocoke is classified as a solid fuel because it is a solid material which is compatible with fuel utilisation to provide thermal energy and to generate electric power [30]. Unlike conventional destructive distillation of coals, biocoke is formed by blending the biomass materials with coal in a coke production process [30] that results in a carbonation or pyrolytic treatment of biomass feedstocks [30]. Additionally, biocoke is a hybrid between conventional coke and renewable biomass resource [30]. Unlike direct biomass fuel utilisation (i.e. combustion of wood, dried agricultural residue, or biomass briquette), biocoke requires a transformation of biomass to adapt coal-like properties [31]. In contrast to coke, biocoke incorporates a renewable biomass resource [31]. This hybridization exhibited several desirable solid fuel properties as listed in Table 1 [32].

An assessment of on the characteristics of each biomass material yielded its viability as a biocoke. For example, the high volatile matter content of a biomass increased the ignitability of the biocoke with a moderate ignition temperature [33]. Moreover, with a calorific value comparable to fossil fuels [34] and biomass fuel pellets [35], biocoke had a higher fixed carbon content that made it more durable with higher control on the heat release compared to a pure biomass resource [35]. Biocoke has multiple resources because it can be produced by using any photosynthetic plant waste [35] or mixed municipal solid waste (MSW) as reviewed in the following section.

2.1. *Agricultural residue*

A review was conducted on the agricultural residue as a biomass [36]. Fruit peels [24,26], waste shell biomass [25], woody and vegetal biomasses [29,30,31] rice wastes [27], biomass sawdust [17,19,24], and oil palm biomass and green wastes [16,26,30], were shown as viable feedstocks for biocoke synthesis.

Biocoke synthesis from orange and banana peels was examined by Murata, Hanaka [37] demonstrated a high mechanical strength with compressive strengths of 98.4 MPa and 167.0 MPa at initial moistures of 1.81 wt% and 0.52 wt% [37] respectively. In another study, waste chestnut sawdust had a very low ash content at about 13 wt% and negligible sulphur content, indicating its high potential as biocoke feedstock with partial briquette for product densification [29]. Despite achieving greenhouse effect mitigation, the incorporation of biomass sawdust in a coal blend could possibly deteriorate the coke quality, bulk density [38], and thermoplastic property [25].

Evidence has shown that the waste shell biomass with an ash content below 12 wt%, was also a viable feedstock for producing biocoke to avoid slag formation during iron production [39]. According to S.Jung et al. [40], the waste shell biomass produced ash content in the range of 7–8 wt% while the apparent density and compressive strength were about 0.9 g/cm^3 and 89–149 MPa at 700 °C. For practical fuel application under high pressure, biocoke's compressive strength should be in the range of 60–200 MPa [27]. Additionally, it was shown that the char resulted from waste shell biomass appeared to meet the essential chemical and mechanical requirements to be qualified as biocoke. Similarly, high-density biocoke products derived from broccoli, dead cherry tree leaves and mango seeds were evaluated by S. Mizuno et.al [41] in terms of their fuel quality. It was found that mango seed, with the highest volatile matter removal rate, exhibited the greatest ignitability whereas broccoli biocoke had the greatest compressive strength of 130 MPa at an initial moisture of 5% and a processing temperature of 413 K.

An investigation on the effect of green tea ground biocoke specimen size (i.e. diameter) on its mechanical strength demonstrated that if fabricated in 12 mm diameter, the biocoke specimen could achieve the high ultimate compressive strength of up to 67 MPa [33]. Moreover, rice husk was found to produce biocoke with the hot maximum compressive strength of 4.8 MPa at a processing temperature of 973 K, which was greater than other biomass materials. In addition, the presence of silica and fibre resulted in an extra structural integrity of rice husk biocoke [42].

Woody and vegetal biomasses were evaluated for their compatibility with biocoke production. In particular, Qin and Thunman [43] verified the compliance of waste wood, straw and bark biocoke with a coke quality requirement (with a low ash content of 0.41 – 7.13 wt% and reasonable char mass yield of 19.4 – 29.5%). The authors found that straw biocoke exhibited the greatest combustion reactivity due to

Table 1
Characteristics of an ideal solid fuel [32].

Characteristic	Definition
1. High calorific value (CV)	It should produce a large amount of heat on burning. CV depends on the nature of the fuel, especially the moisture content.
2. Moderate ignition temperature	Ignition temperature is the lowest temperature in which the fuel must be preheated so that it starts burning smoothly. Fuel with the low ignition temperature catches fire easily which makes it dangerous for storage and transportation. Excessively high ignition temperature may cause difficulty in kindling. Therefore, it should have moderate ignition temperature.
3. Low moisture content	Low moisture content is needed as it will affect the CV.
4. Low non-combustible matter	The non-combustible material will vanish in the form of ash which will decrease the CV of fuel.
5. Inert products of combustion	Waste of combustion should not be harmful and cause pollution to the atmosphere.
6. Low production cost	The continuous production should be cheap which requires high availability of feedstocks and simple production process.
7. Easy to transport	It should be easy to handle at a low-cost.
8. Controllable combustion	It should release heat at a reasonably high rate, but without the explosion hazard.
9. Non-spontaneous combustion	It should be non-spontaneous otherwise may cause fire hazards.
11. Low storage cost	It should be easily stored at a low-cost.
12. High combustion efficiency	It should have low ash content, in which no residues shall remain at the end of combustion process with proper air-to-fuel ratio.