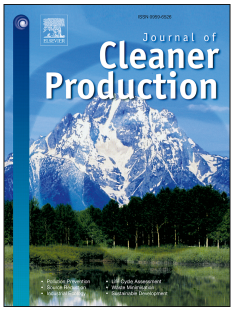

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Abdulhalim Abdulrazik, Mohamed Elsholkami, Ali Elkamel, Leonardo Simon

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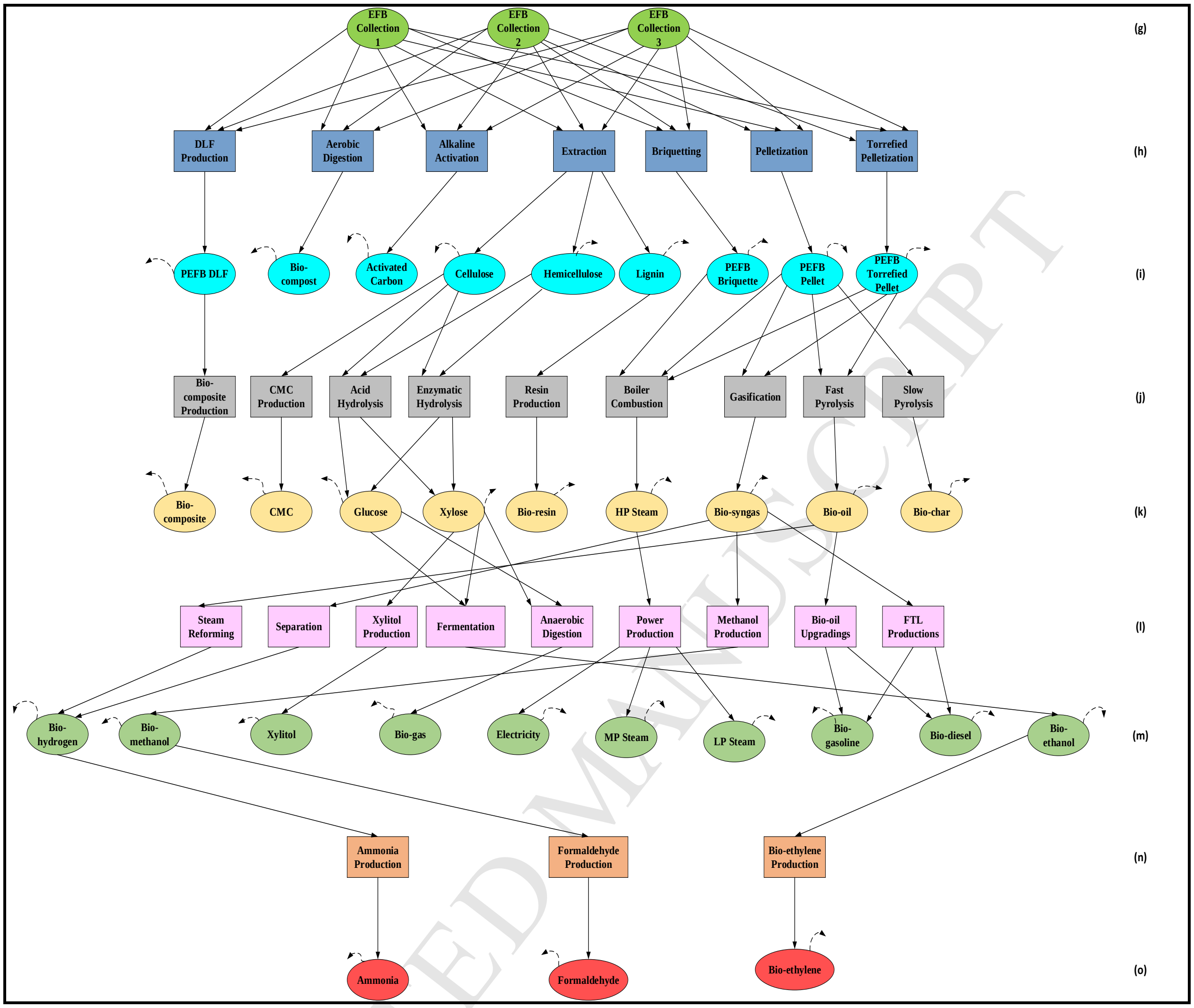
EFB Collection 1
EFB Collection 2
EFB Collection 3
(g)
DLF Production
Aerobic Digestion
Alkaline Activation
Extraction
Briquetting
Pelletization
Torrefied Pelletization
(h)
PEFB DLF
Bio-compost
Activated Carbon
Cellulose
Hemicellulose
Lignin
PEFB Briquette
PEFB Pellet
PEFB Torrefied Pellet
(i)
Bio-composite Production
CMC Production
Acid Hydrolysis
Enzymatic Hydrolysis
Resin Production
Boiler Combustion
Gasification
Fast Pyrolysis
Slow Pyrolysis
(j)
Bio-composite
CMC
Glucose
Xylose
Bio-resin
HP Steam
Bio-syngas
Bio-oil
Bio-char
(k)
Steam Reforming
Separation
Xylitol Production
Fermentation
Anaerobic Digestion
Power Production
Methanol Production
Bio-oil Upgradings
FTL Productions
(l)
Bio-hydrogen
Bio-methanol
Xylitol
Bio-gas
Electricity
MP Steam
LP Steam
Bio-gasoline
Bio-diesel
Bio-ethanol
(m)
Ammonia Production
Formaldehyde Production
Bio-ethylene Production
(n)
Ammonia
Formaldehyde
Bio-ethylene
(o)

Multi-Products Productions from Malaysian Oil Palm Empty Fruit Bunch (EFB): Analyzing Economic Potentials from the Optimal Biomass Supply Chain

Abdulhalim Abdulrazik[a,b], Mohamed Elsholkami[a], Ali Elkamel[a] and Leonardo Simon[a]

[a]Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, Kuantan, Malaysia
[b]Department of Chemical Engineering, University of Waterloo, Ontario, Canada.

Abstract

The economic potentials of Malaysian oil palm empty fruit bunch are realized by several motivating factors such as abundance, cheapness and are generally feasible to produce multi-products that range from energy, chemicals and materials. Amid continuing supports from the government in terms of policies, strategies and funding, manufacturing planning and decision to utilize this biomass resource requires a decision- support tool. In this regard, biomass supply chain modeling serves as the supportive tool and can provide economic indications for guided future investments. Sequential steps in modeling and optimization of the supply chain that utilized empty fruit bunch were shown. In a form of superstructure, the supply chain consisted processing stages for converting the biomass into intermediates and products, transportation networks that used truck, train or pipeline, and the options for product's direct sales or for further refinements. The developed optimization model has considered biomass cost, production costs, transportation costs, and emission treatment costs from transportation and production activities in order to determine the annual profit. By taking a case study of Peninsula Malaysia, optimal value showed a profit of $ 713,642,269/y could be achieved which has assumed a single ownership for all of the facilities in the supply chain. Besides, the tabulated values of yields and emission levels could provide comparative analysis between the processing routes. Sensitivity analysis was then performed to perturb the approximated parameters or data that have been used in this study.

Keywords

Empty fruit bunch (EFB); palm oil industry; biomass supply chain optimization; superstructure; bio-products.

Highlights

- Malaysia is to value the potentials of oil palm's biomass-based industries.
- EFB has obvious advantages and could be utilized for manufacturing products.
- Superstructure presents candidates for optimization.

- Optimization model could be an important decision-making tool for future investments that related to EFB's utilizations.

Introduction

Malaysia is a nation that is endowed with resources of both fossil as well as renewables. For fossil resources, proved reserves and the global share (%) for this country are 3.7 million barrel and 0.2% for oil, and 38.5 trillion cubic feet and 0.6% for natural gas (BP, 2014). These numbers have ranked Malaysia as the 28th and the 15th largest reserves in the world for oil and natural gas, respectively. For renewables, Malaysia has 22,500 MW energy potential of hydropower, 6,500 MW energy potential of solar, and 1,700 MW energy potential of biomass (Mekhilef et al., 2011). Of these renewables, only biomass can be used as a substituted feedstock to the fossil fuels for the manufacturing of multi-products that ranged from energy, chemicals and materials. The substitutions to a certain extent are apparent due to the fact that there were declines in productions of Malaysia's major oil fields and there are abundances of biomass resources available in this country (EIA, 2015; Zafar, 2014). For more general motivations, discouraged attributes of fossil resources such as environmentally harmful and are not renewable, have even elevated the prospects of biomass to become the main renewable feedstocks in the near future.

In Malaysia, biomass resources are mainly generated by the palm oil industry. The crop's planted areas have reached five million hectares in which almost 93 million tonnes of oil palm fruit was harvested (Ng and Ng, 2013). This harvested oil palm fruit will then produce crude palm oil and crude palm kernel oil, the major raw materials for the productions of various basic oleochemicals and biodiesel (Rupilius and Ahmad, 2007). Despite producing valuable products, the palm oil industry also generates agricultural wastes (biomass) such as palm oil fronds, palm oil trunks, empty fruit bunch (EFB), palm oil mill effluent (POME), palm mesocarp fiber (PMF), and palm kernel shell (PKS). In the case of EFB, for every 1 tonne of oil palm fresh fruit bunch processed, it was estimated that 230 kg of EFBs would be generated (Ng and Ng, 2013). As cheap biomass resource, EFB could be important feedstock to produce various products. This move is indeed in line with the current government strategies such as the Renewable Energy Policy, the National Biomass Strategy 2020 and the 1 Malaysia Biomass Alternative Strategy, which encourages biomass utilization for value-added product production and bioenergy generation (Ng and Ng, 2013).

Previous research and commercialization activities have indicated that EFB has been subjected to produce numerous products such as bio-syngas, bio-oil, bio-hydrogen, briquette and pellet fuels, bio-ethanol, bio-composite, bio-resin, bio-gas, bio-compost, activated carbon, xylose, polyhdroxybutyrate, and etcetera (Lahijani and Zainal, 2010; Salema and Ani, 2012; Md. Zin et al., 2012; Chong et al., 2013; Tan et al., 2010; Tan et al., 2012; Tay et al., 2009; Ibrahim et al., 2011; Purwandari et al., 2012; Rosli et al., 2011; Foo and Hameed, 2011; Auta et al., 2012, Zhang et al., 2013, and Rahman et al., 2007). Some of these are intermediates that will be further refined to produce final products. **Table 1** shows huge potentials of products and their applications which are feasibly derived from EFB.

Table 1 Applications for products from oil palm EFB

Bio-products	**Applications**
Dry Long Fiber (DLF)	Mattress and cushion production, ceramic and brick production, and pulp and paper production.
Bio-compost	Organic farming, soil conditioner and fertilizer in gardens, landscaping, horticulture, agriculture as well as it can be used as erosion control.
Activated carbon	Adsorbent for purifications in water treatment, air pollution, gas processing, odor and color removals.
Cellulose	Productions of derivatives from methyl cellulose such as carboxymethyl cellulose (CMC), hydroxyethyl cellulose (HEC), acetate, nitrocellulose, nanofibrillated cellulose (NFC), nanocrystalline cellulose (NCC), and cellulose filaments.
Hemicellulose	Productions of xylitol, ethanol and organic acids (from xylose) and lubricants, coatings, adhesives, resins, nylon-6, and nylon-6,6 (from furfural).
Lignin	Bio-resins (polymer substitution) in phenolic resins and polyurethane foams, carbon fiber composite, glue, dispersants, binder for fuel pellet, and combustion fuel.
Briquette	Thermal applications such as steam generation in boilers, power production, space heating, drying, and cooking.
Pellet	Thermal applications such as steam generation in boilers, power production, space heating, drying, and cooking.
Torrefied Pellet	Thermal applications such as steam generation in boilers, power production, space heating, drying, and cooking.
Bio-composite	Building products productions such as windows, doors, patio furniture, fencing, decking, roofing, and railing. Automotive applications such as dashboard, floor mats, seat fabric, and etc.
Carboxymethyl Cellulose (CMC)	Thickener in the ice cream, canned food, fast cooking food, jam, syrup, sherbet, dessert, drinks, etc. Emulsifying, suspending, fixing, smoothing, and separating agent, dirt absorbent in synthetic detergent, as well as used in the oil and gas drilling process.
Glucose	Simple sugar for fermentation, anaerobic digestion and isomerization.
Xylose	Simple sugar for xylitol production as well as for fermentation and anaerobic digestion processes.
Bio-resin	Compostable and biodegradable plastics such thermoplastic starch (TPS), polyhydroxyalkanoates (PHA) and polyactide (PLA).
High Pressure Steam	Mainly for power generation.
Bio-syngas	Productions of ammonia, hydrogen, methanol, electricity and range of transportation fuels through Fischer-Tropsch process.
Bio-oil	Productions of bio-hydrogen, bio-ethylene, bio-propylene, transportation fuels through refining process, glycolaldehyde, levoglucosan, and etc.
Bio-char	Soil enhancer, carbon sequester, fuels, and metal extraction where carbon is used to remove oxide from metal.
Bio-hydrogen	Ammonia production, refinery applications in hydrotreating and hydrocracking processes, fuel cells, and etc.
Xylitol	Various pharmaceutical and oral hygiene products.
Bio-ethanol/ethanol	Blending with gasoline, and uses commonly in the sectors such as beverages, cosmetics, medical and pharmaceuticals.
Bio-gas	Power generation, heating, combined heat and power, drying, cooling, cooking, compressed liquid fuel for transportation and etc.
Bio-methanol	Formaldehyde production, wastewater denitrification, solvent for biodiesel trans-esterification, and other materials and chemicals productions such as paints, solvents, adhesives, refrigerants, synthetic fibers, and etc.
Electricity	Energy for electrical devices such as pump, compressor, fan, air-conditioner, heater, lighting system, computers, and many more.
Medium Pressure Steam	Power production, heating, cleaning, as reaction medium, humidification, and etc.
Low Pressure Steam	Heating, cleaning, humidification, moisturizing agent, and etc.
Bio-ethylene	Productions of polyethylene (PE), ethanol, ethylene glycol, ethylene oxide, ethylbenzene, ethylene dichloride, fruit ripening agent, and etc.
Bio-diesel	Transportation fuel, steam and power productions for diesel engines.

Bio-gasoline	Main transportation fuel in for road vehicles, motorboats, as well as for chainsaws, lawn movers, and etc.
Ammonia	Mainly used for the productions of fertilizers, plastics such as polyurethane, refrigerant, and etc.
Formaldehyde	Productions of formaldehyde-based resins or adhesives such as urea formaldehyde (UF) resins, phenol formaldehyde (PF) resins, and melamine formaldehyde (MF) resins, polyoxymethylenes (POM), healthcare applications such as disinfectants and vaccines, and etc.

One of the main factors to realize these potentials is by having an optimal supply chain. The supply chain will ensure conversion routes that comprise series of pre-processing, main processing, and further processing steps to produce those above-mentioned products are considered simultaneously and comprehensively. Previous studies that focused on EFB's supply chains including the supply chain analysis and life cycle assessment for the productions of green chemicals (Reeb et al., 2014) the supply chain of EFB for renewable fuel production (Eco-Ideal Consulting Sdn. Bhd. and Mensilin Holdings Sdn. Bhd., 2005), and the synthesis of energy supply chain from EFB (Lam et al., 2010). Optimal EFB's supply chain for multi-products productions of energy, chemicals and materials is yet to be studied based on author's knowledge. This study will focus on modeling an optimization of EFB's supply chain by taking Peninsular Malaysia as a case study.

Model Development for Optimal EFB's Supply Chain

An optimization model of the EFB's supply chain has been developed according to the sequential steps shown by **Fig. 1**. As lignocellulosic biomass sources, EFB will take different processing routes, each will end up to produce the pre-determined bio-products as highlighted in **Table 1**. These processing routes comprise stages of pre-processing, main processing and further processing steps. The routes can be divided into three main categories; thermochemical, chemical and biochemical processes.

Thermochemical processing routes involve a manufacturing platform that apply combustion processes to convert the chemical energy stored in biomass into heat (Mc Kendry, 2002) and use heat to break down biomass feeds into a condensable oil-rich vapor in pyrolysis and syngas in gasification (Abraham et at., 2003). Biomass chemical processing routes will use a strong acid to break down lignocellulosic biomass into its single morphological structure whether cellulose, hemicellulose and lignin. Cellulose, hemicellulose and lignin will then undergo further processes to produce ethanol and other products (PPD Technologies Inc., 2011). Biochemical processing routes will use enzymes of bacteria or other microorganisms to produce products from biomass sources. Schemes in biochemical productions will determine the type of products, for instance, alcohol fermentation will produce ethanol, anaerobic digestion will produce biogas, and aerobic fermentation will produce compost (Garcia et al., 2011)

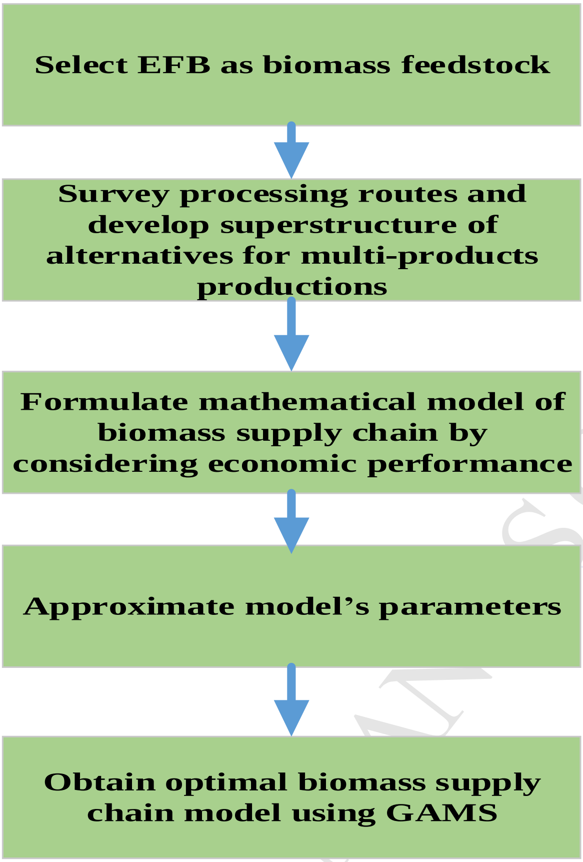

Fig. 1. Sequential steps for optimal EFB's supply chain

In developing the supply chain's superstructure, important steps and approaches, as detailed out by Murillo-Alvarado et al., (2013) were considered. First, suitable biomass feedstocks are recognized and characterized and followed by identification of desired products. In this step, several desired products can be generated by consuming the same feedstocks through a variety of conversion routes. Meanwhile, more than one reactants can be used to produce the desired product. In order to identify the interconnections (processing pathways) between feedstocks and products, two approaches are used which the forward synthesis of biomass and the backward synthesis of desired products. The next step is to match two intermediate compounds obtained from forward and backward syntheses. The final step of superstructure generation involved interception of the two intermediate compounds by identifying the set of processing technologies required for connecting these compounds. The developed superstructure is shown in **Fig 2.**

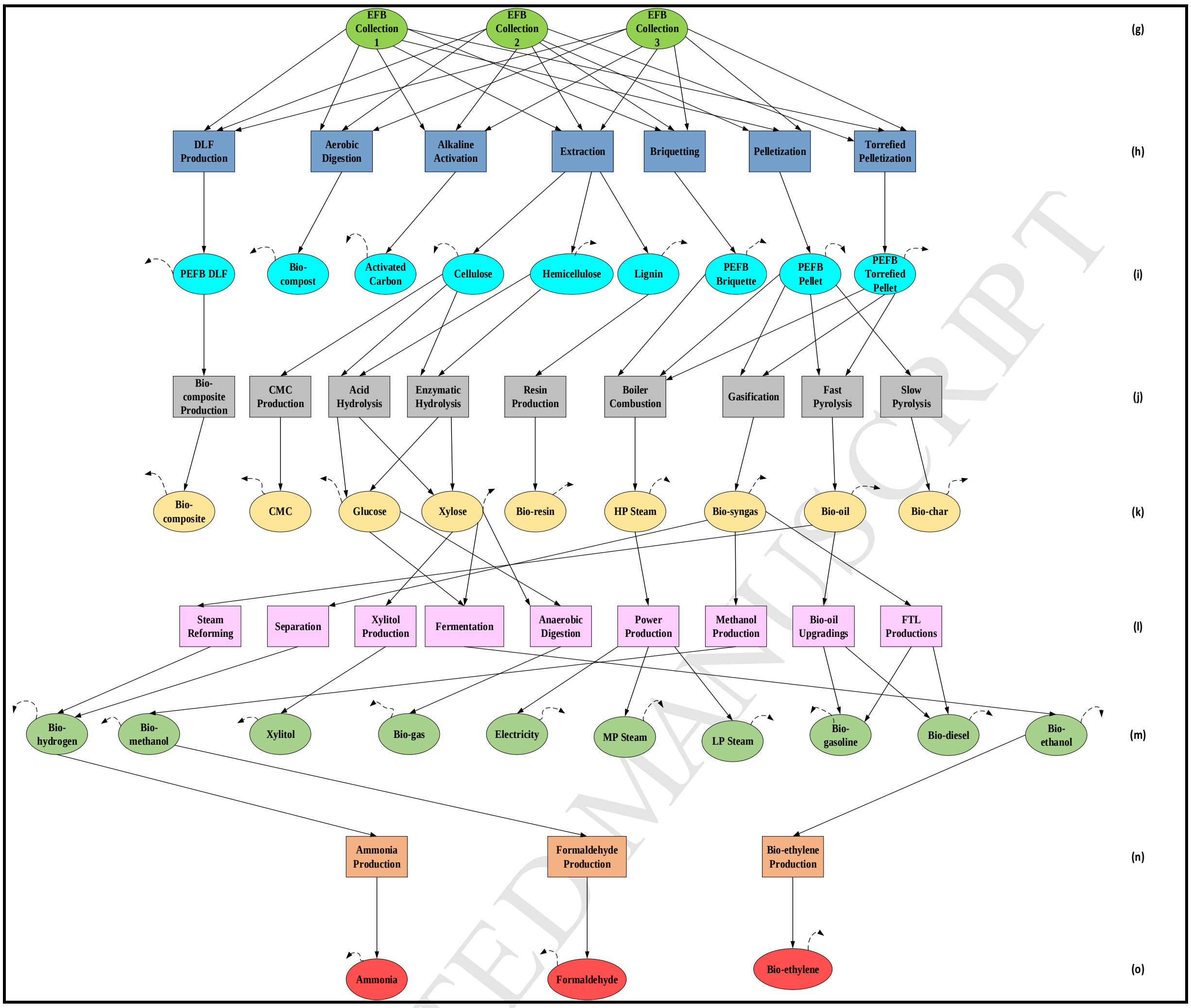

Fig. 2. A superstructure of supply chain for multi-products productions from EFB

In this superstructure, square shapes represent processing facilities while oval shapes depict storages. Each storage was assumed to be located within its facility. The solid lines show processing sequences while the dash lines provide options to sell the products directly. Portions of the products whether to be sold directly or to be transferred to the next processing step would be determined from optimization results. EFB feedstocks were assumed to be blended homogenously. Competitive utilizations could be seen for EFB, cellulose, hemicellulose, pellet, torrefied pellet, glucose, xylose, bio-syngas, and bio-oil. Small letters of *g* to *o* are subscripts and are explained in **Table 2**. The subscript *p* is not shown in **Fig. 2** but will be used in the mathematical model. This subscript *p* represents sum up of products.

Table 2 List of subscripts

Set/Subscript	Descriptions	Contents
g	Biomass source storage locations	EFB collection 1, EFB collection 2, and EFB collection 3.
h	Pre-processing facilities	DLF production, aerobic digestion, alkaline activation,

		extraction, briquetting, palletization, and torrefied palletization.
i	Pre-processed feedstocks storages	PEFB DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PEFB briquette, PEFB pellet, and PEFB torrefied pellet.
j	Main processing facilities	Bio-composite production, CMC production, acid hydrolysis, enzymatic hydrolysis, resin production, boiler combustion, gasification, fast pyrolysis, and slow pyrolysis.
k	Intermediate products 1 storages	Bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, and bio-char.
l	Further processing 1 facilities	Steam reforming, separation, xylitol production, fermentation, anaerobic digestion, power production, methanol production, bio-oil upgrading, and FTL productions.
m	Intermediate products 2 storages	Bio-hydrogen, bio-methanol, xylitol, bio-gas, electricity, MP steam, LP steam, bio-gasoline, bio-diesel, and bio-ethanol.
n	Further processing 2 facilities	Ammonia production, formaldehyde production, bio-ethylene production.
o	Final products storages	Ammonia, formaldehyde, and bio-ethylene
p	Sum of products	PEFB DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PEFB briquette, PEFB pellet, PEFB torrefied pellet, Bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, bio-char, Bio-hydrogen, bio-methanol, xylitol, bio-gas, electricity, MP steam, LP steam, bio-gasoline, bio-diesel, bio-ethanol, ammonia, formaldehyde, and bio-ethylene.

Next, mathematical model of the optimal supply chain will be developed by considering economic performance. This refers to the profitability from the selling of products minus all the associated costs. Hence, the objective function of the optimization model is to maximize the overall profit, i.e.

- Maximize Profit = Revenues – Costs,

where;

- Revenues = (Sales of products), and
- Costs = (Biomass cost + Transportation cost + Production cost + Emission cost from transportation + Emission cost from production).

Therefore,

- Profit = (Sales of products) - (Biomass cost) - (Transportation cost) - (Production cost) - (Emission cost from transportation) - (Emission cost from production)

Each of the term above requires data or parameters which among them are transportation cost factors, production cost factors, carbon dioxide (CO_2) emission factors from transportation, CO_2 emission factors from production and conversion factors. The transportation cost factors were calculated using methods developed by Oo et al., (2012) and Blok et al., (1995). The transportation cost factors will be in $ per tonne, and later will be multiplied with mass flowrate in order to determine the transportation cost. In this study, truck would be pre-selected for distances up to 100 km, while train was chosen for distances beyond 100 km for solid transportation. For liquid and gaseous products, pipeline transportation would be used. Production cost factor was the cost in $ to produce one-unit capacity of product. In this regard, Mani et al. (2006) have reported that this cost factor comprised capital and operating costs for the equipment. CO_2 emission cost factors from transportation were determined from the model that was developed by McKinnon (2008). Depending on the pre-selected mode of transportation, these emission factors would be then multiplied with mass flowrate in the supply chain. The cost for emission treatment was fixed at $40/t of CO_2 equivalent, but in practice the cost much depends on the local's regulation. Conversion factors were defined by mass ratio of inlet to the outlet for each processing facility. For power production, conversion factors have approximated the turbine's efficiencies on how much electricity would be produced per mass of inlet steam which depends on pressure and temperature of inlet and outlet steam.

Table 3 till **Table 21** tabulate all the required parameters for the optimization model. It is worth to mention that, one of the efforts in this study was to collect and record all of these parameters. Since the majority of the biomass utilizations involving EFB are currently still in the conceptual stage, approximations were used. The parameters were assumed to be independent of scale, input types and conditions. This assumption does not restrict the validity of the optimization model that will be presented in a general form.

Table 3 Selling prices of products

Product	**Selling price ($/t or $/MWh)**	**Reference**
Dry Long Fiber (DLF)	210	Ng and Ng (2013)
Bio-compost	100	Ng and Ng (2013)
Activated carbon	1,756	Shanghai Jinhu Inc. (2014)
Cellulose	2,200	Higson (2011)
Hemicellulose	2,000	Assumed value based on cellulose and lignin prices
Lignin	1,500	Lake (2010)
Briquette	120	Ng and Ng (2013)
Pellet	140	Ng and Ng (2013)
Torrefied Pellet	160	Assumed value based on PEFB pellet and PEFB briquette
Bio-composite	625	ERIA (2014)
Carboxymethyl Cellulose (CMC)	3,500	www.trade.ec.europa.eu
Glucose	1,890	www.cascadebiochem.com
Xylose	1,990	www.cascadebiochem.com
Bio-resin	9,072	www.bioresins.eu
High Pressure Steam	26	Ng and Ng (2013)
Bio-syngas	600	IChemE (2014)
Bio-oil	800	Careddi Technology Ltd. (2014)
Bio-char	380	Ng and Ng (2013)
Bio-hydrogen	818	Murillo-Alvarado et al., (2013)
Xylitol	4,200	Shanghai Yanda Biotechnology Ltd. (2014)
Bio-ethanol	523	Murillo-Alvarado et al. (2013)

Bio-gas	398	Oo et al. (2012)
Bio-methanol	870	Murillo-Alvarado et al. (2013)
Electricity	140	Ng and Ng (2013)
Medium Pressure Steam	17	Ng and Ng (2013)
Low Pressure Steam	12	Ng and Ng (2013)
Bio-ethylene	1,544	ICIS (2014)
Bio-diesel	790	Murillo-Alvarado et al. (2013)
Bio-gasoline	1,315	EIA (2014)
Ammonia	745	ICIS (2014)
Formaldehyde	463	ICIS (2014)

Table 4 Annual demands for products in t/y

Product	Five percent of world demands (t/y) or (MWh/y)	Products hypothetical demands (t/y) or (MWh/y)	Reference
Dry Long Fiber	4,270,000	85.4	Lenzing Group AG (2014)
Bio-compost	20,000	0.4	Biocomp Nepal (2014)
Activated carbon	95,000	1.9	www.filtsep.com
Cellulose	290,500	5.81	Lenzing Group AG (2014)
Hemicellulose	750,000	15	Christopher (2012)
Lignin	30,000	0.6	International Lignin Institute (2014)
Briquette	1,500,000	30	Assumed value based on pellet and torrefied pellet demands
Pellet	1,850,000	37	O'Carroll (2012)
Torrefied Pellet	350,000	70	www.biomassmagazine.com
Bio-composite	46,000	0.92	Carus (2012)
Carboxymethyl Cellulose (CMC)	20,000	0.4	www.prweb.com
Glucose	290,500	5.81	Assumed value based on cellulose demand
Xylose	750,000	15	Assumed value based on hemicellulose demand
Bio-resin	10,000	0.2	www.thomasnet.com
High pressure steam	100,000	2	www.enerdata.com
Bio-syngas	23,100,000,000	462,000	Boerrigter and Drift (2005)
Bio-oil	250,000	5	Bradley (2006)
Bio-char	150,000,000	3,000	www.nature.com
Bio-hydrogen	18,775,000	375.5	Santibanez-Aquilar et al. (2011)
Xylitol	100	0.002	www.companiesandmarket.com
Bio-ethanol	180,000	3.6	Santibanez-Aquilar et al. (2011)
Bio-gas	450,000	9	Svensson (2010)
Bio-methanol	15,000	0.3	Murillo-Alvarado et al. (2013)
Electricity	1,000,000	20	www.enerdata.com
Medium pressure steam	45,000	0.9	Assumed value for 50% of high pressure steam
Low pressure steam	22,500	0.45	Assumed value for 50% of medium pressure steam
Bio-ethylene	7,000,000	140	Technip (2014)
Bio-diesel	40,000	0.8	Santibanez-Aquilar et al. (2011)
Bio-gasoline	60,000	1.2	EIA (2014)
Ammonia	8,500,000	170	www.hazmatmag.com
Formaldehyde	2,100,000	42	Lubon Industry Ltd. (2013)

Malaysia is geographically separated by two regions by the South China Sea. These two regions are called as Peninsula Malaysia and East of Malaysia. In the Peninsula as shown in **Fig. 3**, the main areas of palm oil plantations, and hence the main areas of EFB producers are situated in states of Johore, Pahang, and Perak (MPOB, 2013). Only these three states were considered for EFB collection points as shown by **Table 5**. Locations of the processing facilities (pre-processing, main processing, further processing 1, and further processing 2) were considered only for the Peninsula Malaysia. Operational status of these processing facilities are either fully operational, nearly operation or at a demonstration level. Distances for connecting two processing facilities were determined using Google Maps. Biomass cost of the EFB was $6/t.

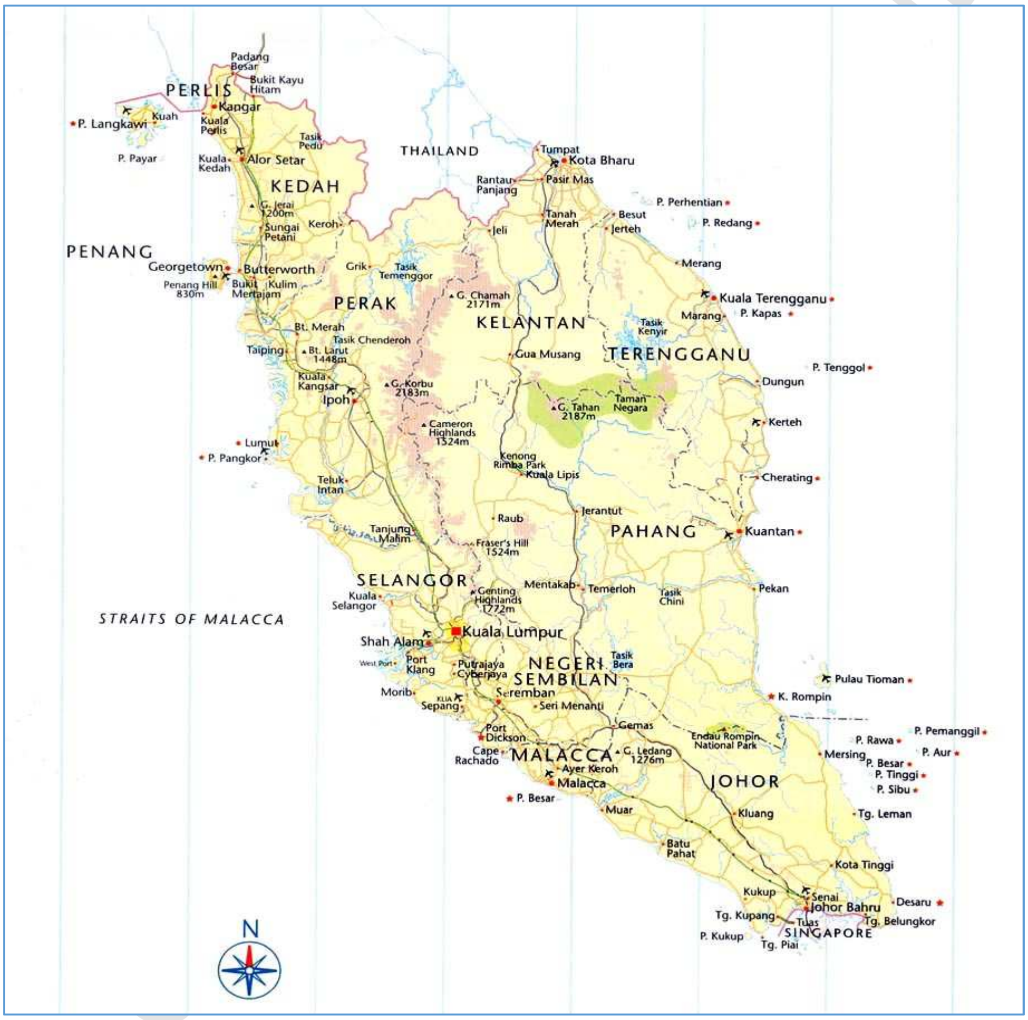

Fig. 3. Map of Peninsula Malaysia (www.etawau.com)

Table 5 Biomass feedstock availability for Johore, Pahang and Perak

Biomass feedstock	Fresh fruit bunch yield (t/ha)	Plantation area (ha)	Fresh fruit bunch production (t)	Palm empty fruit bunch productions (t)*	Reference
EFB Collection 1 (Johore)	19.49	730,694	14,241,226.06	3,275,481.99	MPOB
EFB Collection 2 (Pahang)	20.21	710,195	14,353,040.95	3,301,199.42	

EFB Collection 3 (Perak)	20.31	384,594	7,811,104.14	1,796,553.95	(2014)
Total	60.01	1,825,483	36,405,371.15	8,373,235.36	

* 23% of fresh fruit bunch will be assumedly to produce EFB as reported by Ng and Ng (2013)

Table 6 Approximated transportation cost and CO_2 emission factor for EFB feedstock from *g* to *h*

EFB storage, *g*	**Pre-processing facility, *h***	**Distance (km)**	**Transportation mode**	**Cost ($/t)**	**CO_2 emission factor (t CO_2 equivalent /t of biomass transported)**
EFB Collection 1	Aerobic Digestion	0	-	0	0
EFB Collection 1	DLF Production	271	Train	29.54	0.0060
EFB Collection 1	Extraction Plant	322	Train	31.24	0.0071
EFB Collection 1	Briquetting Plant	271	Train	29.54	0.0060
EFB Collection 1	Pelletization Mill	287	Train	29.98	0.0063
EFB Collection 1	Torrefied Pelletization	208	Train	27.45	0.0046
EFB Collection 1	Alkaline Activation (Activated Carbon) Plant	208	Train	27.45	0.0046
EFB Collection 2	Aerobic Digestion	0	-	0	0
EFB Collection 2	DLF Production	165	Train	26.01	0.0036
EFB Collection 2	Extraction Plant	230	Train	28.18	0.0051
EFB Collection 2	Briquetting Plant	165	Train	26.01	0.0036
EFB Collection 2	Pelletization Mill	195	Train	27.01	0.0043
EFB Collection 2	Torrefied Pelletization Mill	224	Train	27.98	0.0049
EFB Collection 2	Alkaline Activation (Activated Carbon) Plant	224	Train	27.98	0.0049
EFB Collection 3	Aerobic Digestion	0	-	0	0
EFB Collection 3	DLF Production	274	Train	29.64	0.0060
EFB Collection 3	Extraction Plant	486	Train	36.70	0.0107
EFB Collection 3	Briquetting Plant	274	Train	29.64	0.0060
EFB Collection 3	Pelletization Mill	289	Train	30.14	0.0064
EFB Collection 3	Torrefied Pelletization Mill	346	Train	32.04	0.0076
EFB Collection 3	Alkaline Activation (Activated Carbon) Plant	346	Train	32.04	0.0076

Table 7 Approximated transportation cost and CO_2 emission factor for pre-processed feedstock from *h* to *j*

Pre-processing facility, *h*	**Main processing facility, *j***	**Distance (km)**	**Transportation mode**	**Cost ($/t)**	**CO_2 emission factor (t CO_2 equivalent /t of product transported)**
Extraction Plant	CMC Production	0	-	0	0
Extraction Plant	Acid Hydrolysis	546	Train	38.70	0.0120
Extraction Plant	Enzymatic Hydrolysis	315	Train	31.00	0.0069
Extraction Plant	Resin Production	386	Train	33.37	0.0085
DLF Production	Bio-composite Production	33	Truck	12.26	0.0020
Briquetting Plant	Boiler Combustion	83	Truck	20.46	0.0051
Pelletization Mill	Boiler Combustion	88	Truck	21.28	0.0055
Pelletization Mill	Gasification	17	Truck	9.63	0.0011
Pelletization Mill	Fast Pyrolysis	0	-	0	0
Pelletization Mill	Slow Pyrolysis	345	Train	32.01	0.0076
Torrefied Pelletization Mill	Boiler Combustion	23	Truck	10.61	0.0014
Torrefied Pelletization Mill	Gasification	78	Truck	19.64	0.0048
Torrefied Pelletization Mill	Fast Pyrolysis	86	Truck	20.95	0.0053

Table 8 Approximated transportation cost and CO_2 emission factor for intermediate product 1, *k* from *j* to *l*

Main processing facility, *j*	**Further processing 1 facility, *l***	**Distance (km)**	**Transportation mode**	**Cost ($/t)**	**CO_2 emission factor (t CO_2 equivalent /t of product transported)**
Acid Hydrolysis	Fermentation Plant	327	Train	31.41	0.0072
Acid Hydrolysis	Anaerobic Digestion Plant	338	Train	31.78	0.0074
Acid Hydrolysis	Xylitol Production	0	-	0	0
Enzymatic Hydrolysis	Fermentation Plant	65	Truck	17.51	0.0040
Enzymatic Hydrolysis	Anaerobic Digestion Plant	37	Truck	12.91	0.0023
Enzymatic Hydrolysis	Xylitol Production	379	Train	33.14	0.0083
Boiler Combustion	Power Production	0	-	0	0
Gasification	Separation Plant	0	-	0	0
Gasification	Methanol Production	404	Pipeline	20.20	0
Gasification	FTL production	19	Pipeline	0.95	0
Fast Pyrolysis	Bio-oil Upgrading	94	Pipeline	4.70	0
Fast Pyrolysis	Steam Reforming Plant	0	-	0	0

Table 9 Approximated transportation cost and CO_2 emission factor for intermediate product 2, m from *l* to *n*

Further processing 1 facility, *l*	**Further processing 2 facility, *n***	**Distance (km)**	**Transportation mode**	**Cost ($/t)**	**CO_2 emission factor (t CO_2 equivalent /t of product transported)**
Steam Reforming Plant	Ammonia Production	361	Pipeline	18.05	0
Separation Plant	Ammonia Production	367	Pipeline	18.35	0
Methanol Production	Formaldehyde Production	686	Pipeline	34.30	0

Fermentation Plant	Bio-ethylene	316	Pipeline	15.80	0

Table 10 Approximated production cost factor at *h* in $ per tonne

Biomass type, *g*	**Pre-processing, *h***	**Pre-processed product, *i***	**$/t**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	85	www.hempfarm.com
Blended EFBs	Aerobic Digestion	Bio-compost	10	Fabian et al. (1993)
Blended EFBs	Alkaline Activation	Activated Carbon	144	Lima et al. (2008)
Blended EFBs	Extraction	Cellulose	125	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Hemicellulose	130	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Lignin	135	Murillo-Alvarado et al. (2013)
Blended EFBs	Briquetting	Briquette	50	Kanna (2010)
Blended EFBs	Pelletization	Pellet	60	PPD Technologies Inc. (2011)
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	70	PPD Technologies Inc. (2011)

Table 11 Approximated conversion factor at *h*

Biomass type, *g*	**Pre-Processing, *h***	**Pre-processed product, *i***	**Conversion factor**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	0.37	Ng and Ng (2013)
Blended EFBs	Aerobic Digestion	Bio-compost	0.95	Hubbe et al. (2010)
Blended EFBs	Alkaline Activation	Activated Carbon	0.50	Kaghazchi et al. (2006)
Blended EFBs	Extraction	Cellulose	0.63	Assumed value based on hemicellulose and lignin conversion factor
Blended EFBs	Extraction	Hemicellulose	0.18	www.ipst.gatech.edu
Blended EFBs	Extraction	Lignin	0.19	www.purelignin.com
Blended EFBs	Briquetting	Briquette	0.38	Ng and Ng (2013)
Blended EFBs	Pelletization	Pellet	0.38	Ng and Ng (2013)
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.38	Ng and Ng (2013)

Table 12 Approximated CO_2 emission factor at *h*

Biomass type, *g*	**Pre-Processing, *h***	**Pre-processed product, *i***	**CO_2 emission factor (t CO_2 equivalent/t of product produced)**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	0.0041	www.oecotextiles.wordpress.com
Blended EFBs	Aerobic Digestion	Bio-compost	0.0200	www.epa.gov
Blended EFBs	Alkaline Activation	Activated Carbon	0.0176	www.omnipure.com
Blended EFBs	Extraction	Cellulose	0.0590	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Hemicellulose	0.0650	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Lignin	0.0620	Assumed value based on values for cellulose and hemicellulose
Blended EFBs	Briquetting	Briquette	0.0500	Assumed value
Blended EFBs	Pelletization	Pellet	0.0500	Assumed value
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.0805	Kaliyan et al. (2014)

Table 13 Approximated production cost factor at *j* in \$/t

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**\$/t**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	107.0	ERIA (2014)
Cellulose	CMC Production	CMC	2,500.0	www.trade.ec.europa.eu
Cellulose	Acid Hydrolysis	Glucose	73.4	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis	Glucose	85.7	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis	Xylose	168.7	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis	Xylose	83.1	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	1,900.0	Chiarakorn et al. (2013)
Briquette	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Pellet	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Pellet	Fast pyrolysis	Bio-oil	1,003	Thorp (2010)
Pellet	Slow pyrolysis	Bio-char	111.5	www.irena.org
Torrefied Pellet	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Torrefied Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Torrefied Pellet	Fast pyrolysis	Bio-oil	1003	Thorp (2010)

Table 14 Approximated conversion factor at *j*

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**Conversion factor**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	0.75	Karbstein et al. (2013)
Cellulose	CMC Production	CMC	0.86	Saputra et al. (2014)
Cellulose	Acid Hydrolysis	Glucose	0.37	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis	Glucose	0.47	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis	Xylose	0.91	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis	Xylose	0.88	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	0.95	Yin et al. (2012)
Briquette	Boiler Combustion	HP Steam	0.20	Searcy and Flynn (2009)
Pellet	Boiler Combustion	HP Steam	0.25	Searcy and Flynn (2009)
Pellet	Gasification	Bio-syngas	0.70	Boerrigter and Drift (2005)
Pellet	Fast pyrolysis	Bio-oil	0.60	Zhang et al. (2013)
Pellet	Slow pyrolysis	Bio-char	0.50	www.biocharfarms.org
Torrefied Pellet	Boiler Combustion	HP Steam	0.30	Searcy and Flynn (2009)
Torrefied Pellet	Gasification	Bio-syngas	0.80	Boerrigter and Drift (2005)
Torrefied Pellet	Fast pyrolysis	Bio-oil	0.60	Zhang et al. (2013)

Table 15 Approximated CO_2 emission factor at *j*

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**CO_2 emission factor (t CO_2 equivalent/t of product produced)**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	7.481	www.winrigo.com
Cellulose	CMC Production	CMC	0.097	Assumed value
Cellulose	Acid Hydrolysis	Glucose	0.097	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis	Glucose	0.085	Murillo-Alvarado et al. (2013)

Hemicellulose	Acid Hydrolysis	Xylose	0.075	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis	Xylose	0.082	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	2.500	www.netcomposites.com
Briquette	Boiler Combustion	HP Steam	0.750	www.sarawakenergy.com.my
Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Pellet	Gasification	Bio-syngas	0.680	Basu (2013)
Pellet	Fast pyrolysis	Bio-oil	0.580	Zhang et al. (2013)
Pellet	Slow pyrolysis	Bio-char	0.580	Zhang et al. (2013)
Torrefied Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Torrefied Pellet	Gasification	Bio-syngas	0.680	Basu (2013)
Torrefied Pellet	Fast pyrolysis	Bio-oil	0.580	Zhang et al. (2013)

Table 16 Approximated production cost factor at *l* in $/t or per MWh

Intermediate product 1, *k*	Further processing 1, *l*	Intermediate product 2, *m*	$/t or MWh	Reference
Bio-oil	Steam Reforming	Bio-hydrogen	455.0	Sarkar and Kumar et al. (2010)
Bio-oil	Bio-oil Upgrading	Bio-gasoline	1,089.0	Wright and Brown (2011)
Bio-oil	Bio-oil Upgrading	Bio-diesel	918.0	Wright and Brown (2011)
Glucose	Fermentation	Bio-ethanol	98.2	Murillo-Alvarado et al. (2013)
Xylose	Fermentation	Bio-ethanol	98.2	Murillo-Alvarado et al. (2013)
Glucose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Xylitol Production	Xylitol	2,100.0	Assumed value for 50% less of the xylitol price
HP Steam	Power Production	Electricity	58.9/MWh	Searcy and Flynn (2009)
HP Steam	Power Production	MP Steam	12.0	Assumed valued based on the steam price
HP Steam	Power Production	LP Steam	7.0	Assumed valued based on the steam price
Bio-syngas	Methanol Production	Bio-methanol	83.6	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	112	Schubert (2013)
Bio-syngas	FTL Productions	Bio-diesel	167.3	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-gasoline	519.8	Wright and Brown (2011)

Table 17 Approximated conversion factor at *l*

Intermediate Product 1, *k*	Further Processing 1, *l*	Intermediate Product 2, *m*	Conversion Factor	Reference
Bio-oil	Steam Reforming	Bio-hydrogen	0.84	Dillich (2013)
Bio-oil	Bio-oil Upgrading	Bio-gasoline	0.40	Kim et al. (2011)
Bio-oil	Bio-oil Upgrading	Bio-diesel	0.20	Kim et al. (2011)
Glucose	Fermentation	Bio-ethanol	0.33	Murillo-Alvarado et al. (2013)
Xylose	Fermentation	Bio-ethanol	0.33	Murillo-Alvarado et al. (2013)
Glucose	Anaerobic Digestion	Bio-gas	0.70	Hubbe et al. (2010)
Xylose	Anaerobic Digestion	Bio-gas	0.70	Hubbe et al. (2010)
Xylose	Xylitol Production	Xylitol	0.70	Prakasham et al. (2009)
HP Steam	Power Production	Electricity	0.30 MWh/tonne of steam	www.turbinesinfo.com
HP Steam	Power Production	MP Steam	0.35	Ng and Ng (2013)
HP Steam	Power Production	LP Steam	0.35	Ng and Ng (2013)

Bio-syngas	Methanol Production	Bio-methanol	0.41	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	0.46	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-diesel	0.71	Boerrigter and Drift (2005)
Bio-syngas	FTL Productions	Bio-gasoline	0.29	Assumed value from bio-diesel conversion factor

Table 18 Approximated CO$_2$ emission factor at *l*

Intermediate Product 1, *k*	**Further Processing 1, *l***	**Intermediate Product 2, *m***	**CO$_2$ emission factor (t CO$_2$ equivalent/t of product produced)**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	16.930	Zhang et al. (2013)
Bio-oil	Bio-oil Upgrading	Bio-gasoline	13.000	Zhang et al. (2013)
Bio-oil	Bio-oil Upgrading	Bio-diesel	13.000	Zhang et al. (2013)
Glucose	Fermentation	Bio-ethanol	0.098	Murillo-Alvarado et al. (2013)
Xylose	Fermentation	Bio-ethanol	0.098	Murillo-Alvarado et al. (2013)
Glucose	Anaerobic Digestion	Bio-gas	0.250	Whiting & Azapagic, (2014)
Xylose	Anaerobic Digestion	Bio-gas	0.250	Whiting & Azapagic, (2014)
Xylose	Xylitol Production	Xylitol	0.082	Assumed value based on value of xylose
HP Steam	Power Production	Electricity	0.050	Assumed value
HP Steam	Power Production	MP Steam	0.050	Assumed value
HP Steam	Power Production	LP Steam	0.050	Assumed value
Bio-syngas	Methanol Production	Bio-methanol	0.083	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	0.090	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-diesel	0.067	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-gasoline	0.639	Murillo-Alvarado et al. (2013)

Table 19 Approximated production cost factor at *n* in \$/t

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**\$/t**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	377	www.hydrogen.energy.gov
Bio-methanol	Formaldehyde Production	Formaldehyde	232	www.icis.com
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1,200	www.irena.org

Table 20 Approximated conversion factor at *n*

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**Conversion factor**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	0.80	www.hydrogen.energy.gov
Bio-methanol	Formaldehyde Production	Formaldehyde	0.97	Chu et al. (1997)
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	0.99	www.irena.org

Table 21 Approximated CO_2 emission factor at *n*

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**CO_2 emission factor (t CO_2 equivalent/t of product produced)**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	1.694	Jubb et al. (2006)
Bio-methanol	Formaldehyde Production	Formaldehyde	0.083	Assumed value
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1.400	www.irena.org

Mathematical Model

Since the aim of this study was to optimize the supply chain of multi-products productions from EFB, profitability was selected as an economic potential indicator. Mathematical model was written as below;

Maximize Profit =

Max (Sales of Products - Biomass cost - Transportation cost - Production cost - Emission treatment cost from transportation - Emission treatment cost from production) (1)

$$\text{Sales of products} = \sum_{p=1}^{P} Q_p * Product's\ selling\ price \quad (2)$$

$$Biomass\ cost = \sum_{g}^{G} F_g * EFB\ Cost \quad (3)$$

$$Transportation\ cost = \left(\sum_{g}^{G}\sum_{h}^{H} FTF_{g,h} * TCGH_{g,h}\right) + \left(\sum_{h}^{H}\sum_{i}^{I}\sum_{j}^{J} FTH_{h,i,j} * TCHIJ_{h,i,j}\right) + \left(\sum_{j}^{J}\sum_{k}^{K}\sum_{l}^{L} FTJ_{j,k,l} * TCJKL_{j,k,l}\right) + \left(\sum_{l}^{L}\sum_{m}^{M}\sum_{n}^{N} FTL_{l,m,n} * TCLMN_{l,m,n}\right) \quad (4)$$

$$Production\ cost = \left(\sum_{h}^{H}\sum_{i}^{I} FPH_{h,i} * PROCH_{h,i}\right) + \left(\sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{K} FPJ_{i,j,k} * PROCJ_{i,j,k}\right) + \left(\sum_{k}^{K}\sum_{l}^{L}\sum_{m}^{M} FPL_{k,l,m} * PROCL_{k,l,m}\right) + \left(\sum_{m}^{M}\sum_{n}^{N}\sum_{o}^{O} FPN_{m,n,o} * PROCN_{m,n,o}\right) \quad (5)$$

$$Emission\ treatment\ cost\ from\ transportation = \left[\left(\sum_{g}^{G}\sum_{h}^{H} FTFE_{g,h}\right) + \left(\sum_{h}^{H}\sum_{i}^{I}\sum_{j}^{J} FTHE_{h,i,j}\right) + \left(\sum_{j}^{J}\sum_{k}^{K}\sum_{l}^{L} FTJE_{j,k,l}\right) + \left(\sum_{l}^{L}\sum_{m}^{M}\sum_{n}^{N} FTLE_{l,m,n}\right)\right] * Emission\ treatment\ cost\ per\ tonne\ CO2e \quad (6)$$

$$FTFE_{g,h} = FTF_{g,h} * ETCGH_{g,h} \quad (7)$$

$$FTHE_{h,i,j} = FTH_{h,i,j} * ETCHIJ_{h,i,j} \quad (8)$$

$$FTJE_{j,k,l} = FTJ_{j,k,l} * ETCJKL_{j,k,l} \tag{9}$$

$$FTLE_{l,m,n} = FTL_{l,m,n} * ETCLMN_{l,m,n} \tag{10}$$

$$Emission\ treatment\ cost\ from\ production = [\left(\sum_h^H \sum_i^I FPHE_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K FPJE_{i,j,k}\right) + \left(\sum_k^K \sum_l^L \sum_m^M FPLE_{k,l,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O FPNE_{m,n,o}\right) * Emission\ treatment\ cost\ per\ tonne\ CO2e \tag{11}$$

$$FPHE_{h,i} = FPH_{h,i} * EPROCH_{h,i} \tag{12}$$

$$FPJE_{i,j,k} = FPJ_{i,j,k} * EPROCJ_{i,j,k} \tag{13}$$

$$FPLE_{k,l,m} = FPL_{k,l,m} * EPROCL_{k,l,m} \tag{14}$$

$$FPNE_{m,n.o} = FPN_{m,n,o} * EPROCN_{m,n,o} \tag{15}$$

For the inequality constraints, the amount of EFBs at each resource location must be not exceeding their availability. The demands for each of the products must be met. Both constraints are represented by (16) and (17).

$$\sum_g^G F_g \leq Biomass\ Availability \tag{16}$$

$$Five\ percent\ of\ World\ Demands \geq Q_p \geq Product's\ Demand \tag{17}$$

Equations for mass balances are represented by (18) through (27). Descriptions about each equation in the model and terms were shown in **Table 22** and **Table 23**.

$$\sum_h^H FTF_{g,h} \leq F_g \tag{18}$$

$$\sum_g^G FTF_{g,h} * CONVH_{h,i} = FPH_{h,i} \tag{19}$$

$$FPH_{h,i} = \sum_j^J FTH_{h,i,j} + FSH_{h,i} \tag{20}$$

$$\sum_h^H FTH_{h,i,j} * CONVJ_{i,j,k} = FPJ_{i,j,k} \tag{21}$$

$$\sum_i^I FPJ_{i,j,k} = FSJ_{j,k} + \sum_l^L FTJ_{j,k,l} \tag{22}$$

$$\sum_j^J FTJ_{j,k,l} * CONVL_{k,l,m} = FPL_{k,l,m} \tag{23}$$

$$\sum_k^K FPL_{k,l,m} = FSL_{l,m} + \sum_n^N FTL_{l,m,n} \tag{24}$$

$$\sum_{l}^{L} FTL_{l,m,n} * CONVN_{m,n,o} = FPN_{m,n,o} \tag{25}$$

$$\sum_{m}^{M} FPN_{m,n,o} = FSN_{n,o} \tag{26}$$

$$\sum_{h}^{H} FSH_{h,i} + \sum_{j}^{J} FSJ_{j,k} + \sum_{l}^{L} FSL_{l,m} + \sum_{n}^{N} FSN_{n,o} = Q_p \tag{27}$$

Table 22 Description about model's formulations

Formulation	Description
(1)	Objective function
(2)	Equation to calculate total sales of products
(3)	Equation to calculate total biomass cost
(4)	Equation to calculate total transportation cost
(5)	Equation to calculate total production cost
(6)	Equation to calculate total emission treatment cost from transportations
(7)	Equation to calculate emission from transportation between *g* and *h*
(8)	Equation to calculate emission from transportation between *h* and *j*
(9)	Equation to calculate emission from transportation between *j* and *l*
(10)	Equation to calculate emission from transportation between *l* and *n*
(11)	Equation to calculate total emission treatment cost from productions
(12)	Equation to calculate emission from production at *h*
(13)	Equation to calculate emission from production at j
(14)	Equation to calculate emission from production at *l*
(15)	Equation to calculate emission from production at *n*
(16)	Amount of EFB in tonne per year must not exceed availability
(17)	Amount of produced product in tonne or MWh per year must at least meet the demand
(18)	Mass balance for EFB storages outlet in tonne per year
(19)	Mass balance for yield of pre-processed feedstocks in tonne per year
(20)	Mass balance for pre-processing facilities outlet in tonne per year
(21)	Mass balance for yield of intermediate products 1 in tonne per year
(22)	Mass balance for main processing facilities outlet in tonne per year
(23)	Mass balance for yield of intermediate products 2 in tonne or MWh per year
(24)	Mass balance for further processing facilities 1 outlet in tonne per year
(25)	Mass balance for yield of final products in tonne per year
(26)	Mass balance for further processing facilities 2 outlet in tonne per year
(27)	Summation of sales for all products at *h*, *j*, *l*, and *n*

Table 23 Descriptions of terms used in (1) through (27)

Term	Category	Description
Q_p	Variable	Sum up of products from each of product storage in t/y or MWh/y
F_g	Variable	Amount of biomass available at resource location and stored in t/y
$FTF_{g,h}$	Variable	Amount of biomass transported to pre-processing facilities *h* in t/y
$TCGH_{g,h}$	Parameter	Transportation cost factor for biomass feedstock from g to *h* in \$/t
$FTFE_{g,h}$	Variable	Amount of emission from transportation between g and h in t CO_2 equivalent/y

$ETCGH_{g,h}$	Parameter	CO_2 emission factor for EFB feedstock transported from *g* to *h*
$FTH_{h,i,j}$	Variable	Amount of pre-processed feedstocks *i* transported from pre-processing facilities *h* to main processing facilities *j* in t/y
$FSH_{h,i}$	Variable	Amount of pre-processed feedstocks *i* produced from pre-processing facilities *h* to be sold directly in t/y
$TCHIJ_{h,i,j}$	Parameter	Transportation cost factor for pre-processed feedstock from *h* to *j* through *i* in $/t
$FTHE_{h,i,j}$	Variable	Amount of emission from transportation between *h* and *j* in t CO_2 equivalent/y
$ETCHIJ_{h,i,j}$	Parameter	CO_2 emission factor for pre-processed feedstock transported from *h* to *j*
$FTJ_{j,k,l}$	Variable	Amount of intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *l* in t/y
$FSJ_{j,k}$	Variable	Amount of intermediate products 1 *k* produced from main processing facilities *j* to be sold directly in t/y
$TCJKL_{j,k,l}$	Parameter	Transportation cost factor for intermediate product 1 from *j* to *l* through *k* in $/t
$FTJE_{j,k,l}$	Variable	Amount of emission from transportation between *j* and *l* in t CO_2 equivalent/y
$ETCJKL_{j,k,l}$	Parameter	CO_2 emission factor for intermediate product 1 transported from *j* to *l*
$FTL_{l,m,n}$	Variable	Amount of intermediate products 2 *m* transported from further processing 1 facilities *l* to further processing 2 facilities *n* in t/y
$FSL_{l,m}$	Variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *l* to be sold directly in t/y
$TCLMN_{l,m,n}$	Parameter	Transportation cost factor for intermediate product 2 from *l* to *n* through *m* in $/t
$FTLE_{l,m,n}$	Variable	Amount of emission from transportation between l and n in t CO_2 equivalent/y
$ETCLMN_{l,m,n}$	Parameter	CO_2 emission factor for intermediate product 2 transported from *l* to *n*
$FSN_{n,o}$	Variable	Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* to be sold in t/y
$FPH_{h,i}$	Variable	Amount of pre-processed feedstocks *i* produced from biomass feedstocks *g* through pre-processing facilities *h* in t/y
$PROCH_{h,i}$	Parameter	Production cost factor at *h* to produce *i* from *g* in $/t
$FPHE_{h,i}$	Variable	Amount of emission from production at *h* in t CO_2 equivalent/y
$EPROCH_{h,i}$	Parameter	CO_2 emission factor at production *h*
$FPJ_{i,j,k}$	Variable	Amount of intermediate product 1 *k* produced from pre-processed feedstocks *i* through main processing facilities *j* in t/y
$PROCJ_{i,j,k}$	Parameter	Production cost factor at *j* to produce *k* from *i* in $/t

$FPJE_{i,j,k}$	Variable	Amount of emission from production at j in t CO_2 equivalent/y
$EPROCJ_{i,j,k}$	Parameter	CO_2 emission factor at production *j*
$FPL_{k,l,m}$	Variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *l* in t/y or MWh/y
$PROCL_{k,l,m}$	Parameter	Production cost factor at *l* to produce *m* from *k* in $/t or $/ MWh
$FPLE_{k,l,m}$	Variable	Amount of emission from production at l in t CO_2 equivalent/y
$EPROCL_{k,l,m}$	Parameter	CO_2 emission factor at production *l*
$FPN_{m,n,o}$	Variable	Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* in t/y
$PROCN_{m,n,o}$	Parameter	Production cost factor at *n* to produce *o* from *m* in $/t
$FPNE_{m,n.o}$	Variable	Amount of emission from production at n in t CO_2 equivalent/y
$EPROCN_{m,n,o}$	Parameter	CO_2 emission factor at production *n*
$CONVH_{h,i}$	Parameter	Conversion factor at *h* to produce *i*
$CONVJ_{i,j,k}$	Parameter	Conversion factor at *j* to produce *k* from *i*
$CONVL_{k,l,m}$	Parameter	Conversion factor at *l* to produce *m* from *k*
$CONVN_{m,n,o}$	Parameter	Conversion factor at *n* to produce *o* from *m*

Results and Discussions

The developed optimization model for the multi-products productions from EFB was implemented in General Algebraic Modeling System (GAMS) Rev 149, using CPLEX 11.0.0 as a solver. The solution was performed in AMD A10-4600M APU processor and contained 42 blocks of equations, 31 blocks of variables, 5401 single equations, 6,844 single variables and took 0.079s to solve. For the given parameters, the optimal profit was found to be $ 713,642,269/**y** for a single ownership of all facilities in the EFB's supply chain. **Table 24** shows optimal level of productions for all products which utilized 1,900,400.458 t/y, 6,451,782.271 t/y and 21,052.632 t/y of EFBs from Johore, Pahang and Perak, respectively. As was mentioned earlier, blending of EFBs were assumed so that it could meet the supply requirements to the pre-processing facilities. In addition, optimization results have determined portions of the produced products whether to be further processed or to be sold directly depending on the economic profitability. **Table 25** shows distributions of EFB sources to the respective pre-processing facilities and their transportation emissions.

Table 24 Optimal production level of products

Product	Production (t/y or MWh/y)
DLF	2,302,323.090
Bio-compost	20,000.000
Activated carbon	95,000.000
Cellulose	134,363.904
Hemicellulose	37,862.333
Lignin	30,000.000
Briquette	30.000
Pellet	37.000
Torrefied pellet	70.000
Bio-composite	0.920
CMC	0.400
Glucose	5.810
Xylose	15.000
Bio-resin	10,000.000
HP steam	2.000
Bio-syngas	462,000.000
Bio-oil	5.000
Bio-char	3,000.000
Bio-hydrogen	375.500
Xylitol	0.002
Bio-ethanol	3.600
Bio-gas	9.000
Bio-methanol	0.300
Electricity	20.000
MP Steam	23.333
LP Steam	23.333
Bio-ethylene	140.000
Bio-diesel	40,000.000
Bio-gasoline	16,338.028
Ammonia	170.000
Formaldehyde	42.000

Table 25 Amount of EFB biomass transported to pre-processing facilities h, $FTF_{g,h}$ in tonne per year and (emission), $FTFE_{g,h}$ in t CO_2 equivalent/y

Biomass source	**DLF production**	**Aerobic digestion**	**Alkaline activation**	**Extraction**	**Briquetting**	**Pelletization**	**Torrefied pelletization**
EFB collection 1 (Johore)	-	-	190,000.000 (874.000)	-	-	-	1,710,400.458 (7,867.842)
EFB collection 2 (Pahang)	6,222,498.153 (22,400.993)	-	-	213,296.399 (1,087.812)	78.947 (0.284)	15,908.772 (68.408)	-
EFB collection	-	21,052.632	-	-	-	-	-

3 (Perak)							

Next, from the pre-processing facilities, the pre-processed products would have two options in which either to be processed in the main processing facilities or to be purchased by the users directly. These are shown by **Table 26** and **Table 27**. For example, considering demand and EFB availability, it was more economical to sell dry long fiber (DLF) than to send it the next stage of processing. These were similar cases for cellulose and hemicellulose at the given parameters. Oppositely, the results indicated that it was more economical to process the extracted lignin in the main processing facilities (resin production) than to sell it directly. Summation of the portions to be sent for main processing and the portions to be sold are equal to the amount of pre-processed feedstocks produced by the respective pre-processing facility. For the transportation emissions, facilities with zero distances and that have used pipeline transportations would produce no emission.

Table 26 Amount of pre-processed feedstocks *i* transported from pre-processing facilities *h* to main processing facilities *j*, $FTH_{h,i,j}$ in t/y and (emission), $FTHE_{h,i,j}$ in t CO_2 equivalent/y

Path	**Bio-composite production**	**CMC production**	**Acidic hydrolysis**	**Enzymatic hydrolysis**	**Resin production**	**Boiler combustion**	**Gasification**	**Fast pyrolysis**	**Slow pyrolysis**
DLF from DLF production	1.227 (0.002)	-	-	-	-	-	-	-	-
Cellulose from extraction	-	0.465	-	12.362 (0.085)	-	-	-	-	-
Hemicellulose from extraction	-	-	0.003 (3.768 x 10^{-5})	531.016 (3.664)	-	-	-	-	-
Lignin from extraction	-	-	-	-	10,526.316 (89.474)	-	-	-	-
Torrefied pellet from	-	-	-	-	-	228.889	649,653.285	-	-

torrefied pelletization						(0.320)	(3,118.336)		
Pellet from pelletization	-	-	-	-	-	8.333	-	-	6,000.00 (45.600)

Table 27 Amount of pre-processed feedstocks *i* produced from pre-processing facilities *h* to be sold directly, $FSH_{h,i}$ in t/y

Path	**Amount to be sold directly (t/y)**	**Sales of products ($/y)**
DLF from DLF production	2,302,323.090	483,487,848.9
Bio-compost from aerobic digestion	20,000.000	200,0000.0
Activated carbon from alkaline activation	95,000.000	166,820,000.0
Cellulose from extraction	134,363.904	295,600,588.8
Hemicellulose from extraction	37,862.333	75,724,666.0
Lignin from extraction	30,000.000	45,000,000.0
Briquette from briquetting	30.00	3,600
Pellet from pelletization	37.00	5,180
Torrefied pellet from torrefied pelletization	70.00	11,200

After exiting the main processing facilities, the intermediate products 1 again would either be sending for next processing step (further processing facilities 1) or to be sold directly. **Table 28** and **Table 29** show the both options. The amounts of bio-syngas from gasification was shown by the model's results to be sold directly in preference over to further refine it in methanol production and FTL production facilities. Since there was no further processing for bio-resin as shown in the superstructure, it would be automatically sold directly to the customer. The amount of bio-oil however was larger to for further refinement as compared to be sold directly.

Table 28 Amount of intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *l*, $FTJ_{j,k,l}$ in t/y and (emission), $FTJE_{j,k,l}$ in t CO_2 equivalent/y

Path	**Separation**	**Xylitol production**	**Fermentation**	**Anaerobic digestion**	**Power production**	**Methanol production**	**FTL production**

Xylose from acidic hydrolysis	-	0.003	-	-	-	-	-
Xylose from enzymatic hydrolysis	-	-	439.437 (1.758)	12.857 (0.030)	-	-	-
Bio-syngas from gasification	1,278.261	-	-	-	-	106.339	56338.028
HP steam from boiler combustion	-	-	-	-	66.667	-	-

Table 29 Amount of intermediate products 1 k produced from main processing facilities j to be sold directly, $FSJ_{j,k}$ in t/y

Path	**Amount to be sold directly (t/y)**	**Sales of products (\$/y)**
Bio-composite from bio-composite production	0.920	575.0
CMC from CMC production	0.400	1,400.0
Glucose from enzymatic hydrolysis	5.810	10,980.9
Xylose from enzymatic hydrolysis	15.000	29,850.0
Bio-resin from resin production	10,000	90,720,000.0
HP Steam from boiler combustion	2.00	52.0
Bio-syngas from gasification	462,000.00	277,200,000.0
Bio-oil from fast pyrolysis	5.000	4,000.0
Bio-char from slow pyrolysis	3,000.00	1,140,000

The further processing 1 facilities will produce intermediate products 2. These intermediates need to be further processed or the manufactures can sell them directly to fulfill the specified demands. **Table 30** and **Table 31** show these options. At this point, majority of the produced products would be sold directly as no further processing required except for the portions of bio-hydrogen, bio-ethanol and bio-methanol. With the given parameters, product such as xylitol could be neglected for production especially if the demand is too low.

Table 30 Amount of intermediate products 2 *m* transported from further processing 1 facilities *l* to further processing 2 facilities *n*, $FTL_{l,m,n}$ in t/y

Path	Ammonia production	Formaldehyde production	Bio-ethylene production
Bio-hydrogen from steam reforming	212.500	-	-
Bio-ethanol from fermentation	-	-	141.414
Bio-methanol from methanol production	-	43.229	-

Table 31 Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *l* to be sold directly, $FSL_{l,m}$ in t/y or MWh/y

Path	Amount to be sold directly (t/y)	Sales of products ($/y)
Bio-hydrogen from steam reforming	375.500	307159.0
Xylitol from xylitol production	0.002	8.4
Bio-ethanol from fermentation	3.600	1,882.8
Bio-gas from anaerobic digestion	9.000	3,582.0
Bio-methanol from methanol production	0.300	261.0
Electricity from power production	20.000	2,800.0
MP Steam from power production	23.333	396.6
LP Steam from power production	23.333	280.0
Bio-diesel from FTL production	40,000.000	31,600,000.0
Bio-gasoline from FTL production	16,338.028	21,484,506.8

Finally, the further processing 2 facilities will produce the final products. These three products are then ready to be shipped for selling as shown by **Table 32**.

Table 32 Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* to be sold, $FSN_{n,o}$ in t/y

Path	Amount (t/y)	Sales of products ($/y)
Ammonia from ammonia production	170.000	126,650.0
Formaldehyde from formaldehyde production	42.000	19,446.0
Bio-ethylene from bio-ethylene production	140.000	216,160.0

The amount of emissions from production were the result of multiplications between the emission factors and the mass flowrates. Having said this, the owner of the EFB's facilities would be aware of which production facilities have emitted large amounts of CO_2 equivalent per year, despite the optimal overall profitability has already considered the emission treatment costs. **Table 33** till **Table 36** tabulate these emission results that originated from productions.

Table 33 Amount of emission from production at h in t CO_2 equivalent/y, $FPHE_{h,i}$

Product	DLF production	Aerobic digestion	Alkaline activation	Extraction	Briquetting	Pelletization	Torrefied pelletization
DLF from	9,439.530	-	-	-	-	-	-
Bio-compost from	-	400.000	-	-	-	-	-
Activated carbon from	-	-	1,672.000	-	-	-	-
Cellulose from	-	-	-	7,928.227	-	-	-
Hemicellulose from	-	-	-	2,495.568	-	-	-
Lignin from	-	-	-	2,512.632	-	-	-
Briquette from					1.500		
Pellet from						302.267	
Torrefied pellet from							52,321.150

Table 34 Amount of emission from production at j in t CO_2 equivalent/y, $FPJE_{i,j,k}$

Product	**DLF in bio-composite production**	**Cellulose in CMC production**	**Cellulose in enzymatic hydrolysis**	**Hemicellulose in acid hydrolysis**	**Hemicellulose in enzymatic hydrolysis**	**Lignin in resin production**	**Torrefied pellet in boiler combustion**	**Torrefied pellet in gasification**	**Pellet in fast pyrolysis**	**Pellet in slow pyrolysis**
Bio-composite from	6.883	-	-	-	-	-	-	-		-
CMC from	-	0.039	-	-	-	-	-	-		-
Glucose from	-	-	0.494	-	-	-	-	-		-
Xylose from	-	-	-	2.143 x 10^{-4}	38.318	-	-	-		-
Bio-resin from	-	-	-	-	-	25,000.000	-	-		-
HP steam from	-	-	-	-	-	-	51.500	-		-
Bio-syngas from	-	-	-	-	-	-	-	353,931.110		-
Bio-oil from	-	-	-	-	-	-	-	-	2.900	-
Bio-char from	-	-	-	-	-	-	-	-	-	1,740.000

Table 35 Amount of emission from production at l in t CO_2 equivalent/y, $FPLE_{k,l,m}$

Product	**Bio-syngas in steam separation**	**Xylose in xylitol production**	**Xylose in fermentation**	**Xylose in aerobic digestion**	**Bio-syngas in methanol production**	**HP steam in power production**	**Bio-syngas in FTL production**
Bio-hydrogen from	52.920	-	-	-	-	-	-

Xylitol from	-	1.640 x 10^{-4}	-	-	-	-	-
Bio-ethanol from	-	-	14.211	-	-	-	-
Bio-gas from	-	-	-	2.250	-	-	-
Bio-methanol from	-	-	-	-	3.619	-	-
Electricity from	-	-	-	-	-	1.000	-
MP steam from	-	-	-	-	-	1.167	-
LP steam from	-	-	-	-	-	1.167	-
Bio-diesel from	-	-	-	-	-	-	2,680.000
Bio-gasoline from	-	-	-	-	-	-	10,440.000

Table 36 Amount of emission from production at n in t CO_2 equivalent/y, $FPNE_{m,n.o}$

Product	**Bio-ethanol in bio-ethylene production**	**Bio-hydrogen in ammonia production**	**Bio-methanol in formaldehyde production**
Bio-ethylene	196.000	-	-
Ammonia	-	287.980	-
Formaldehyde	-	-	3.486

From these results, economic decision could be made in a more guided way especially in prioritizing investments for productions. Facility owner was also being informed with potential emissions from both transportation and production activities. The owner has grater flexibilities in making decision on whether to sell the produced product directly to the customer or to further processing it depending on the market situations.

Sensitivity Analysis

Sensitivity analysis was performed by varying the selling prices for three selected products i.e bio-hydrogen, ammonia and bio-ethylene. Other products could be selected as well because the purpose of this analysis was to observe effects on the objective function by manipulating the model's parameter. Three scenarios were created to demonstrate these effects as shown in **Table 37**. It can be seen that the variations in selling prices, which might happen due to changes in demands have definitely affected the original recorded profit.

Table 37 Sensitivity analysis for the profitability ($/y) of the selected bio-products with selling prices' variations

Scenario in selling price for the three products	**Difference in annual profit ($/y)**
Scenario 1: All bio-hydrogen, ammonia and bio-ethylene have shown 10% increase in selling price	+64,997
Scenario 2: Bio-hydrogen has shown 10% increase, ammonia has decreased 10% and bio-ethylene remain the same	+18,051
Scenario 3: Only bio-ethylene has decreased 10%	-21,616

Conclusion and Future Works

The economic potentials of exploiting palm oil EFB as renewable feedstocks for the productions of products that range from energy, chemicals and materials were realized by having the optimal supply chain. The optimal value for the objective function was found to be $ 713,642,269/**y**, and the other decision variables were tabulated clearly. Pre-requisite steps for obtaining the optimal supply chain were presented, and those steps would still be applicable when dealing with different kind of biomass feedstocks and products. The parameters used in the model were approximated from various literature sources and were sufficient to illustrate the applicability of the model. By considering single ownership of all facilities in the EFB's supply chain, informed decision could be made to prioritize investments for manufacturing profitable products.

For the future works, this model will be further developed to include optimal selections of processing route and transportation mode from the options found in the superstructure. Such optimal selections are required to eliminate unnecessary or uneconomical options.

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Reference

Abraham S., Evans D.L., and Marburger III J.H. (2003), *U.S. Climate Change Technology Program: Technology Options for the Near and Long Term*, Washington D.C, USA.

Auta M., Jibril M., Tamuno P.B.L, and Audu A.A. (2012), *Preparation of Activated Carbon from Oil Palm Fruit Bunch for the Adsorption of Acid Red 1 Using Optimized Response Surface Methodology*, Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622, pp. 1805-1815.

Basu P. (2013), *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*, 2nd Edition, Academic Press, UK.

Blok K., Williams R.H., Katofsky R.E., and Hendriks C.A. (1995), *Hydrogen Production from Natural Gas, Sequestration of Recovered CO2 in Depleted Gas Wells and Enhanced Natural Gas Recovery*, Energy Vol. 22, No. 2/3, pp. 161-168.

Boerrigter H. and van der Drift B. (2005*), Biosyngas Key-Intermediate in Production of Renewable Transportation Fuels, Chemicals, and Electricity: Optimum Scale and Economic Prospects of Fischer-Tropsch Plants*, 14th European Biomass Conference & Exhibition, Paris.

BP Statistical Review of World Energy (2014), http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BPstatistical-review-of-world-energy-2014-full-report.pdf, (accessed in January 8, 2015).

Bradley D. (2006), *A Report for European Market Study for Bio-oil (Pyrolysis Oil),* Climate Change Solutions, Ottawa, Ontario.

Carus M. (2012), *Market Overview of Wood-Plastic Composites and Other Bio-composites in Europe*, Presentation Slides, Nova-Institut GmbH, Heurth, Germany.

Chiarakorn S., Permpoonwiwat C.K., and Nanthachatchavankul P. (2013), Cost Benefit Analysis of Bioplastic Production in Thailand, Economics and Public Policy, 3 (6): 44-73, ISSN 1906-8522.

Chong P.S., Md. Jahim J., Harun S., Lim S.S., Abd. Mutalib S., Hassan O., and Mohd Nor M.T. (2013), *Enhancement of Batch Biohydrogen Production from Prehydrolysate of Acid Treated Oil palm Empty Fruit Bunch*, International Journal of Hydrogen Energy 38, 9592-9599.

Christopher L. (2012), *Adding Value Prior to Pulping: Bio-products from Hemicellulose, Global Perspectives on Sustainable Forest Management,* ISBN: 978-953-51-0569-5.

Chu P.M., Thorn W.J., Sams R.L., Guenther F.R. (1997), *On-Demand Generation of a Formaldehyde-in-Air Standard,* Journal of Research of the National Institute of Standards and Technology, Vol. 102(5).

Dayana Amira R., Roshanida A.R., Rosli M.I., Siti Fatimah Zahrah M.F., Mohd Anuar J. and Nazrul Adha C.M. (2011), *Bioconversion of Empty Fruit Bunches (EFB) and Palm Oil Mill Effluent (POME) into Compost Using Trichoderma Virens,* African Journal of Biotechnology Vol. 10(81), pp. 18775-18780.

Dillich S. (2013), *Distributed Bio-Oil Reforming,* A Report for the National Renewable Energy Laboratory (NREL), U.S.

Eco-Ideal Consulting Sdn. Bhd. & Mensilin Holdings Sdn. Bhd. (2005) *Barrier Analysis for the Supply Chain Palm Oil Processing Biomass (Empty Fruit Bunch) as Renewable Fuel,* Technical report for Malaysian-Danish Environmental Cooperation Programme, Malaysia.

Energy Information Administration (EIA), *Independent Statistics & Analysis for Malaysia*, http://www.eia.gov/countries/country-data.cfm?fips=my, (accessed in January 8, 2015).

Fabian E.E., Richard T.L., and Kay D. (1993), *A Report of Agricultural Composting: A Feasibility Study for New York Farms,* Cornell Waste Management Institute, Cornell University, New York.

Foo K.Y. and Hameed B.H. (2011), *Preparation of Oil Palm (Elaeis) Empty Fruit Bunch Activated Carbon by Microwave-Assisted KOH Activation for the Adsorption of Methylene Blue*, Desalination 275, 302-305.

Garcia R., Pizarro C., Lavin A.G, Bueno J.L. (2011), *Characterization of Spanish Biomass Wastes for Energy Use*, Bioresource Technology 103, 249-258.

Higson A. (2011), *Cellulose as Natural Polymer*, Renewable Chemicals Factsheet, NNFCC, UK.
Hubbe M.A., Nazhad M., and Sanchez C. (2010), *Composting as a Way to Convert Cellulosic Biomass and Organic Waste into High-Value Soil Amendments: A Review*, BioResources 5(4), 2808-2854.

Jubb C., Nakhutin A. and Cianci V.C.S., (2006), *Chapter 3: Chemical Industry Emissions, 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Geneva, Switzerland.

Kaghazchi T., Soleimani M., Yeganeh M.M. (2006), *Production of Activated Carbon from Residue of Liquorices Chemical Activation,* 8th Asia-Pacific International Symposium on Combustion and Energy Utilization, ISBN 5-89238-086-6, Sochi, Russian.

Kaliyan N., Morey R.V., Tiffany D.G., and Lee W.F. (2014*), Life Cycle Assessment of Corn Stover Torrefaction Plant Integrated with Corn Ethanol Plant and Coal Fired Power Plant*, Biomass and Bioenergy, Volume 63 (92-100).

Kanna S.U. (2010), *Value Addition of Agroforestry Residues through Briquetting Technology for Energy Purpose*, Presentation Slides, Forest College and Research Institute, Tamil Nadu Agricultural University, Tamil Nadu, India.

Karbstein H., Funk J., Norton J., and Nordmann G. (2013), *Lightweight Bio-Composites with Acrodur resin Technology,* Presentation Slides, BASF AG, Germany.

Kim J., Realff M.J., and Lee J.H. (2011), *Optimal Design and Global Sensitivity Analysis of Biomass Supply Chain Networks for Biofuels under Uncertainty*, Computers and Chemical Engineering 35, 1738-1751.

Lahijani P. and Zainal Z.A. (2010), *Gasification of Palm Empty Fruit Bunch in a Bubbling Fluidized Bed: A Performance and Agglomeration Study*, Bioresource Technology 102, 2068-2076.

Lake M.A. (2010), *Potential Commercial Uses for Lignin,* Presentation Slides for Southeastern Bioenergy Conference, Tifton, Georgia, USA.

Lam H.L, Foo D.C.Y, Kamal M., and Klemes J.J. (2010), *Synthesis of Regional Energy Supply Chain Based on Palm Oil Biomass*, Chemical Engineering Transactions Vol. 21, pp. 589-594.

Lima I.M, McAloon A., and Baoteng A.A. (2008), *Activated Carbon from Broiler Litter: Process Description and Cost of Production*, Biomass and Bioenergy, Vol. 32, Issue 6, 568-572.
Malaysian Palm Oil Board (MPOB), *Biomass Availability for 2013*, bepi.mpob.gov.my/index.php/statistics/yield, (accessed in July 15, 2014).

Mani S., Sokhansanj S., Bi X., Turhollow A. (2006), *Economics of Producing Pellets from Biomass*, Applied Engineering in Agriculture Vol. 22(3): 421-426.

McKendry P. (2002), *Energy Production from Biomass (Part 2): Conversion Technologies*, Bioresource Technology 83(2002) 47-54.

Mckinnon A. (2008), *CO_2 Emission from Freight Transport: An analysis of UK Data*, Logistic Research Centre, Heriot-Watt University, Edinburgh, Scotland.

Md Zin R., Lea-Langton A., Dupont V., and Twigg M.V. (2012), *High Hydrogen Yield and Purity from Palm Empty Fruit Bunch and Pine Pyrolysis Oils*, International Journal of Hydrogen Energy 37, 10627-10638.

Mekhilef S., Saidur R., Safari A., and Mustaffa W.E.S.B. (2011), *Biomass Energy in Malaysia: Current State and Prospects*, Renewable and Sustainable Energy Reviews 15, 3360-3370.

Mohamad Ibrahim M.N., Zakaria N., Sipaut C.S., Sulaiman O., and Hashim R. (2011), *Chemical and Thermal Properties of Lignins from Oil Plam Biomass as a Substitute for Phenol Formaldehyde Resin Production*, Carbohydrate Polymers 86, 112-119.

Murillo-Alvarado P.E, Ponce-Ortega J.M., Serna-Gonzalez M., Castro-Montoya A.J., and El-Halwagi M.M. (2013), *Optimization of Pathways for Biorefineries Involving the Selection of Feedstocks, Products, and Processing Steps,* I & EC Research 2013, 52, 5177-5190.

Ng R.T.L. and Denny Ng D.K.S. (2013), *Systematic Approach for Synthesis of Integrated Palm Oil Processing Complex. Part 1: Single Owner*, Ind. Chem. Res. 52, 102061-102220.

O’ Carroll C. (2012), *Biomass Pellet Prices, Drivers and Outlooks*, Presentation Slides of Poyry Management Consulting, London.

Oo A., Kelly J. and Lalonde C. (2012), *Assessment of Business Case for Purpose-Grown Biomass in Ontario,* A Report for Ontario Federation of Agriculture, Ontario, Canada.

PPD Technologies Inc. (2011), *Literature Review and Study Energy Market Alternatives for Commercially Grown Biomass in Ontario,* A Report for Ontario Federation of Agriculture, Ontario, Canada.

Prakasham R.S, Rao S., and Hobbs P.J. (2009), *Current Trends in Biotechnological Production of Xylitol and Future Prospects,* Current Trends in Biotechnology and Pharmacy, Vol. 3(1), 8-36.

Purwandari F.A., Sanjaya A.P., Millati R., Cahyanto M.N., Horvath I.S., Niklasson C., and Taherzadeh M.J. (2012), *Pretreatement of Oil Palm Empty Fruit Bunch (OPEFB) by N-methylmorpholine-N-oxide (NNMO) for Biogas Production: Sturctural Changes and Digestion Improvement,* Bioresource Technology 128, 461-466.

Rahman S.H.A., Choudhury J.P., Ahmad A.L., and Kamaruddin A.H. (2006), *Optimization Studies on Acid Hydrolysis of Oil Palm Empty Fruit Bunch Fiber for Production of Xylose,* Bioresource Technology 98, 554-559.

Reeb C.W., Hays T., Venditti R.A., Gonzalez R., and Kelley S. (2014), *Supply Chain Analysis, Delivered Cost, and Life Cycle Assessment of Oil Palm Empty Fruit Bunch Biomass for Green Chemical Production in Malaysia*, BioResources 9(3) 5385-5416.

Rupilius W. and Ahmad S. (2007), *Palm Oil and Palm Kernel Oil as Raw Materials for Basic Oleochemicals and Biodiesel*, European Journal of Lipid Science and Technology, Volume 109, Issue 4.

Salema A.A. and Ani F.N. (2012), *Pyrolysis of Oil Palm Empty Fruit Bunch Biomass Pellets Using Multimode Microwave Irridation,* Bioresource Technology 125, 102-107.

Santibanez-Aguilar J.E., Gonzalez-Campos J.B., Ponce-Ortega J.M., Serna-Gonzalez M., and El-Halwagi M.M. (2011), *Optimal Planning of a Biomass Conversion System Considering Economic and Environmental Aspects,* Ind. Chem. Res. 50, 8558-8570.

Saputra A.H, Qadhayna L., and Pitaloka A.B. (2014), *Synthesis and Characterization of CMC from Water Hyacinth using Ethanol-Isobutyl Alcohol Mixture as Solvents*, International Journal of Chemical Engineering and Applications, Vol. 5, No. 1.

Sarkar S. and Kumar A. (2010), *Large-scale Bio-hydrogen Production from Bio-oil,* Bioresource Technology 101, 7350-7361.

Schubert P.J. (2013), *Bio-hydrogen for Power Plants*, Presentation Slides for TransTech Energy Conference, West Virginia University, West Virginia, USA.

Searcy E. and Flynn P. (2009), *The Impact of Biomass Availability and Processing Cost on Optimum Size and Processing Technology Selection*, Applied Biochemistry and Biotechnology, 154:271-286.

Svensson M. (2010), *Fact Sheet: Bio-methane Production Potential in the EU-27 + EFTA Countries, Compared with Other Biofuels*, Technical Report of NGVA Europe, Brussels, Belgium.

Tan H.T., Lee K.T., and Mohamed A.R. (2010), *Second-generation Bio-ethanol (SGB) from Malaysian Palm Empty Fruit Bunch: Energy and Exergy Analyses*, Bioresource Technology 101, 5719-5727.

Tan L., Yu Y., Li X., Zhao J., Qu Y., Choo Y.M., and Loh S.K. (2012), *Pretreatment of Empty Fruit Bunch from Oil Palm for Fuel Ethanol Production and Proposed Biorefinery Process*, Bioresource Technology 135, 275-282.

Tay G.S., Mohd. Zaim J., and Rozman H.D. (2009), *Mechanical Properties of Polypropylene Composite Reinforced with Oil Palm Empty Fruit Bunch Pulp*, Journal of Applied Polymer Science, Vol. 116, 1867-1872.

Thorp B.A. (2010), *Key Metric Comparison of Five Cellulosic Biofuel Pathways, Advances*, Developments, *Applications in the Field of Cellulosic Biomass*, TAPPI, Georgia, USA.

Whiting A. and Azapagic A. (2014), *Life Cycle Environmental Impacts of Generating Electricity and Heat from Biogas Produced from Anaerobic Digestion*, Energy Volume 70, 181-193.

Wright M.M. and Brown R.C. (2011), *Costs of Thermochemical Conversion of Biomass to Power and Liquid Fuels (Chapter 10), Thermochemical Processing of Biomass Conversion into Fuels, Chemicals and Power*, John Wiley & Sons, USA.

www.biocharfarms.org, *Conversion Factor of Bio-char Production*, biocharfarms.org/biochar_production_energy, (accessed in July 23, 2014).

www.biocompnepal.com, *World Demand for Bio-compost*, www.slideshare.net/BiocompNepalBiocompost/prsentation-de-biocompnepal-biocompost, (accessed in May 29, 2014).

www.biomassmagazine.com, *World Demand for Torrefied Biomass*, biomassmagazine.com/blog/article/2012/02/report-projects-upswing-in-torrefied-biomass-use, (accessed in Jun 3, 2014).

www.bioresins.eu, *Bio-resin Price*, antimac.meloncreative.co.uk/chris/bioresins, (accessed in May 18, 2014).

www.careddi.com, *Bio-oil Price from Careddi Technology Co. Ltd.*, www.careddi.com/Pyrolysis_plant, (accessed in May 18, 2014).

www.cascadebiochem.com, *Glucose and Xylose Prices*, www.cascadebiochems.com/monosaccharides, (accessed in May 18, 2014).

www.companiesandmarket.com, *Xylitol Demand and Consumption for 2013*, www.companiesandmarkets.com/News/Food-and-Drink/Global-Xylitol-demand-to-surge-to-US-1Bn-by-2020/NI8994, (accessed in May 27, 2014).

www.ed.icheme.org, *Approximated Price for Bio-syngas*, ed.icheme.org/costchem, (accessed in May 18, 2014).

www.eia.gov, *Fuels Prices and Demands from United States Energy Information Administration*, www.eia.gov/petroleum/gasdiesel, (accessed in July 9, 2014).

www.enerdata.com, *World Power Consumption for 2013*, yearbook.enerdata.net/electricity-domestic-consumption-data-by-region, (accessed in July 14, 2014).

www.epa.gov, *Composting's CO_2 Emission Factor*, epa.gov/epawaste/conserve/tools/warm/pdfs/Composting_Overview.pdf, (accessed in November 22, 2014).

www.eria.org, *Price and Production Cost of Bio-composites from Oil Palm*, Economic Research Institute for ASEAN and East Asian.

www.filtsep.com, *World Demand for Activated Carbon*, www.filtsep.com/view/25932/demand-for-activated-carbon-to-reach-two-million-metric-tons, (accessed in May 29, 2014).

www.hazmatmag.com, *Ammonia Worldwide Demand for 2013*, www.hazmatmag.com/news/countries-driving-global-demand-for-ammonia-ihs-study-finds, (accessed in May 27, 2014).

www.hempfarm.com, *Production Cost for Fiber*, www.hempfarm.org/Papers/Market_Analysis_for_Hemp, (accessed in July 16, 2014).

www.hydrogen.energy.gov, *Conversion Factor and Cost for Ammonia Production*, www.hydrogen.energy.gov/pdfs/nh3_paper.pdf, (accessed in July 21, 2014).

www.icis.com, *Chemicals Prices and Demands*, www.icis.com/contact/free-sample-price-report, (accessed in May 13, 2014).

www.ili-lignin.com, *World Production of Lignin and Demand*, www.ili-lignin.com/aboutlignin.php, (accessed in May 29, 2014).

www.ipst.gatech.edu, *Hemicellulose Extraction Efficiency from Institute of Paper Science and Technology*, ipst.gatech.edu/faculty/ragauskas_art/research_opps/Hemicellulose%20Extraction%20for%20Enhanced-Biofuels%20Production.pdf, (accessed in July 16, 2014).

www.irena.org, *Bio-char Production Cost per tonne*, www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf, (accessed in July 21, 2014).

www.irena.org, *Carbon Dioxide Emission Factor for Bio-ethylene Production*, www.irena.org/.../IRENA-ETSAP%20Tech%20Brief%20I13%20Product, (accessed in November 24, 2014).

www.jinhucarbon.com, *Activated Carbon Price from Shanghai Jinhu Activated Carbon*, Co.Inc., www.jinhucarbon.com/cgi/searchen.cgi, (accessed in July 9, 2014).

www.lenzing.com, *The Global Fiber Market in 2013*, www.lenzing.com/en/concern/investor-center/equity-story/global-fiber-market, (accessed in July 10, 2014).

www.lubonchem.com, *Global Formaldehyde Consumption and Demand*, www.lubonchem.com, (accessed in July 15, 2014).

www.nature.com, *Demand for Charcoal (Biochar) from, Nature Publishing Group*, www.nature.com/climate/2009/0906/full/climate., (accessed in Jun 9, 2014).

www.netcomposites.com, *Carbon Dioxide Emission Factor for Bio-resin Production*, www.netcomposites.com/news/sustainable-industrial-resins-from-vegetable-oil, (accessed in November 25, 2014).

www.oecotextiles.wordpress.com, Carbon Dioxide Emission Factor for Dried Long Fibre, oecotextiles.wordpress.com/2011/01/19/estimating-the-carbon-footprint-of-a-fabric, (accessed in August 4, 2014).

www.omnipure.com, *Carbon Dioxide Emission Factor for Activated Carbon Production*, www.omnipure.com/sustain/emissions, (accessed in November 22, 2014).

www.prweb.com, *Worldwide Demand for CMC*, www.prweb.com/releases/carboxymethyl_cellulose/CMC_cellulose_ethers/prweb8070281, (accessed in Jun 3, 2014).

www.purelignin.com, *Lignin Production*, http://purelignin.com/products, (accessed in July, 16 2014).

www.sarawakenergy.com.my, *Carbon Dioxide Emission Factor for Briquette Utilization* www.sarawakenergy.com.my/index.php/r-d/biomass-energy/palm-oil-biomass, (accessed in November 25, 2014).

www.shyanda.en.gongchang.com, *Xylitol Price of Shanghai Yanda Biotechnology Co. Ltd.*, shyanda.en.gongchang.com/product, (accessed in July 9, 2014).

www.technip.com, *World Demand for Ethylene*, www.technip.com/sites/default/files/technip/publications/attachments/Ethylene_September_2013_Web_0.pdf, (accessed in Jun 9, 2014).

www.thomasnet.com, *Demand for Bio-resins*, http://www.thomasnet.com/articles/plastics-rubber/bioresin-plastics, (accessed in July 14, 2014).

www.trade.ec.europa.eu, *Carboxy Methyl Cellulose (CMC) Selling Price and Production Cost*, trade.ec.europa.eu/doclib/html/112178.htm, (accessed in July 9, 2014).

www.turbinesinfo.com, *Steam Turbine Efficiency*, http://www.turbinesinfo.com/steam-turbine-efficiency, (accessed in July 21, 2014).

www.winrigo.com, *Carbon Dioxide Emission Factor for Bio-composite Production*, winrigo.com.sg/pdf/WinrigoCatalogue.pdf, (accessed in November 25, 2014).

www1.eere.energy.gov, *Steam Production Cost*, www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/steam15_benchmark.pdf, (accessed in July 19, 2014).

www.etawau.com, Map of Peninsula Malaysia (accessed in February 17, 2016)

Yin Q., Yang W., Sun C., and Di M. (2012), *Preparation and Properties of Lignin-Epoxy Resin Composite*, Bioresources 7(4), 5737-5748.

Zafar S. (2014), *Bioenergy Developments in Malaysia*, A Technical Report of BioEnergy Consult, http://www.bioenergyconsult.com/bioenergy-developments-malaysia/, (accessed in January 8, 2015).

Zhang Y., Brown T.R., Hu G., and Brown R.C. (2013), *Techno-economic Analysis of Two Bio-Oil Upgrading Pathways*, Chemical Engineering Journal 225, 895-904.

Zhang Y., Hu G. and Brown R.C. (2013), *Life Cycle Assessment of the Production of Hydrogen and Transportation Fuels from Corn Stover via Fast Pyrolysis*, Environmental Research Letters, Environ. Res. Lett. 8, 025001 13pp.

Zhang Y., Sun W., Wang H., and Geng A. (2013), *Polyhydroxybutyrate Production from Oil Palm Empty Fruit Bunch Using Bacillus Megaterium R11*, Bioresource Technology 147, 307-314.