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Potential thermochemical conversion of bioenergy from *Acacia* species in Brunei Darussalam: A review

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ABSTRACT

As the demand for energy increases and fossil fuel resources are depleted, the search for clean sources of energy has intensified worldwide. This is coupled with a strong global desire to reduce CO_2 emissions to curb global warming. Brunei Darussalam is committed to reduce its CO_2 emissions but currently utilizes fossil fuels to meet almost all of its energy requirements. This situation provides good incentives to search for renewable and sustainable resources to produce energy in the country. *Acacia* species are exotic species that have invaded and spread to natural habitats in Brunei Darussalam. *Acacia* species are a sustainable source of high quality biomass feedstock to produce bioenergy in the country. Hot tropical weather of the country is highly suitable for the rapid growth of *Acacias* without requiring any major agricultural input. This study reviews the thermochemical conversion of *Acacia* species especially; *Acacia mangium* and *Acacia auriculiformis* to produce biofuels and bio-products. The prospective of using *Acacia* biomass as feedstock in pyrolysis, gasification, liquefaction and combustion is also discussed. *Acacia* biomass is a sustainable and renewable energy resource for Brunei Darussalam to be exploited for energy requirements and can be beneficial for the economy of the country by providing new investment and employment opportunities.

1. Introduction

The threat of diminishing of fossil fuel resources and the impact of their burning on environmental pollution is well-known problem and has motivated researchers to look for alternative sustainable and renewable fuel resources. There has been a significant increase in the efforts to search for clean, socially acceptable methods of producing energy [1]. The demand of energy is continuously increasing due to economic development and rapid increase of population of the world. The world's demand for energy is predicted to be doubled within upcoming few decades [2–4].

On 12 December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement on climate change in which 195 participating countries committed to keeping the global temperature rise limit well below 2 °C above pre-industrial levels [5].

Energy is considered to be one of the most important commodities of life. Secure and sustainable supply of energy is mandatory for the socio-economic development of any country. Rapid human population rise along with increasing urbanization and industrialization trends are putting worldwide challenges in terms of energy resource development and management. Existing fossil energy resources based technologies cannot meet the ever rising demand of energy [6]. Utilization of fossil fuels has contributed substantially to increasing environmental pollution causing serious problems such as acid rain, ozone depletion, and global warming which results from the emission of harmful gases like SO_X, NO_X and CO_2 [7,8]. Encouraging reports have been published recently to show the expanding usage of low-carbon energy resources [9]. It is believed that the global economy growth and energy-related emissions might have started to decouple. Thus, non-renewable fossil resources are not the reliable option in long term future basis [10].

Many renewable and sustainable energy resources of energy are available to replace fossil resources such as biomass, sunlight, tidal and geo thermal energy [11,12]. Biomass is an abundant and renewable source of energy derived from organic materials originating from living organisms [13]. Worldwide biomass ranks fourth as energy resource

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providing approximately 14% of the energy requirements [14]. Plant biomass results from photosynthesis processes in plants, and is sometimes referred to as lignocellulosic biomass and its constituting components include carbohydrate polymers and aromatic polymers. Carbohydrate polymers in plant biomass are called as cellulose and hemicellulose; while the aromatic polymers are called as lignin [15]. Energy in the biomass is basically the solar energy stored as chemical energy, This chemical energy can be released by breaking the chemical bonds between adjacent oxygen, carbon, and hydrogen molecules using biological or thermochemical processes [16]. Non-renewable resources are also believed to be derived from biomass through microbial anaerobic degradation and metamorphic geological conversions over millions of years [17]. This review paper deals with plant biomass and will refer to it as biomass. Despite the fact that biomass conversion to energy has various environmental and social benefits over the use of petroleum fuels; many challenges are there in terms of commercialization of technologies which are much expensive than the traditional ones. Also, for sustainable development, biomass conversion processes are needed to improve their efficiencies [18].

Lignocellulosic biomass is the most abundantly available raw material on earth to produce biofuels and chemical feedstock for industry. Various studies are reported in literature on the viability of bio-energy production from forest-based biomass with financial feasibility and sustainability [19–22]. Thus, biomass is a logical choice which can contribute for energy requirements of the world to minimize dependency on fossil resources [23,24].

Acacia is a large genus of 1350 species of shrubs and trees that are found in Australia, Africa, Madagascar, throughout the Asia-Pacific region and in the Americas. They are most diverse in Australia, with close to 1000 species recorded, and is the largest genus of vascular plants in Australia [25].

This study is aimed to review the potential of thermochemical conversion of *Acacia* biomass to produce value added materials such as biofuels and other bio-products in Brunei Darussalam. Studies reported in literature on the pyrolysis, gasification, liquefaction and combustion of different *Acacia* species are discussed and summarized. Brunei Darussalam is located between 4° N and 5.8° N latitude and 114.6° E and 115.4°E longitudes on the north-west coast of Borneo island; map is shown in Fig. 1 [26]. Brunei Darussalam's tropical climate is aseasonal with high temperatures and rainfall year round [27] and this climate appears to be highly suitable for the growth of different *Acacia* species.

Biomass from *Acacia* species and waste biomass could be important renewable resources to meet the future needs of the country. As assessed by Malik et al., Brunei Darussalam has a potential to produce 13 $\times 10^5$ kWh/year electricity from its solid waste biomass resources [28]. *Acacia* species along with their potential to produce biofuels and bioenergy have been researched for various scientific applications and to produce many valuable products [29–42]. The current situation is challenging and demanding for the utilization of biomass from *Acacia* species which are sustainable and renewable energy resources to produce biofuels via thermochemical conversion route which will contribute to future energy requirements and to reduce the green houses gases in the country. There is also an urgent need for Brunei Darussalam to maintain its bio-resources inventory so that proper planning can be made in terms of utilization of its green resources to produce energy. Research activities should be carried out to determine the individual biofuel potential of different tree parts of *Acacia* species such as trunk, phyllodes, bark and branches because *Acacia* trees are bigger in size and produce large quantities of biomass from their different parts. Utilization to *Acacia* species to produce biofuels will impart positive effects on the economy of country by generating new investment and employment opportunities in engineering, agriculture, transportation and services sectors.

2. Energy scenario in Brunei Darussalam

Brunei Darussalam is well known for its vast fossil hydrocarbon reserves. Situation is alarming as studies have revealed that oil and gas reserves of Brunei Darussalam will be finishing within 17 and 30 years respectively if their exploration will be continued at the current rate [43]. As per World Bank country indicators data, Brunei Darussalam is the largest emitter of carbon dioxide per capita in ASEAN region as shown in Table 1 [44]. This is because of almost all the energy requirements of Brunei Darussalam are being generated from fossil fuels. Research reports show that major portion of greenhouse gases (GHG) in the world are coming from the burning of fossil fuels, producing CO_2 and other gas emissions [45]. In Brunei Darussalam major contributors to CO_2 emissions are power generation and transportation sectors as shown in Fig. 2. Brunei Darussalam is also the highest consumer of electricity per capita in Asia, with maximum of its consumption in domestic households which is may be due to high government subsidy on electricity tariffs [46,47]. The primary energy demand of the country is expected to rise at an average rate of 3.9% annually over the forecast period to reach 6.8 MTOE in 2030 [48]. Consequently, CO_2 emission rates are also expected to rise with the energy demand of the country if green energy resources are not exploited to contribute in the energy mix of the country. Being a signatory of the Paris Agreement on global warming, Brunei Darussalam is committed to reduce its CO_2

Fig. 1. Political map of Brunei Darussalam (photo credit: www.nationsonline.org) [26].

Table 1
CO_2 emission per capita in ASEAN countries in 2001, 2006 and 2011 [44].

Country	CO_2 Emissions Per Capita (metric ton per capita)		
	2001	2006	2011
Cambodia	0.2	0.2	0.3
Brunei Darussalam	17.1	11.6	24.4
Indonesia	1.4	1.5	2.3
Malaysia	5.7	6.5	7.9
Myanmar	0.2	0.3	0.2
Philippines	0.9	0.8	0.9
Singapore	12	7.2	4.3
Thailand	3.2	4.0	4.5
Vietnam	0.8	1.2	2.0

emissions and to shift a major portion of its energy production from fossil fuels to renewable fuel resources. Brunei Darussalam's long-term development plan, the Brunei Vision 2035, includes various plans including to reduce its energy intensity by 45% by the end of 2035, with 2005 as the base year and to generate 10% of its energy requirements from renewable energy resources available in the country [49,50]. Many countries across the world are also motivated to search for renewable energy resources to contribute into their energy requirements [51–55].

3. Background of *Acacia* species

3.1. General information about Acacia species

Acacia species are shrubs and trees belonging to *Acacia* genus which are native to Australia, Africa, Madagascar, throughout the Asia-Pacific region and in the Americas. *Acacia* species can adapt to a wide range of tropical and temperate environments, and this adaptability has made them popular for planting on degraded lands in Asia and other parts of the world [57]. There are 1350 different species of *Acacia* which make it one of the large plant taxa in the world that can grow in warm, tropical and even in deserts [25]. Most popular types of *Acacia* species based on their physical appearance and special characteristics are Flat-topped *Acacia*, Swollen-thorn *Acacia*, Koa *Acacia* and Flowering *Acacia* [58]. *Acacia* species are important economically in various parts of Asia and Africa, and some common uses of *Acacia* species include as a source of wood, feedstock to produce pulp and paper, gum arabic, tannin, blossoms, food for domestic animals and source of high quality biomass.

3.2. Acacia species in Brunei Darussalam

Brunei Darussalam is one of the countries with high forest cover, with tropical forests covering 75% of the country's total land area [59]. The climate of the country is aseasonal with high temperatures and rainfall throughout the year. Introduction of *Acacia* species in Brunei

Fig. 3. *Acacia mangium* in Brunei Darussalam.

Darussalam dates back to the early 1990s when *Acacia mangium* was first planted in country to produce high quality wood for timber industry. Before being planted in Brunei, *Acacia mangium* was introduced to Malaysian Borneo as a plantation tree in the early 1980s [60]. In the mid-1990s two other fast growing species of *Acacia* family *Acacia auriculiformis* and *Acacia cincinnata* were cultivated with along *Acacia mangium* to rehabilitate vegetation along Tutong - Muara highway to prevent soil erosion [61]. The introduction of *Acacia* species in Brunei Darussalam went well because these species can grow rapidly at fast rates by fixing nitrogen and thus can grow and establish even in nutrient-poor soils. These introduced species contributed well in the reduction of soil erosion problem and closed up the open canopy along the highway. However, since this initial introduction, *Acacia* species have spread to other habitats in Brunei, particularly in degraded forests and lands, and they are commonly seen as roadside vegetation throughout Brunei Darussalam. *Acacia* species are well known for their invasiveness and studies have reported the negative effects of *Acacias* on native tree species, causing serious threats to the biodiversity of Brunei Darussalam [32,62]. There are four species of *Acacia* currently found in Brunei Darussalam: *Acacia mangium* (Fig. 3), *Acacia auriculiformis* (Fig. 4), *Acacia cincinnata* (Fig. 5) and *Acacia holosericea* (Fig. 6). Of these, *Acacia mangium* appears to be the most abundant, *Acacia auriculiformis* and *Acacia cincinnata* are fairly abundant, but *Acacia holosericea* is less commonly found in Brunei. When grown in large numbers, these *Acacia* species are capable of producing large quantities of biomass as feedstock for thermochemical conversion processes to produce biofuels and bio-products in the country.

Fig. 2. CO_2 Emissions contribution from different sectors in Brunei Darussalam [56].

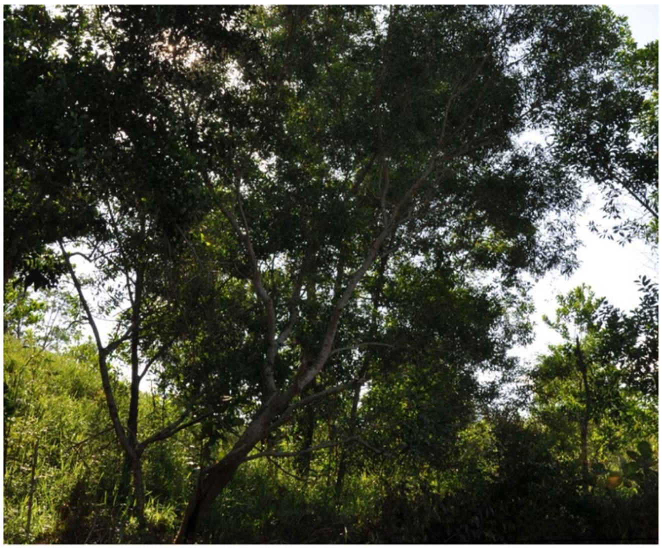

Fig. 4. *Acacia auriculiformis* in Brunei Darussalam.

Fig. 5. *Acacia cincinnata* in Brunei Darussalam.

Fig. 6. *Acacia holosericea* in Brunei Darussalam.

4. Potential of *Acacia* species for bioenergy production

Acacia species meet the criteria in general set for the species to be an ideal energy crop by McKendry, 2002 which are (i) high yield of biomass per hectare, (ii) less energy input to grow, (iii) minimum cost requirement for cultivation (iv) should produce biomass with minimum contaminants and minimum external nutrient requirements to grow [17]. *Acacia* species have been potentially investigated to have good thermochemical properties required to produce biofuels via thermochemical processes. In Brunei Darussalam, *Acacia* species are abundant in invaded habitats. As a potential management solution to the problem of *Acacia* invasion, these *Acacia* can potentially provide biomass supply for bioenergy production via thermochemical conversion processes. For continuous energy production, sustainable supply of biomass feedstock and decent thermochemical properties of biomass feed stock are very important; for *Acacia* species these are discussed below.

4.1. Biomass accumulation from Acacia species

Calculations regarding the biomass production from the source plays very important role in sustainable management of feedstock resources and in designing the process by estimating the carbon resources. Any mistake or overlook in terms biomass estimation can cause serious setbacks to the energy production project [63]. Mass of trees grown above ground divided by area, harvested in a specific time is called above ground standing biomass of tree and the change in standing biomass in an area per specific time is called productivity. Biomass productivity of tree species in specific area helps in calculating the biomass that can be extracted continuously for required application. The standing biomass of the specie per area is estimated by the harvest method or by using allometric equations. Using allometric equations are an effective way of estimating the biomass of trees [64] as harvest method requires the harvesting of trees and then weighing which is very hectic and time taking exercise. In literature various studies are reported in relevance to calculate the above ground biomass of *Acacia* species showing satisfactory quantity of biomass production per hectare to ensure the sustainability of the feedstock for biofuels production processes. *Acacia* species are evergreen trees and can generate large quantities of biomass per annum. *Acacia mangium* can grow up to 30 m height with straight trunk. The colour of the bark varies from pale grey-brown to brown. Mean stem diameter of mature *Acacia mangium* tree can reach up to 60 cm. Mature *Acacia mangium* trees drop their leaves and instead the leaf stalks are modified into leaf-like structures called phyllodes which are found to be 25 cm in length and 10 cm in width approximately depending on the growing soil conditions [57]. *Acacia auriculiformis* can grow up to 28 m in height, having straight trunk up to 12 m long and average stem diameter up to 50 cm. Phyllodes of *Acacia auriculiformis* are usually dark green coloured with length between 10 and 20 cm [65]. *Acacia cincinnata* grows up to 10 − 25 m tree height having stem diameter up to 60 cm [25].

The above ground biomass contribution for *Acacia mangium* comes from stems, branches, bark and phyllodes as 55–80%, 10–22%, 7–10% and 2–9% respectively depending on the growing conditions [66]; while, another study shows contribution from stems, branches, roots and phyllodes as 63–71%, 11–17%, 14–16% and 2–10% respectively [67]. Biomass productivity varies with respect to age, soil conditions, gaps between the tress and location of the species. Various researchers have estimated the biomass accumulation rate for *Acacia* species at different age groups and locations. The studies are summarized in Table 2.

4.2. Thermochemical properties of Acacia biomass

Information about the biomass properties of any specie is very important for its better utilization. Thermochemical characterization of biomass prior to its use as feedstock for thermochemical conversion

Table 2
Biomass accumulation from *Acacia mangium* and *Acacia auriculiformis* with respect to different age and location.

Specie Name	Country	Age (years)	Stem (ton/ha)	Branches (ton/ha)	Bark (ton/ha)	Leaf (ton/ha)	Total Biomass Accumulation (ton/ha)	Reference
Acacia mangium	Indonesia	1	5.20	1.70	3.70	1.70	12.30	[68]
Acacia mangium	Philippines	1	–	–	–	–	14.38	[69]
Acacia mangium	Indonesia	2	22.40	8.60	3.70	3.30	38.00	[68]
Acacia mangium	Philippines	2	–	–	–	–	29.23	[69]
Acacia mangium	Philippines	3	–	–	–	–	48.66	[69]
Acacia mangium	Sabah, Malaysia	4	57.60	14.10	–	5.40	90.40	[70]
Acacia mangium	Philippines	4	–	–	–	–	70.61	[69]
Acacia mangium	Indonesia	5	123.60	14.00	12.00	4.80	154.40	[68]
Acacia mangium	Indonesia	5	–	–	–	–	169.60	[71]
Acacia mangium	Indonesia	5	29.80	8.30	–	2.40	47.50	[67]
Acacia mangium	Philippines	5	–	–	–	–	110.64	[69]
Acacia auriculiformis	Philippines	10	–	–	–	–	70.84	[72]
Acacia auriculiformis	Bangladesh	18	–	–	–	–	211.10	[73]
Acacia auriculiformis	Philippines	20	–	–	–	–	149.25	[72]

process is necessary. Proximate analysis, ultimate analysis, compositional analysis, heating value analysis, FTIR analysis, thermogravimetric (TGA) and derivative thermogravimetric (DTG) analyses are done to know suitability of biomass for its thermochemical conversion [74]. Physical properties of biomass such as biomass type, density, particles size, physical appearance and specific gravity are also important [75,76]. Standard procedures such as American Society of Testing Materials (ASTM) methods are followed to find out the calorific values and to perform the proximate analysis of biomass [77–80]. Ultimate analyses are used to determine the elemental composition of biomass, and are performed through CHNSO analyzer. Compositional analyses of biomass show the percentage composition of cellulose, hemicellulose, lignin and organic extractives. Compositional analyses show whether a biomass is more suitable for bio-oil or solid biochar production; they also give idea about the composition of the products. Biomass rich in cellulose and hemicellulose contents tend to yield higher percentages of liquid oil while higher lignin percentage indicates suitability to produce more biochar [75]. *Acacia* species show biomass composition comparable to standard lignocellulosic biomass. Density of air dried *Acacia mangium* biomass ranges between 0.5–0.6 g/cm^3 with moisture content up to 12% [81–83]; while its specific gravity range is between 0.4 and 0.45 [84]. Proximate analysis and ultimate analysis of *Acacia mangium* along with the higher heating values and density reported in literature are summarized in Table 3 while the compositional analysis are given in Table 4. Variation in the biomass properties with respect to location of trees can be seen in the table. In proximate analysis, the weight percentages of volatile matter, moisture contents, fixed carbon and ash contents for *Acacia mangium* are reported in the range of 64.40–88.30%, 3.78–13.60%, 11.30–26.46% and 0.24 –3.77% respectively. Ultimate analysis of *Acacia mangium* reported the weight percentages of Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen elements in the range of 44.01–56.90%, 3.94–6.71%, 0.2–1.11%, 0–0.02% and 39.65–48.26% respectively. Higher heating values of *Acacia*

Table 4
Summary of compositional analysis of *Acacia mangium* reported in the various investigations.

Country	Compositional Analysis (wt%)				Reference
	Cellulose	Hemicellulose	Lignin	Extractives	
Cuba	42.11	28.3	29.80	-	[89]
Cuba	48.44	23.93	27.11	-	[89]
Indonesia	44.69	22.39	27.91	5.55	[95]
Thailand	43.99	30.14	23.71	4.27	[36]
Cuba	44.05	-	29.70	4.45	[91]
Indonesia	70.90		27.55	4.05	[99]
Indonesia	72.14		29.91	6.76	[97]
Indonesia	-	-	Bottom 23.30 Middle 24.30 Top 21.60	Bottom 2.20 Middle 3.70 Top 1.40	[98]

Table 3
Summary of proximate analysis, ultimate analysis, heating value and density of *Acacia mangium* reported in the various investigations.

Country	Proximate Analysis (wt%)				Ultimate Analysis (wt%)					HHV (MJ/Kg)	Wood density (gm/cm^3)	Reference
	MC	VM	FC	Ash	C	O	H	N	S			
Thailand	10.86	79.60	16.63	3.77	47.60	47.85	3.94	0.59	0.02	–	–	[88]
Cuba	11.70	82.43	16.18	0.78	45.45	48.02	6.60	0.23	–	16.96	–	[89]
Cuba	10.50	88.30	11.30	0.45	47.37	45.46	6.06	1.11	–	16.97	–	[89]
India	–	84.00	14.97	1.03	50.22	43.01	5.90	–	–	19.20	–	[90]
Cuba	3.78	82.43	17.57	0.97	45.45	48.26	6.30	0.23	–	–	–	[91]
Columbia	5.79	73.25	26.46	0.29	53.02	39.65	6.71	0.33	0.02	18.694	–	[92]
Papua New Guinea	–	–	–	1.14	46.87	44.83	6.36	0.44	–	18.960	0.34	[93]
Indonesia	9.11	72.55	17.30	1.04	44.01	39.79	5.41	–	–	17.84	0.64	[94]
Indonesia	–	82.01	17.47	0.52	–	–	–	–	–	–	–	[95]
Brazil	–	83.94	14.94	1.12	48.93	43.44	6.06	0.43	0.02	19.50	–	[96]
Indonesia	-	-	-	0.55	48.90	44.50	5.90	0.20	–	19.70	–	[97]
Indonesia	Bottom 13.60 Middle 10.80 Top 12.60	Bottom 64.40 Middle 66.00 Top 65.40	Bottom 21.60 Middle 23.00 Top 21.80	Bottom 0.31 Middle 0.25 Top 0.24	Bottom 53.80 Middle 56.90 Top 51.60	Bottom 45.00 Middle 41.80 Top 48.00	–	–	–	Bottom 17.00 Middle 17.50 Top 16.60	Bottom 0.43 Middle 0.35 Top 0.41	[98]

MC: Moisture Contents; VM: Volatile Matter; FC: Fixed Carbon; HHV: Higher Heating Value.

Table 5
Summary of proximate analysis, ultimate analysis, heating value and density of *Acacia auriculiformis* reported in the various investigations.

Country	Proximate Analysis (Wt. %)				Ultimate Analysis (Wt. %)					HHV (MJ/Kg)	Density (gm/Cm^3)	Reference
	MC	VM	FC	Ash	C	O	H	N	S			
Cambodia	-	-	-	0.87	48.45	44.27	6.12	0.26	-	20.00	-	[100]
India	-	81.30	18.40	0.30	47.70	46.32	5.84	0.14	-	20.06	0.651	[38]
Thailand	6.07	64.46	20.15	9.32	29.74	63.35	5.16	1.75	-	19.85	-	[86]
Malaysia	-	-	-	-	-	-	-	-	-	-	0.64	[39]
Indonesia	Bottom 13.30 Middle 11.20 Top 13.00	Bottom 64.80 Middle 65.70 Top 65.60	Bottom 21.40 Middle 22.70 Top 21.20	Bottom 0.42 Middle 0.36 Top 0.25	Bottom 52.40 Middle 53.10 Top 48.80	Bottom 47.30 Middle 42.80 Top 43.70	-	-	-	Bottom 17.20 Middle 17.40 Top 16.80	Bottom 0.53 Middle 0.44 Top 0.38	[98]

MC: Moisture Contents; VM: Volatile Matter; FC: Fixed Carbon; HHV: Higher Heating Value

mangium as reported in different studies range between 16.60 and 19.70 MJ/Kg. Compositional analysis of *Acacia mangium* are reported for the weight percentages of cellulose, hemicellulose, lignin components and organic extractives in the range of 42.11–48.44%, 22.39–30.14%, 23.30–29.91% and 1.4–6.76% respectively.

Density of *Acacia auriculiformis* as reported in the literature ranges between 0.50–0.65 g/cm^3 [38,39,85]. Proximate analysis and ultimate analysis of *Acacia auriculiformis* as reported in literature along with higher heating values and density are summarized in Table 5; while the compositional analysis is given in Table 6. In proximate analysis, the range of weight percentages of volatile matter, moisture contents and fixed carbon and ash contents for *Acacia auriculiformis* are 64.46–81.30%, 6.07–11.20%, 18.40–22.70% and 0.25–0.87% respectively. One study has reported the ash contents up to 9.32% which is likely because the researcher used samples from the residues of pulp and paper industry [86]. Ultimate analysis as reported in literature for *Acacia auriculiformis* the weight percentages of Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen elements ranged between 29.74–48.80%, 5.16–6.12%, 0.14–1.75% and 42.80–63.35% with negligible Sulphur contents. The range of higher heating values of *Acacia mangium* reported in different studies is between 16.80 and 20.06 MJ/Kg. Compositional analyses of *Acacia auriculiformis* showed the range of weight percentage of cellulose, hemicellulose, lignin components and organic extractives as 36.15–49.02%, 13.78–20.10%, 16.63–44.88% and 2.30–5.56% respectively. Characterization of *Acacia mangium* and *Acacia auriculiformis* biomass reported in literature showed their suitability as feedstocks for thermochemical processes to produce biofuels. From Brunei Darussalam perspective; comprehensive knowledge about the thermochemical properties of all *Acacia* species available in Brunei Darussalam would still be required prior to their utilization as these properties can vary considerably with changes in location and growing conditions [87]. Any major change in the properties of biomass feedstock can affect the process designing, performance, associated costs and most importantly the quality and yields of biofuels products.

Table 6
Summary of compositional analysis of *Acacia auriculiformis* reported in the various investigations.

Country	Compositional Analysis (wt%)				Reference
	Cellulose	Hemicellulose	Lignin	Extractives	
Russia	49.02	20.10	25.16	5.56	[85]
Brazil	36.15	13.78	44.88	4.84	[35]
Thailand	67.53		16.63	-	[86]
Indonesia	-	-	Bottom 24.60 Middle 24.30 Top 21.60	Bottom 3.30 Middle 3.60 Top 2.30	[98]

5. Thermochemical options to produce energy from *Acacia* species

A wide range of biochemical and thermochemical processes can be employed to produce bioenergy in terms of biofuels and other bio-products utilizing *Acacia* biomass as feedstock. In this study only thermochemical conversion options are discussed as these seem more applicable for Brunei Darussalam. Thermochemical conversion of biomass to produce bioenergy in terms of biofuels and bio-products is achieved by controlling the heating rate under inert, controlled oxidation or combustion conditions following number of pathways to give out intermediate energy products or direct heat [101]. Processes developed under thermochemical conversion of biomass are pyrolysis, gasification, liquefaction and direct combustion [97,102,103]. Differentiation among these processes is based on the oxidation environment of biomass ranging from inert to fully exothermic oxidation, heating rate and particle size of the biomass.

Thermal decomposition of biomass under oxygen free condition is called Pyrolysis. The products from pyrolysis include a heterogeneous mixture of liquid oil which is often called as pyrolysis oil, non-condensable gases, and solid char often named as biochar [104]. Pyrolysis in comparison to liquefaction has proved to be a more viable option to produce liquid oil from biomass as it has low installation and operating cost; and its process conditions are easy to maintain [105].

Gasification of biomass is adopted to produce higher yield of gaseous product enriched with CO, H_2, CH_4 and CO_2 gases. This can be achieved by optimizing process conditions under controlled oxidation of biomass. This gas contains few impurities and after purification can be used as fuel directly or can be converted to chemical feedstock via biological fermentation and catalytic upgrading [106,107].

Liquefaction of biomass to produce bio oil is still under development phase. In this process, a superheated solvent under highly pressurized conditions is used to cause more penetration of solvent into biomass molecules resulting in greater decomposition of biomass to liquid oil. This process is more flexible to the moisture contents of biomass and can deal with wide range of biomasses [108]. Combustion is the thermochemical process in which biomass is burned in excess oxygen or open air to produce heat and flue gases. A complete chart of biomass conversion to bioenergy along with intermediate products is shown in the Fig. 7. Research studies using *Acacia* species as feedstock of thermochemical conversion processes including pyrolysis, gasification, liquefaction and combustion are summarized in Table 8. It is important to mention that *Acacia mangium* and *Acacia auriculiformis* are the species commonly investigated for bioenergy production and till date no significant work has been reported on the bioenergy potential of *Acacia cincinnata* and *Acacia holosericea* by using thermochemical conversion processes.

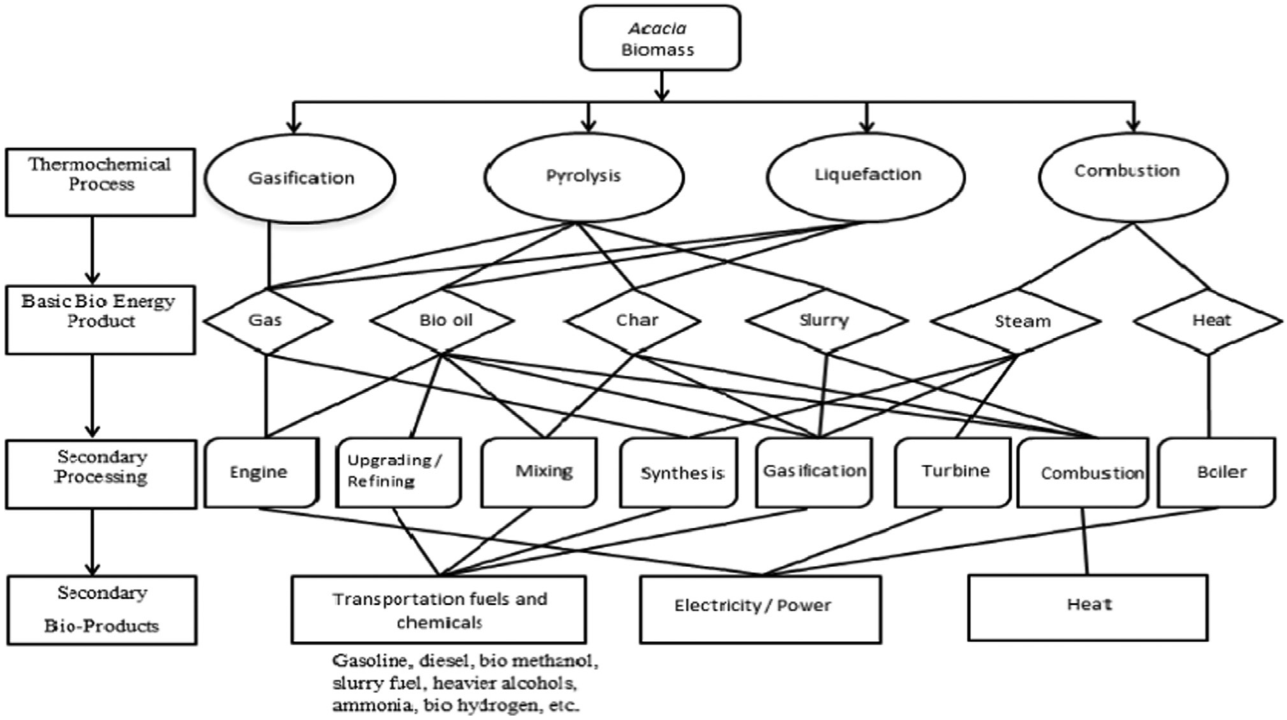

Fig. 7. Overview of the thermochemical conversion of *Acacia* biomass to bioenergy [101,109].

Table 7
Chemical compounds detected by GC-MS in the bio-oil obtained from the pyrolysis of *Acacia auriculiformis* residues from paper mill industry [86].

Retention Time (min)	Compounds	Peak area (%)
2.643	1-propen – 2-ol	0.04
2.912	1,3-Cyclopentanedione	10.57
2.998	1H-Pyrazole, 4,5-dihydro – 1,5-dimethyl-	4.13
3.115	2,3 dimethl – 2-cyclopenten – 1-one	1.13
3.435	2-Pentanone, 4-hydroxy – 4-methyl-	28.72
3.561	1,2-benzenediol	1.86
5.561	2-Cyclopenten – 1-one, 3-methyl-	1.57
5.638	Phenol	1.16
5.712	Phenol,2-methoxy	1.02
6.017	Phenol,3,4-dimethyl-	0.3
6.112	Piperidine, 3-methyl-	0.83
6.439	2-Cyclopenten – 1-one, 2-hydroxy – 3-methyl-	0.35
7.714	4-Piperidinone, 2,2,6,6-tetramethyl-	10.82
8.935	.beta.-(N-*tert*-Butylformamido) acrolein	3.54
9.315	1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	0.5
12.998	d-Allose	1.84
17.915	Hexadecanoic acid	0.17
18.752	Cyclohexane, hexaethylidene-	0.07
20.912	Benzene, 1,1′-sulfonylbis[4-chloro-	1.44
21.038	Benzene, 1,1′-sulfonylbis[4-chloro-	1.44
21.967	hexanadioic acid bis(2-ethylhexyl) ester	0.75
23.336	Benzene, 1-butyl – 4-	0.06

5.1. Pyrolysis

Thermal decomposition of biomass under oxygen free conditions is called Pyrolysis. The products from pyrolysis include a heterogeneous mixture of gases, liquid oil which is often called as pyrolysis oil and solid char often named as biochar. In pyrolysis process, chemical constituents of biomass including cellulose, hemicellulose and lignin are decomposed at high temperature resulting in mixture of gases and charcoal. Some of these resulting gases from biomass decompositions can be condensed to produce liquid oil usually called as bio oil. Cellulose contents in biomass contribute for the production of CO, CO_2 and H_2, while hemicellulose for CO_2, H_2O with some hydrocarbons; and lignin contents contribute mainly for the production of CO, CO_2, CH_4 and char [110]. Pyrolysis process can be classified as slow pyrolysis, fast pyrolysis and flash pyrolysis on the basis of heating rate of biomass. Yield percentage of the resulting products varies significantly by changing type of pyrolysis process selected; even with same biomass feedstock [75]. On the basis of pyrolytic environment of biomass, pyrolysis can be classified as hydrous-pyrolysis, hydro-pyrolysis, vacuum pyrolysis, oxidative pyrolysis and catalytic pyrolysis [111].

Research studies have reported the pyrolysis of various *Acacia* species using different heating rates and reaction conditions. Generally, four stages of biomass decomposition are observed in the pyrolysis of *Acacia* species. Every stage proceeds over a different temperature range, while overlapping of the stages also exist. Each stage represents decomposition of specific component of biomass producing a mix of pyrolysis products. Usually the first stage of *Acacia* pyrolysis is associated with the removal of moisture from the biomass, starting from room temperature and lasts up to 130 °C approximately. In the second stage, hemicellulose contents start to break down at 200 °C and continue up to approximately 270 °C. During this stage primarily non-condensable vapor and some bio-oil is produced. Third stage of biomass decomposition ranges between 270 °C and 380 °C is associated with the decomposition of cellulose contents producing some condensable vapor, bio-oil and char. In the fourth stage lignin is decomposed around temperature range of 280–500 °C producing bio-oil and char. Researchers have reported the four stage decomposition for other biomasses of similar types [112,113]. While pyrolyzing *Acacia* species particularly *Acacia mangium* and *Acacia auriculiformis* the temperature range between 250 and 400 °C is very important as maximum decomposition of hemicellulose and cellulose takes place during this range giving out maximum condensable gases to produce bio-oil. Montesino et al., 2015 studied the pyrolysis of *Acacia mangium* wood with out and with bark to produce biochar, bio oil and gases [89]. Yields of pyrolysis products reported in weight percentage for gases, liquid, water and char in the case of wood without bark as 23.18%, 25.45%, 32.35% and

Table 8
Summary of the recent research investigations reported on thermochemical conversion of *Acacia* species.

Acacia Specie	Process and Reactor Specifications	Temp range, heating rate and time	Products Yields (%)		Products Characterization (%)				Findings and the Comments on Study	Reference
Acacia mangium without bark (A1) *Acacia mangium* with bark (A2)	Pyrolysis Vertical furnace D = 8 cm L = 30 cm	400-500 °C 10 (°C min^{-1}) 2 hours	**(A1)** Gases = 23.18 Liquids = 25.45 Water = 32.35 Char = 18.91	**(A2)** Gases = 26.9 Liquids = 24.31 Water = 32.07 Char = 17.43	**Gas (A1)** H_2 = 2.81 O_2 = 7.45 N_2 = 59.20 CH_4 = 3.92 CO = 17.01 CO_2 = 9.61 CV = 3858.7 KJ/m^3	**Gas (A2)** H_2 = 0.55 O_2 = 3.26 N_2 = 56.03 CH_4 = 3.77 CO = 27.25 CO_2 = 9.12 CV = 4859.4 KJ/m^3	**Bio Oil (A1)** Aliphatic HC = 1 Aromatic HC = 33 Oxy. Com. = 55 Nit. Com. = 9 Others = 2	**Bio Oil (A2)** Aliphatic HC = 1 Aromatic HC = 4 Oxy. Comp. = 84 Nitro. Comp = 10 Others = 1	● Maximum de-volatilization of biomass occurred between 250 ± 20 up to 380 ± 20 °C. ● In pyrolytic degradation of *Acacia mangium* with bark kinetic study showed less activation energy values may be because of catalytic activity of ash in the bark. ● The values of correlation coefficient for both cases indicated the reliability of first order reaction model.	[89]
Acacia mangium	Pyrolysis Fixed bed D = 40 mm L = 140 mm Cap. = 20 g	250 -600°C 50 (°C min^{-1}) 3 hours	-		**Char at 600 °C** Volatile Matter = 67 % lost from initial valueFixed Carbon = increased up to 65.23 % from the initial value		**Gas at 600 °C (Vol %)** CO = $46CO_2$ = $16(N_2+O_2)$ = $14CH_4$ = 24HHV = 15.33 MJ/Nm^3		● *Acacia mangium* along with two other short rotation species were studied to know their biofuel potentials. ● Volume of CH_4 in the product gas increases with temperature hence increasing HHV of product gas. ● In this study *Acacia mangium* is recommended to be used as feedstock to produce gaseous product.	[88]
Acacia mangium	Pyrolysis Lab scale furnace (10 gm) N_2 = 100 mL min^{-1}	270 - 500 °C 15 (°C min^{-1})	**Temp = 500 °C, HR = 10 °Cmin^{-1} & PS = 0.4 mm** Bio Oil = 32.9 Biochar = 26.3 Gases = 25.3 Water = 15.4		**Bio Oil Characterisation** Phenol and derivatives = 40.22 Furans and derivatives = 17.44 Ketones = 16.05 Alcohols = 14.27 Nitrogen compounds = 4.56 Others = 7.47				● Experimental study was conducted by two experimental models; two level factorial design (TLFD) and response surface methodology (RSM–BB). ● TLFD was used to find the effect of temperature, heating rate and particle size on the bio oil production while RSM–BB was employed to find the	[115]

(*continued on next page*)

Table 8 (*continued*)

Acacia Specie	Process and Reactor Specifications	Temp range, heating rate and time	Products Yields (%)	Products Characterization (%)	Findings and the Comments on Study	Reference
					Optimisation of the process parameters. ● Statistical analysis predicted optimum yield of bio oil as 33.13% at temperature of 499.57 °C, heating rate of 12 °C min^{-1} and particle size of 0.46 mm while the highest yield obtained experimentally was 32.9%.	
Acacia mangium	Pyrolysis Thermogravimetric Study	25 – 800 °C 5–15 (°C min^{-1})	-	-	● Values of activation energy, pre-exponential factors and contribution factor were similar to other same type biomass when calculated using independent parallel reaction model. ● Less than 3% deviation was predicted between the experimental and model curve at different heating rates confirming the suitability of model to study pyrolysis.	[91]
Acacia mangium	Pyrolysis steel-capped graphite reactor 30 gm wood + 15 gm of activating agent	773 K Constant Temp for 2 hours	**COAC** 70.27 ± 0.93 Burn off percentage **POAC** 73.30 ± 0.20 Burn off percentage	**CO Activated Carbon** Carbon = 74.72 Oxygen = 18.89 Chlorine = 2.15 Calcium = 4.24 **PO Activated Carbon** Carbon = 54.31 Oxygen = 17.92 Phosphorous = 5.58 Potassium = 22.19	● *Acacia mangium* wood was used to prepare activated carbons by pyrolyzing in the presence of calcium oxide (COAC) and potassium hydroxide (KOH) as basic activating agents. ● • A strong influence of activating agents was observed on the surface functional group and elemental composition of activated carbon.	[124]
Acacia auriculi-formis	Pyrolysis Continues screw feed reactor of	380 – 580 °C 10 (°C min^{-1}) 2 hours	**Bio Oil** Bio oil = 53.38 Aromatic contents (bio oil) = 27.19	**Char** - **Gas** - **Bio Oil** C = 42.73 H = 8.28 N = 0.86	● Optimization of bio oil production, aromatic contents and acidity was done by	[86]

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Table 8 (*continued*)

Acacia Specie	Process and Reactor Specifications	Temp range, heating rate and time	Products Yields (%)	Products Characterization (%)	Findings and the Comments on Study	Reference
	L = 120 cm Feed rate = 120 to 240 rpm			O = 48.13 PH = 3.2 Acid No = 78 mg KOH/g HHV = 26.82 MJ/kg	using 2 level factorial experimental designs. ● The optimum pyrolysis condition to produce maximum yield of bio oil were reported as 515.18 °C temperature, 120.01 rpm of feed rate and 20 cm^3/min of nitrogen flow using 5 wt. % of Dolomite catalyst. ● The ash content in the biomass is reported as 9.32 % which is on higher side which may be is because of some contaminations present in the biomass as pulp and paper industry residue is used in the study.	
Acacia mearnsii	Pyrolysis Studied by TGA and DSC analyses	25 – 900 °C 2–50 (°Cmin^{-1})	-	-	● In this study the effects of heating rate and pyrolysis environment (N2 and Air) is studied by determining the efficiency and kinetic parameters of the process. ● The results showed that lower heating rate with air environment in pyrolysis ensure the complete decomposition of the process.	[120]
Acacia auriculiformis and Acacia mangium	Gasification	-	-	-	● Characterization of potential feedstocks is done to find out their suitability for the gasification process and to make suggestion. ● Potential of biomass gasification for the electrification of rural area in Cambodia is studied using	[100]

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Table 8 (*continued*)

***Acacia* Specie**	**Process and Reactor Specifications**	**Temp range, heating rate and time**	**Products Yields (%)**	**Products Characterization (%)**	**Findings and the Comments on Study**	**Reference**
					geographic and economic databases. ● Cost per unit of electricity from biomass gasification would be less than cost from diesel generation if the plant capacity factor exceeds by 13 %	
Acacia mangium	Gasification Downdraft fixed bed reactor I.D= 0.102 m OD=0.185 m bed length = 0.4 m	chip size = 4 –10 mm Superficial velocity = 0.1 ms^{-1} atmospheric pressure	**Producer Gas** Gas mixture containing CO, CO_2, CH_4 and H_2	**Producer Gas Composition (Vol %)** ***A. mangium***: CO = 13.0CO_2 = 18.0CH_4 = 1.8H_2 = 1.5 **G Arborea**: CO = 11.0CO_2 = 17.0CH_4 = 1.5H_2 = 3.0 **Euca. Sp**: CO = 13CO_2 = 16CH_4 = 1.5H_2 = 4.0 **Pinus sp**: CO = 14CO_2 = 16CH_4 = 1.5H_2 = 3.0 **P patula**: CO = 14.0CO_2 = 16.0CH_4 = 1.5H_2 = 3.0	● This study concluded that the species with higher bulk density and higher heating value with low moisture contents perform well during the gasification process. ● *Acacia mangium* was found to be low efficient in comparison to the other species used in study which was may be because of the lower bulk density of the wood.	[92]
Acacia mangium	Liquefaction Autoclave (Cap. 300 ml) 10 gm biomass + 100ml water + 0.05 gm Na_2CO_3 catalyst	300 °C P = 10 MPa Time = 30 min	**Yield (organic basis)** Oil = 31.7 Gas = 16.1 Residue = 7.9 Aqueous = 14.2 Loss = 30.2 **Yield (mass balance of Carbon)** Oil = 46.2 Gas = 9.6 Residue = 11.4 Aqueous = 29.8 Loss = 3.0	**Bio Oil** C = 71.7 H = 6.5 N = 0.4 O = 21.5 Ash = - L.C.V = 29.8 (MJ/Kg) **Residue** C = 70.5 H = 4.7 N = 0.5 O = 23.8 Ash = 0.6 L.C.V = 26.3 (MJ/Kg)	● Eighteen different species of biomass were studied for their liquefaction at 300 °C and 10 MPa pressure using hot compressed water as solvent with sodium carbonate catalyst. ● Bio oil was produced by having calorific values comparable with high quality coal. ● Liquefaction process to produce bioenergy from biomass in terms of biofuels and other bio-products showed significant potential in this study.	[97]

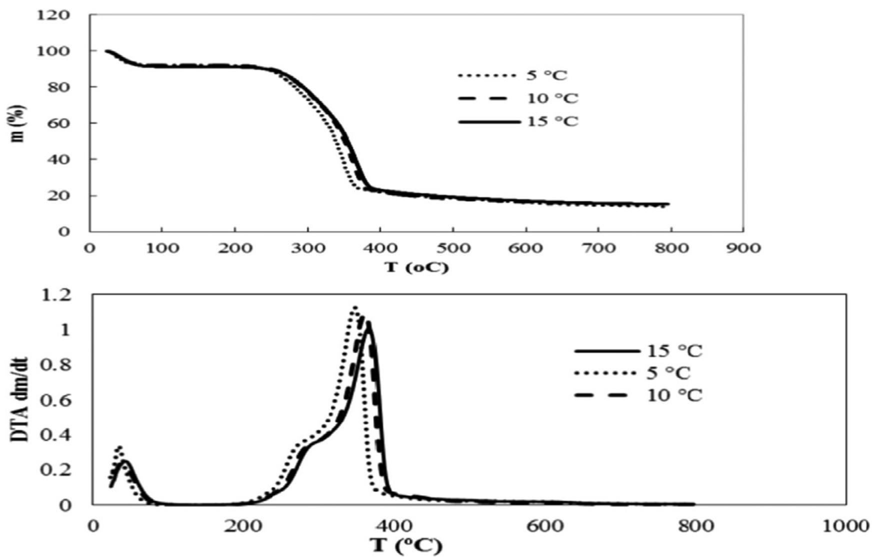

Fig. 8. TGA and DTG curves of *Acacia mangium* wood without bark [89].

18.91% respectively; and for wood with bark as 26.9%, 24.31%, 32.07% and 17.43% respectively. Prior to pyrolysis TGA and DTG tests of the samples were carried out to explain the decomposition stages of biomass and confirmed that 2 h′ time would be required for the pyrolysis process [89]. TGA and DTG curves showed maximum decomposition of biomass components in the temperature range of 250 ± 20 °C to 380 ± 20 °C confirming the four stages decomposition patron. First stage showed the 10 – 15% weight loss of sample representing the loss of moisture and extractable components. During the second and third stage of weight loss between 250 and 380 °C most of the hemicellulose and cellulose components were decomposed accounting for approximately 60–70% of the total mass. Fourth stage of decomposition reached 800 °C, where about 90% of the initial mass of sample was lost [89]. During decomposition of biomass, mainly in lignin a rearrangement of the carbon atoms present in original structure takes place. Decomposition behavior of cellulose, hemicelluloses and lignin indicates the structural stability of biomass. Yang et al., 2006 reported maximum weight loss in terms of hemicellulose decomposition observed at 268 °C as 80%; for cellulose at 400 °C as 94.5% and for lignin even at 900 °C only 54.3% [114]. It can be concluded that higher yield of bio-oil is dependent on the hemicellulose, cellulose components not on adopting higher pyrolysis temperature and that lignin majorly contributes for the char production. TGA and DTG curves of *Acacia mangium* wood without and with bark are given in Fig. 8 and Fig. 9. Crespo et al., [91] reported the maximum thermal degradation of *Acacia mangium* biomass taking place between 300 – 400 °C by studying pyrolysis from room temperature up to 800 °C. The values of kinetic parameters of the reactions such as activation energy, pre-exponential factor and contribution factors calculated using independent parallel reaction model were similar to the other biomasses of similar type reported in literature [91]. Another study reported the effect of pyrolysis temperature (from 250 − 600 °C) on the char and non-condensable gases production for *Acacia mangium* in a fixed bed reactor. Decrease in the volatile matter of biochar produced with the increase in fixed carbon contents was reported with the increase in temperature. Methane production was increased with temperature rise and was reported as 23.47% of the gas produced; while concentration of carbon dioxide decreased with rise in temperature. Higher yield of methane in product gas caused an increase in the higher heating of the gas and its maximum value was achieved at 600 °C as 15.33 MJ/Nm^3 concluding its possible use as fuel for kilns, steam boilers and internal combustion engines [88]. Crespo et al., [115] conducted the experimental study by two experimental models; two level factorial design (TLFD) and response surface methodology (RSM–BB). TLFD was used to find out the effect of temperature, heating rate and particle size on the bio oil production while RSM–BB was employed to find the optimisation of the process parameters. Statistical analysis predicted the optimum yield of bio oil as 33.13% at temperature of 499.57 °C, heating rate of 12 °C min^{-1} and particle size of 0.46 mm, while the highest yield obtained experimentally was 32.9% at temperature of 500 °C, heating rate of 10 °C min^{-1}

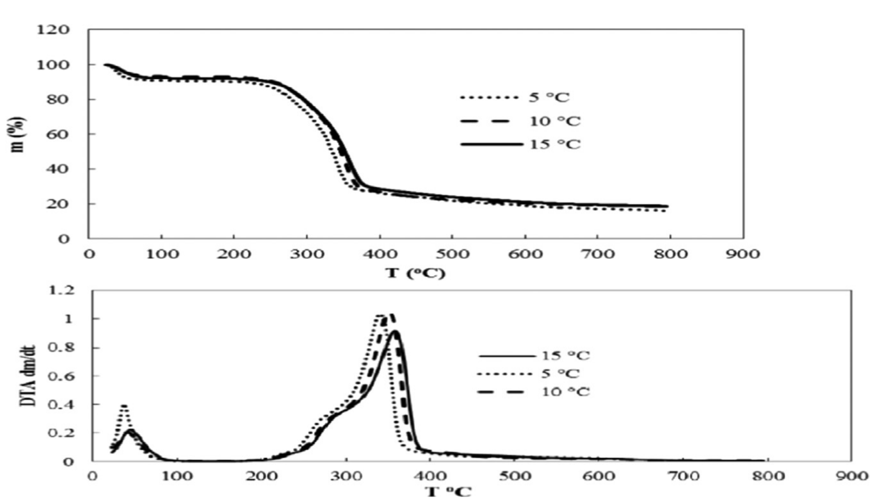

Fig. 9. TGA and DTG curves of Acacia mangium wood with bark [89].

and particle size of 0.4 mm [115]. Catalytic pyrolysis of *Acacia auriculiformis* residues from pulp and paper mill is reported using dolomite catalyst to find out the optimum bio oil production conditions us continuous screw feeder reactor between the temperature range of 380 – 580 °C and 20–80 Cm^3/min of Nitrogen as carrier gas. The optimum pyrolysis condition were reported as 515.18 °C temperature, 120.01 rpm of feed rate and 20 Cm^3/min of Nitrogen flow rate and 5% weight of dolomite catalyst. Results showed that the *Acacia auriculiformis* residues can be used for the production of biofuels and other valuable chemicals. Chemicals compounds detected in the bio oil by GC-MS are given in Table 7 [86]. Bio oil is dark brown organic liquid which can flow freely. Limitations with bio oil exist that they cannot be used directly as fuels. This is because of high oxygen contents; viscosity; corrosiveness; complex chemical composition and relatively instable nature during storage. In order to use them as direct fuels they are upgraded to enhance their fuel properties. Various methods are available to upgrade bio oils to fuel oil such as catalytic cracking of pyrolysis vapors, hydrodeoxygenation, extracting chemicals and esterification [116–119]. The effect of heating rate and reaction conditions using N_2 and Air was reported for *Acacia mearnsii* (black wattle) studying the efficiency and kinetics parameters of the pyrolysis using TGA and differential scanning calorimetry (DSC) [120]. Pyrolysis process can be adopted for the *Acacia* species to produce bio oil, bio char and gases. Yield and quality of the desired products can be enhanced by selecting the appropriate type of pyrolysis process and by varying the process parameters. Fast pyrolysis process is adopted if the more yield of bio oil is desired; while slow pyrolysis can be adopted to produce more biochar and less bio oil [121,122]. Difference among different types of pyrolysis process is based on the heating rate of biomass and vapor residence time.

From Brunei Darussalam perspective, utilization of upgraded bio oil in power generation and transportation sectors can contribute to the energy requirements of the country. Bio char is also a very useful product and have the potential to be used in many sectors such as in agriculture as fertilizers; animal farming sector as feed supplement; in building sector for insulation, air decontamination, decontamination of earth foundations and humidity regulation; for soil decontamination; in biogas production; for the wastewater treatment; for drinking water treatment; in textile sector; for wellness purposes like filling in mattresses and pillows and to provide shield against electromagnetic radiations [123], while the non-combustible gases from the pyrolysis of *Acacia* species can be uses for preheating or drying of the biomass prior feeding it to the reactor.

5.2. Gasification

Gasification is a thermochemical process in which biomass or fossil carbonaceous materials are burned in (> 700 °C) limited supply of gasifying agents to produce gaseous products rich in carbon monoxide, hydrogen, carbon dioxide, and methane [125,126]. Gasifying agents can be air, pure oxygen and steam etc. or a mixture of these agents. In gasification process combustible gases are produced by converting the inherent chemical energy of the carbon in biomass in two stages. The properties of the biomass feedstock and its pre-treatment are the key parameters to design a gasification system. Important feedstock properties include the moisture, ash, alkalis and volatile contents of the biomass while pre-treatment of biomass includes its drying, size reduction, fractionation and leaching [127]. Three different product gas qualities with respect to its calorific value can be achieved by varying the gasifying agent for process, process operating conditions and method of operation. High calorific value, medium calorific value and low calorific value gas product can be achieved. Usually, low calorific value gas (CV = 4–6 MJ / Nm^3) is obtained by using air and steam/air gasifying agent; medium calorific value (CV = 12–18 MJ/Nm^3) gas is obtained by using oxygen and steam gasifying agent and high calorific value (CV = 40 MJ/Nm^3) gas by using hydrogen and hydrogenation gasifying agent [128]. Gasification process can be used for the biomass having moisture contents lower than 35%. Using biomass with high moisture percentage directly in gasifier results in the great loss of energy. It is recommended to dry biomass between 10 – 20% moisture contents before feeding in gasifier [129,130]. Abe et al., 2008 studied the potential of gasification of biomass from fast growing species including *Acacia mangium* and *Acacia auriculiformis* for the rural electrification in Cambodia [100]. These species can produce biomass at higher rates to ensure sustainable feedstock for gasification in rural areas. Cost per unit of electricity generated from biomass gasification could be less than cost from diesel generation if the plant capacity factor exceeds by 13% [100]. Musinguzi et al., 2013 reported the suitability of *Acacia hockii* and three other biomass species grown in Uganda for their gasification by studying thermochemical properties. High volatile and low ash contents ensure the suitability of the species for gasification process [131]. Lenis et al., 2013 studied the effects of biomass moisture content, bulk density, heating value, and H/C molar ratio on the gasification of *Acacia mangium* and four other forest species using down draft fixed be reactor in conjunction to use them for electricity production in Columbia. *Acacia mangium* showed different behavior as compared to the other species in study with LHVg from 2.5 − 3.0 MJ/Nm3, and cold gas efficiency of 25.8% and 30.9%. As concluded low efficiency due to the low fuel/air equivalence ratio caused by the lower bulk density of *Acacia mangium* wood [92]. Sharma et al., 2008 have conducted experimental study by developing downdraft gasifier system to produce 75kWh electricity [132]. The gas produced from gasification of biomass usually contains some impurities and it is required to remove those impurities by treatment of gas. These impurities can include very fine particles, some tar, nitrogen, sulphur and alkali compounds. Management of higher molecular weight particles is a major challenge in gasification as they condense to form tars; these tars such as polycyclic aromatic hydrocarbons can cause fouling in the process lines and also environmental pollution [133]. Syngas or producer gas produced through the gasification of *Acacia species* can be potentially used as direct fuel in a furnace, steam boilers, engine or turbine. Producer gas can mix easily with chemical catalysts and can be converted into useful chemicals and materials. The gas generated is an easy and efficient way to utilize biomass rather than using it in its original biomass form.

5.3. Liquefaction

Liquefaction of *Acacia* or any other biomass is another potential thermochemical process to produce bioenergy from biomass in terms of biofuels and other bio-products. Both direct and indirect liquefaction of biomass can be carried out. Hydrothermal liquefaction and rapid pyrolysis of the biomass feedstock is carried out in case of direct liquefaction to produce tars, oils and condensable vapors. While in the case of indirect liquefaction; catalysts are applied for the conversion of non-condensable and vapors to the liquid bio oil [2]. Compounds having macromolecular structure are broken down to the lighter molecule fragments and from these fragment reactive one re-polymerize to form bio oil. Important factors determining the quantity and quality of bio oil from biomass in case of direct liquefaction are type of biomass being used as feedstock, solvent for the liquefaction, catalyst used, ratios of solvent to biomass, temperature and pressure of the reactor. Catalysts are widely applied in direct liquefaction processes with purpose to minimize the char formation which results in the increase of liquid oil product [134]. A supply of hydrogen gas during the liquefaction process is also found to be effective to increase the liquid oil yield and to minimize the oxygen contents in the oil [135].

Water can be used as solvent and has few advantages over organic solvents from economic and environmental aspects but, major disadvantage associated with water is its higher critical point and its disability to absorb water insoluble components. Typically the water insoluble components have higher heating values as compared to the soluble components because of the presence of high oxygen contents in the water soluble components [136]. It is preferred to use organic solvents for liquefaction of biomass such as ethanol, 2-propanol, acetone, and tetralin so that the concentration of the less oxygenated components can be increased in the bio oil.

Minova et al., [97] have reported the liquefaction of 18 different types of biomass feedstocks including *Acacia mangium* and other species from Indonesia. Hot compressed water was used as solvent with Na_2CO_3 catalyst at 300 °C temperature and 10 MPa pressure. Results showed the bio oil yield from *Acacia mangium* liquefaction as 31.7% which is one of the highest values obtained from all of the specie. Overall yield of oil from all the species was in range of 21 – 36%. The gross heating value of the bio oil from *Acacia mangium* was reported to be 29.8 KJ/g [97]. The bio oil produced can be upgraded to use as direct fuel in the furnaces, steam boilers and internal combustion engines.

5.4. Combustion

Combustion is ancient thermochemical process known to human being for the production of energy from biomass and is still the leading method to grab energy across the world particularly in the rural areas not having modern commodities to meet energy needs [14]. The objective of combustion of biomass is to produce heat to utilize for different applications. The chemical composition of biomass has important influence on its combustion properties. Excess amount of air ensures the complete combustion of biomass producing fully oxidized permanent gases and water vapors. In the combustion of biomass highly resistant carbon and ash are left over as residue. The carbon and hydrogen goes under exothermic reaction with oxygen producing CO_2, H_2O and heat. Combustion is highly affected by the moisture contents present in the biomass feedstock and the rate of combustion is inversely proportional to the moisture contents. Tenorio et al., 2013 studied the burning efficiency of ten short rotation species including *Acacia mangium* and concluded that burning efficiency is influenced by the calorific value of biomass; which becomes significantly less with increasing moisture contents [137]. Other constraints in directly combusting the biomass for energy with regards to the process include the physical feeding problems; lower energy contents; direct substitution involves high costs for burner replacement and large energy installations are needed to meet the energy requirements. The constraints associated with the direct burning of biomass are overcome by prior conversion of biomass to better fuels, via gasification or pyrolysis processes. Browne explained the combustion of biomass to proceed in four zones like pyrolysis; first zone prolongs to below 200 °C giving out non-combustible gases such as water vapor, formic acids and acetic acids. In the second zone exothermic oxidation reactions take place between the temperature ranges from 200 °C to 280 °C. Third stage involves the exothermic reaction without burning (pyrolysis) in temperature range of 280 −500 °C. The products of third zone are mostly fuel gases. Above 500 °C is the fourth zone of combustion in which waste is formed mostly from carbon leftover the secondary reactions may occur [138]. The parts of tree which are more flammable can burn more easily and vigorously to produce larger amount of energy with less pollutants. Saharjo et al., 1999 studied the flammability in *Acacia mangium* plantation by considering shrubs and trees. Study concluded that phyllodes have higher flammability than stems and silica-free ash quantity can indicate the more flammable part of tree [139]. The leaf litter and pods of *Acacia* species can be combusted to produce energy at domestic level and for small scale energy production. These parts of *Acacia* species have higher energy contents and burn more vigorously without generating heavy smokes and solid particulate pollutants. Other possible way of improving fuel wood combustion and properties of biomass is to make wood pellets from *Acacia* biomass. Acda, 2015 showed considerable improvement in physicochemical properties of wood pellets from short rotation tress including *Acacia mangium* species [140].

6. Brunei Darussalam perspective

6.1. Environmental aspects

Brunei Darussalam is the largest emitter of CO_2 per capita in the region of South East Asia [44]. Electricity generation and transport sectors are the major contributors of CO_2 emissions in the country as shown in Fig. 2 [56]. Almost all the power generation in Brunei Darussalam is based on the fossil fuels utilization. Brunei Darussalam is a signatory of the Paris Agreement to keep the CO_2 emission to the minimum level. In Brunei Darussalam reduction in CO_2 emission is possible to achieve in two ways; firstly by educating the people to minimize the use of energy; and secondly by generating energy from the renewable resources available in the country. To achieve this goal Government of Brunei Darussalam has launched many programs and initiatives including "Brunei Vision 2035" which aims to reduce energy intensity by 45% with 2005 as base year and to generate 10% of energy requirements from renewable resources [49,141].

Biomass is a source of renewable energy that is sustainable and environment friendly to use for energy production. *Acacia* species have been able to successfully establish in degraded habitats in Brunei Darussalam. *Acacia* species particularly *Acacia mangium* and *Acacia auriculiformis* are considered to exhibit high biomass production within a few years of their growth as given in Table 2. Furthermore, these invasive species can be utilized as an energy crop to provide a sustainable resource of biomass while also providing a management solution by using it for the biofuels production and removing these invasive Acacia species from Brunei's natural ecosystems. *Acacia* species have been potentially investigated to produce biofuels via thermochemical conversion processes including pyrolysis, gasification, liquefaction and direct combustion as discussed in the above sections. It is recommended to assess the feasibility and commercial viability of using *Acacia* species as an alternative renewable energy resource to help achieve Brunei's aims in reducing CO_2 emissions while also ensuring that the country's biodiversity is not adversely impacted by these invasive species.

6.2. Potential economic aspects

While the economy of Brunei Darussalam is heavily dependent on its oil and gas exports, the Government is committed to diversifying its economy by exploring new sectors which can contribute for the betterment of its people. The utilization of renewable energy resources to produce bioenergy in terms of biofuels and other bio products can offer wide range of benefits to the society [142,143]. Bhattacharya et al., 2016 showed the positive impact of using renewable energy on the economic growth of many countries across the world [51]. *Acacia* biomass is one of the potential candidates to produce renewable energy in Brunei Darussalam. Utilization of biomass resources can contribute positive economic impacts in a number ways. New employment opportunities can be created in various sectors including engineering, agriculture, transportation, research and development sectors. Energy expenses of the country can be reduced as a study in Cambodia have reported the cheap electricity generation from agricultural residues and woody biomass including *Acacia mangium* in comparison to diesel generation when plant capacity factor exceed by 13% [100]. Furthermore; the utilization of *Acacia* species from invaded areas in Brunei Darussalam will help to ensure that the bio-diversity of the country does not continue to be negatively affected by *Acacia* species.

7. Conclusion

Brunei Darussalam is heavily dependent on its oil and gas resources in terms of its economy and energy requirements. With the threats of depletion of fossil resources and the impact of their burning on environment it is time for Brunei Darussalam to search for renewable and sustainable energy resources to diversify its economy and to ensure sustainable supply of energy for future without polluting the environment. In this study we have reviewed bio energy potential of *Acacia* species in terms of producing biofuels and bio products by thermochemical conversion processes. All the studies related to the thermochemical conversion of *Acacia* species are summarized and discussed to prove feasibility of the theme. *Acacia* species are abundant invasive plants in Brunei Darussalam and are potentially a sustainable feedstock for bioenergy production through pyrolysis, gasification liquefaction and combustion processes. Pyrolysis and gasification processes seem to be more feasible from Brunei Darussalam prospective. However detailed research studies in terms of knowing biofuels potential and economic aspects would be needed prior to the commercial scale utilization of these species. *Acacia mangium* and *Acacia auriculiformis* are the most investigated species with respect to bioenergy production; while research gap still exists in terms of exploiting the bioenergy potential of *Acacia cincinnata* and *Acacia holosericea* species. Utilization of *Acacia* biomass to produce biofuels can also impart positive impacts on the economy of the country by offering multiple benefits to the society including new investment and employment opportunities. Also, these studies are expected to help the policy makers of the country to formulate future energy planning in Brunei Darussalam.

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