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Design and development of a fixed-bed pyrolysis plant for the production of biofuel from biomass and agricultural wastes

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Abstract

Thermo decomposition of biomass and agricultural products to produce biochar, bio-oil, and biogas is an environmentally friendly process. Bio-oil is the most valuable among the three products and is an alternative to fossil fuel. Energy crisis is a global issue that requires sustainability of energy sources. Using fossil fuels has resulted in ozone layer depletion, global warming, and greenhouse gas effects with negative consequences. Palm kernel shells (PKS) and other agricultural wastes are underutilized in various ways. A fixed-bed batch reactor was designed and developed to convert palm kernel shells to bio-oil (biofuel) as an alternative to fossil fuel. In the 4 kg batch, the biochar reduced from 54 to 17wt%, bio-oil from 32 to 60 wt%, biogas from 12 to 23wt%, and bio-oil volume from 1256 to 1968 cm^3 at the pyrolysis temperature of 300 to 600 ^oC. The 5 kg batch produced changed from 54 to 24 wt% of biochar, 31 to 56wt% of bio-oil, 15 to 19 wt% of biogas, and bio-oil volume from 2410 to 2655 cm^3 as the temperature increased from 300 to 600 ^oC. The bio-oil is applicable and useful in running internal combustion engines. Biofuel has the physical properties of oil such as smell and colour. Biofuel is an alternative to fossil fuel for a cleaner and greener environment.

Keywords: Agricultural Wastes; Biochar; Biofuels; Biogas; Biomass; Pyrolysis; Reactor

1. Introduction

One of the first chemical processes used by humans to create coke from coal and charcoal from wood is pyrolysis. One synthetic fuel being researched as a potential petroleum replacement is bio-crude. Bio-fuels have been widely researched and seen as future alternatives to fossil and industrial fuels. The thermochemical process used to extract energy from any valuable biomass is called pyrolysis [1] [2]. It is a process that is applicable in chemical technology and used heavily in the chemical industry. For innovations to be commercially adopted, they must be economically competitive with fossil fuel-based technologies, and scaling up pyrolysis is essential to this process [3].

Nowadays, a lot of research has been done on pyrolysis because of its efficient heat conversion and environmentally friendly technology. [4]. The compositions and yields of the finished products are extremely dependent on the operational parameters (temperature, mass of feedstocks, time) during the pyrolysis process [5] [6] [7] [8].

There are three major types of pyrolysis process namely:

- **Slow Pyrolysis:** Slow pyrolysis is the process of slowly heating the feedstock to the maximum temperature to produce the three products of pyrolysis [9] and is applicable in agricultural wastes [9] [10] [11] 12].
- **Fast Pyrolysis:** Fast pyrolysis is the rapid heating of the feedstock for a short time to produce the three products of the pyrolysis process from biomass [13] [14] [15] [16] [17].[18] reported that a high-pressure fast

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pyrolysis process applies to biomass to scale up the product yields depending on feedstock and the process parameters.

- **Flash Pyrolysis:** Longanbach and Bauer developed a flash pyrolysis technique to turn bituminous and sub-bituminous coal into liquid fuels, chars, and gases [19].

Reactors are used to carry out the pyrolysis process of biomass. Continuous stirred-tank reactors (CSTR), plug flow reactors (PFR), continuous oscillatory baffled reactors (COBR), semi-batch reactors (SBR), catalytic reactors (CR), fluidized bed reactors (FBR), and fixed-batch reactors (FBBR) are among the different types of pyrolysis reactors [20] [21] [22]. Pyrolysis reactors exist in different types, shapes, and designs (Garcia-Nunez *et al.,* 2017). Fixed bed pyrolysis and

fluidized bed pyrolysis are the two main types of pyrolysis reactors. The reactor's input material is fixed and heated to high temperatures in fixed-bed pyrolysis. It is known as fixed bed pyrolysis because the feed is fixed in the reaction bed (reactor) [1].

Heat is applied externally while the feed material is fed into the reactor. Compared to fluidized bed pyrolysis, fixed bed pyrolysis has comparatively lower losses [23]. The simplest reactor type to design, a fixed-bed reactor loads and fills the bed with solid catalyst particles, and is the most practical for the pyrolysis process because of its low operating costs and straightforward operation. [24].

Palm kernel oil is a tremendous source of myristic, oleic, and lauric acid [25]. The industries that uses it include soap manufacturing, oil processing, food processing, cosmetics, and pharmaceuticals. It has about 80% saturated fat [17]. It can also be used as a machine lubricant. Animals are fed this protein-rich feed. The pyrolysis of palm kernel shells (waste) to produce bio-oil (wealth) makes pyrolysis relevant to the present and future methods of energy conversion, innovations, and environmental preservation [26]. Palm Kernel Shell (PKS) is a biomass. Biomass means biodegradable materials. Biomass is combustible organic matter, readily available, agricultural by-products or residues, forestry residues, municipal bio-solids, and abundant in supply [1].

Biofuel from biomass (palm kernel shell) and agricultural wastes are products that contain economic compounds such as phenol and methyl ester [27] [28] [29]. The unique advantages, benefits, opportunities, and future industrial prospects of palm kernel shells make it necessary to carry out more research work and make more discoveries that will contribute to human knowledge and solve present and future energy problems [30]. The shell of the Tenera palm kernel contains a moderate quantity of moisture (9.8%), a high amount of carbon (48.63%), and low levels of sulfur (0.48%), nitrogen (0.43%), and ash (7.6%) [31]. The analysis yielded a higher heating value of 17.2 MJ/kg, fixed carbon (6.8%), and volatile matter (75.8%). The presence of low crystalline cellulose was revealed by the crystallinity index of 28.29% obtained from XRD data [31].

Fossil fuel comes with the challenges of environmental degradation, greenhouse gas problems, and ozone layer depletion. The reserved chemical energy in PKS and agricultural wastes has not

been fully harnessed. The world must sustain the sources of energy to sustain life and development as the population increases. Direct burning of PKS to produce charcoal causes the evaporation of the bio-oil which results in a waste of the bio-oil resource. The burning of biomass destroys the biofuel in it. The drive for energy sustainability and an eco-friendly environment cannot be achieved when the population engages in the direct burning of biomass and agricultural wastes.

[8] reported that a wide range of biomass feedstock has been used in pyrolysis processes. The characteristics of biomass influence whether it can be pyrolyzed to create biochar [32] [33]. Numerous analyses, including proximate and ultimate analysis, can be used to ascertain these. [34] reported that catalytic pyrolysis could improve the quantity of the bio-fuel product from lignocellulosic biomass and could apply to renewable biofuels and limited lignocellulosic biomass. [35] reported an overview of microflow chemistry, electrification, their incorporation toward sustainable manufacturing, and their significance to biomass upgrade.

The heat exchanger is an important unit of a pyrolysis plant. Recuperators and regenerators, direct and indirect contact transfer processes, tubes, plates, and extended surfaces as construction geometry, single- and two-phase heat transfer mechanisms, and parallel, counter, and cross flow arrangements are the primary criteria used to classify heat exchangers [36] [37]. The heat exchanger can be developed using some locally available and durable materials, through a theoretical formula. The performance evaluation can be carried out under various flow conditions. The heat exchanger converts the gaseous bio-oil from a high temperature to liquid (bio-oil) at a low temperature by extracting the latent heat. This research aims to design and develop a fixed-bed pyrolysis plant for the production of biofuel from biomass and agricultural wastes using the process of pyrolysis.

2. Materials and Methods

The components and parts were installed with adequate analysis to perform satisfactorily in the heating unit. The analysis of the components preceded the fabrication and installation of the parts. The heating unit consists of various components which include

- Furnace metallic case, fabricated from a 2 mm thick sheet metal supported by 25 mm x 25 mm 3 mm angular steel bar
- A-alumina (al_2o_3) refractory clay for preventing heat loss
- Reactor for the thermal decomposition of biomass at elevated temperature
- Electric heating element for the thermal decomposition of the biomass in the reactor
- Automatic temperature control system for the heating element
- Temperature indicators for indicating the heating and reactor temperatures

The furnace wall was fabricated with a 2 mm thick sheet. The furnace leg was fabricated using an angular steel bar specification of 25 x 25 x 3 mm. The furnace wall and legs were joined together by electric arc welding process. The chemical composition and physio-mechanical properties of refractory lining were satisfactory to withstand the high temperatures of the pyrolysis process. The refractory lining (α-alumina, Al_2O_3) was used to contain the heat for effective heat resistance purposes with no threat of any crack [38]. The ASTM E 11 normal opening of 500 μm and DIN ISO 3310-1 standard were utilized to prepare the refractory lining of the furnace. [38] stated that the minimum satisfactory chemical compositions, physio-chemical, and mineralogical properties must be possessed by a refractory furnace lining clay to be useful to provide the needed refractory properties to the furnace.

The refractory lining was moulded in the furnace frame for proper positioning of the reactor. The heating element was connected to the control system using heat resistance 4 mm cable wire. Two thermocouple sensors were connected to the reactor to measure the heating and reactor temperatures. of the reactor. The design of the heating unit of the pyrolysis plant is shown in Figure 1.

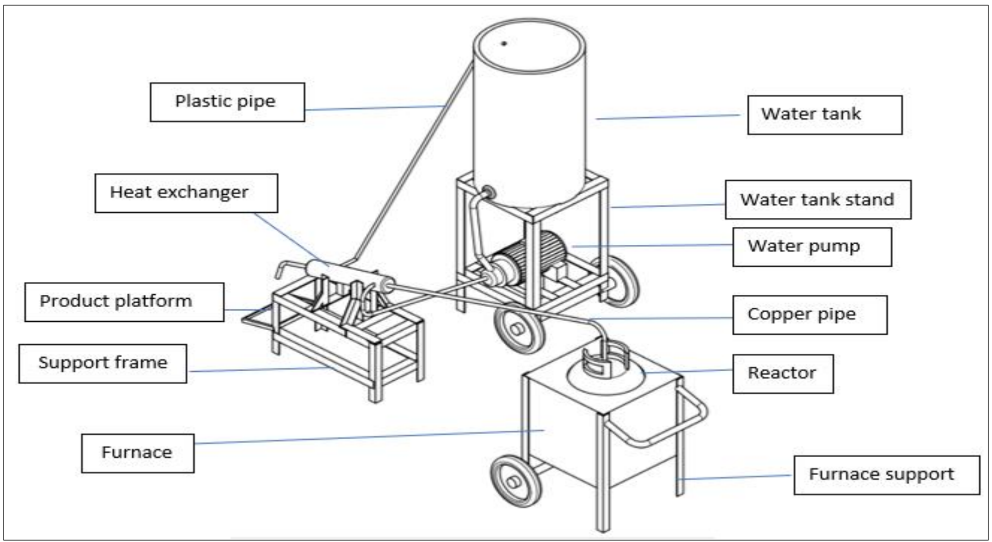

Figure 1 Diagram of the pyrolysis plant

The capacity of the reactor is 10.5 liters and it can withstand a temperature of up to 1350 ^{o}C and a pressure of 2.8 MN/m^2. The parts of the pyrolysis are listed in Figure 1. The refractory lining was moulded in the furnace frame to hold the reactor in position. The heating element was connected to the control system using heat-resistance 4 mm cable wire. Two thermocouple sensors were connected to the reactor to measure the heating and reactor temperatures. The three units of the pyrolysis plant are shown in Figure 2.

Figure 2 The three units of the pyrolysis plant

The dimension of the drilled holes is 8.5 mm each on the two closing flanges. One of the flanges was welded to the reactor while the other was welded to the cover of the reactor. A metallic frustum was welded to the cover of the reactor to connect the reactor to the product flowline which passes through the heat exchanger for condensation of the gaseous fuel from the reactor. Performance evaluation of the pyrolysis plant was done. The pyrolysis process of two batches 4 kg, and 5 kg at the pyrolysis temperatures of 300, 400, 500, and 600 ^oC was carried out. The masses of deposited biochar, bio-oil, and biogas were documented. The heating temperatures of the feedstock were documented at the interval of 20 minutes. However, in this research, PKS was adopted as the biomass and agricultural waste for producing biofuel. PKS is a by-product of palm oil mills and it is available in many parts of the world. The PKS that was used for the performance evaluation is shown in Figure 3.

Figure 3 The biomass and agricultural waste which is the PKS

3. Results and Discussion

The results in Table 1 show that the mass of the biochar produced decreased from 2.25 kg at 300 ^oC to 0.67 kg at 600 ^oC. This was due to the secondary heating of the PKS and an increase in the pyrolysis temperature. The biochar product reduced from 56wt% to 16wt% with corresponding value rise in the pyrolysis temperature from 300 ^oC to 600 ^oC as shown in Figure 4. The mass of bio-oil obtained from the 4 kg batch was 1.28 kg at 300 ^oC and 2.41 kg at 600 ^oC. The quantity of biogas obtained increased significantly from 12wt% to 23wt% with an increase in the pyrolysis temperature according to [39]. The volume of the biofuel produced increased concerning the process temperature as displayed in Table 1.

Table 1 Products of the pyrolysis of 4 kg of PKS at the temperature of 300 °C , 400 °C, 500 °C and 600 °C

S/N	Temp. (°C)	Mass of biochar (kg)	Mass of bio-oil (kg)	Mass of biogas (kg)	Volume of bio-oil (cm^3)
1	300	2.25	1.28	0.48	1256
2	400	1.36	2.03	0.62	1900
3	500	1.21	2.06	0.75	1916
4	600	0.97	2.11	0.91	1968

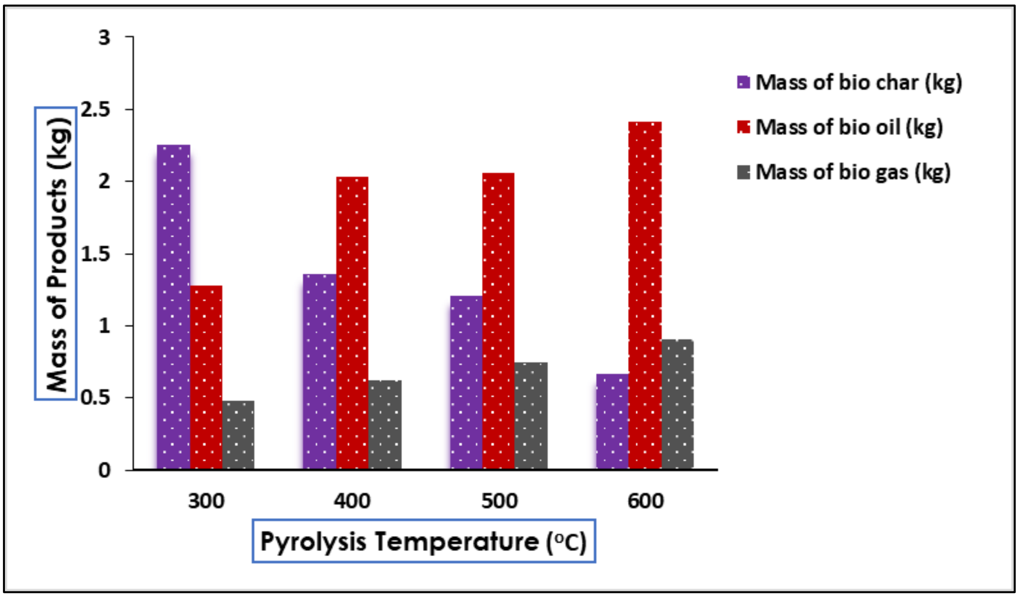

Figure 4 Comparative of the mass of products and the pyrolysis temperature of 4 kg batch

The displayed results in Table 2 revealed that the mass of the biochar produced decreased from 2.17 kg at 300 °C to 1.48 kg at 600 °C. This was due to the secondary cracking of the PKS with an increase in the pyrolysis temperature as shown in Figure 5, which corresponds to the research of [40]. The biochar product reduced from 56wt% to 16wt% as the pyrolysis temperature rose from 300 °C to 600 °C. The mass of bio-oil obtained from the 4 kg batch was 2.04 kg at 300 °C and 2.60 kg at 600 °C. The quantity of biogas obtained increased significantly from 0.78 kg to 0.90 kg with an increase in the pyrolysis temperature from 300 °C to 600 °C.

Table 2 Products of the pyrolysis of 5 kg of PKS at 300 °C, 400 °C, 500 °C and 600 °C

S/N	Temp. (°C)	Mass of biochar (kg)	Mass of bio-oil (kg)	Mass of biogas (kg)	Volume of bio-oil (cm^3)
1	300	2.68	1.54	0.77	2410
2	400	1.83	2.33	0.82	2590
3	500	1.56	2.57	0.87	2630
4	600	1.22	2.80	0.96	2658

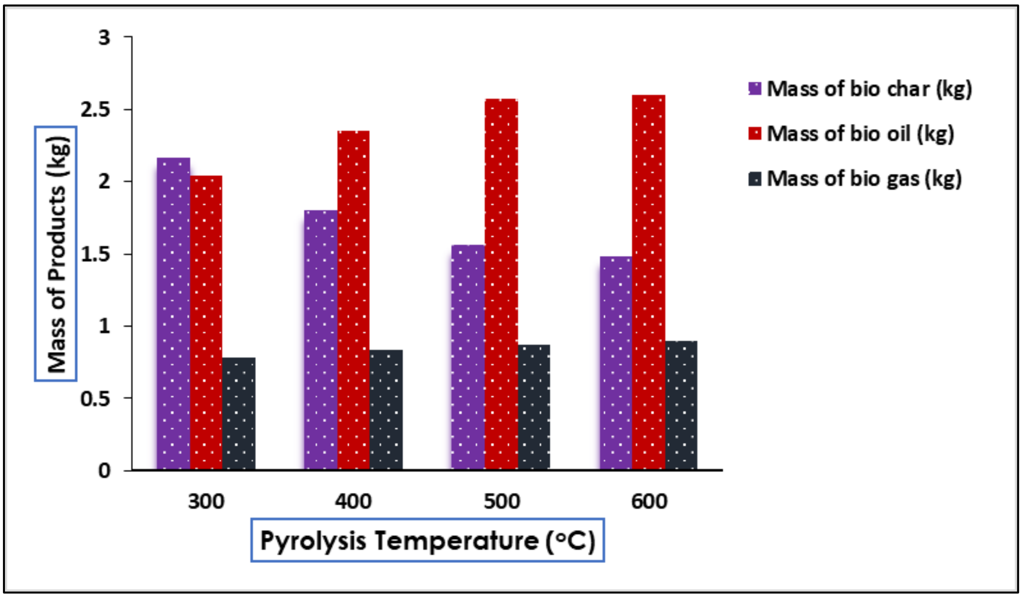

Figure 5 Comparative of the mass of products and the pyrolysis temperature of the 5 kg batch

Biofuel has the physical properties of oil such as smell and colour. The biofuel is shown in Figure 6.

Figure 6 The biofuel obtained from the PKS

The quantity of biofuel obtained in the 5 kg of PKS was more than the biofuel obtained in the 4 kg at the same pyrolysis temperature. This was a result of the increase in the mass of feedstock from 4 kg to a mass of 5 kg. [41]. stated that more feedstock gave more yields of biofuel even at the same pyrolysis temperature. The results of the products from 4 and 5 kg are shown in Figure 3.

The biofuel produced was biodiesel which is an alternative to diesel fuel and can be used to power internal combustion engines. The biofuel is the most useful and significant amongst the three by-products of the pyrolysis of the PKS. The ultimate analysis of the PKS revealed that the calorific value of bio-oil (biofuel) from PKS is 21.99 MJ/kg and the heating value is 23,604.71 KJ/kg [1]. The calorific value of diesel fuel is 45.5 MJ/kg while the heating value is 45,124.4 MJ/kg according to [1]. The report of [1] showed that the calorific and heating values of diesel fuel are greater than that of the biofuel obtained from the PKS. [42] stated that the limited fuel characteristics carried out on the (bio-oil) biofuel from PKS demonstrated that the product can be successfully used to fuel a diesel engine. Figure 7 shows that the volume of the bio-oil produced from the 4 kg and 5 kg increased concerning the pyrolysis temperature [43].

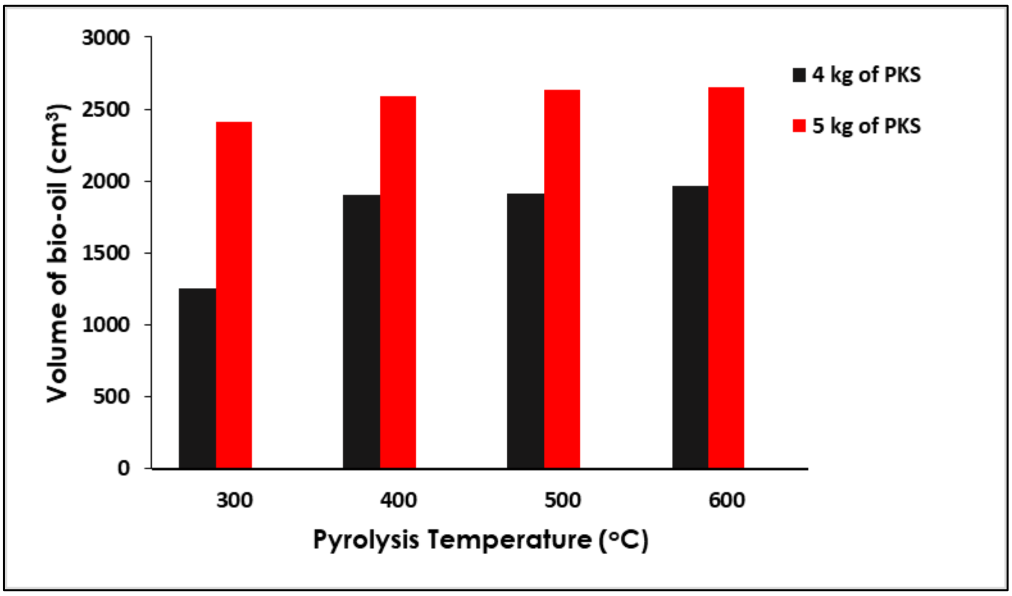

Figure 7 Comparative of the volume of the bio-oil and the pyrolysis temperature of 4 and 5 kg batches

4. Conclusion

Pyrolysis plant can be used to extract bio-oil (bio fuel) from biomass and agricultural waste like PKS. Consequently, the quantity of bio fuel that was obtained from the PKS (biomass) was determined by the mass of the feedstocks, pyrolysis temperature, and process time. Three products were obtained from PKS and the most useful and significant was the bio-oil (bio-fuel). The biofuel possesses significant calorific and heating values properties which make it applicable and useful in running internal combustion engines. Bio fuel is an alternative to fossil. It is eco-friendly and environment friendly. The bio fuel has the physical properties of oil such as smell and colour.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Aziz M. A., Rahman M. A., and Halim M. H. (2018): Design, fabrication, and performance test of a fixed bed batch type pyrolysis plant with scrap tire in Bangladesh. Journal of Radiation Research and Applied Sciences, 11: 311–316.

[2] Azeta O., Ayeni A. O., Agboola O., Elehinafe F. B., (2021). A review of the sustainable energy generation from the pyrolysis of coconut biomass. Scientific African, 13: 245- 256

[3] Huber G.W. and Brown R. C., (2017): Prospects and Challenges of Pyrolysis Technologies for Biomass Conversion. Energy Technology, 5: 5-6

[4] Suman, S., and Gautam, S. Biochar derived from agricultural waste biomass acts as a clean and alternative energy source for fossil fuel inputs. Energy System Environment. 2018

[5] Rodriguez, J., Lustosa Filho, J., Melo, L., de Assis, I., and de Oliveira, T. Influence of pyrolysis temperature and feedstock on the properties of biochars produced from agricultural and industrial wastes. Journal of Analytical Applied Pyrolysis. 2020; 149: 104839

[6] Xie, S., Yu, G., Li, C., Li, J., Wang, G., and Dai, S. Treatment of high-ash industrial sludge for producing improved char with low heavy metal toxicity. Journal of Analytical Applied Pyrolysis. 2020; 150: 104866

[7] Uddin M.N., Techato K., Taweekun, J., Mofijur M., Rasul, M.G., Mahlia, M.I., and Ashrafur, S.M. An Overview of Recent Developments in Biomass Pyrolysis Technologies. Energies. 2018; 11: 3115

[8] Salman Z. Online Trade Magazine; Alternative Energy from Solar, Wind, Biomass, Fuel, Cell and more: Last modified 02/09/2009; http://www.altenergymag.com/content.php?issue_number=09.02.01&article=pyrolysis. Accessed 23 April 2020

[9] Danish, M., Naqvi, M., Farooq, U., and Naqvi, S. Characterization of South Asian agricultural residues for potential utilization in future "energy mix". London, United Kingdom: Elsevier. 2015

[10] Pathak, P., Mandavgane, S., and Kulkarni, B. Fruit peel waste: characterization and its potential uses. 2017

[11] Nanda, S., Mohanty, P., Pant, K., Naik, S., Kozinski, J., and Dalai, A. Characterization of North American lignocellulosic biomass and biochars in terms of their candidacy for alternate renewable fuels. New York, NY: Springer Science+Business Media New York; 2014.

[12] Chang G., Shi P., Guo Y., Wang L., Wang C., and Guo Q. Enhanced pyrolysis of palm kernel shell wastes to bio-based chemicals and syngas using red mud as an additive. Journal of Cleaner Production. 2020; 272: 122847

[13] Nawaz S., Jamil F., Akhter P., Hussain M, Jang H., and Park Y. K. Valorization of lignocellulosic rice husk producing biosilica and biofuels—a review. Journal of Physics Energy. 2023; 5(1): 012003

[14] Vuppaladadiyam A.K., Vuppaladadiyam S.S.V., Sahoo A., Murugavelh S., Anthony E., Bhaskar T., Zheng Y., Zhao M., Duan H., Zhao Y., Antunes E., Sarmah A.K. and Leu S.Y. Bio-oil and biochar from the pyrolytic conversion of biomass: A current and future perspective on the trade-off between economic, environmental, and technical indicators. Science of The Total Environment. 2023; 857: 159155.

[15] Hung Y.C., Ho C.H., Chen L.Y., Ma S.C., Liu T.I. and Shen Y.C. Using a Low-Temperature Pyrolysis Device for Polymeric Waste to Implement a Distributed Energy System. Sustainability. 2023; 15(2):1580

[16] Ilo O.P., Nkomo S.L., Mkhize N.M., and Simatele M.D. The Contribution of Pyrolysis of Water Hyacinth to South Africa's Low-carbon and Climate Resilient Economy Transition: A Mini Review. Environmental and Climate Technologies. 2023; 27(1): 103-16.

[17] Okpala B. (2015): Some Important Facts About Palm Kernel. Global Foodbook: Recipes for Life. https://globalfoodbook.com/some-important-facts-about-palm-kernels Accessed 20 April 2023,

[18] Rasaq, W.A., Golonka, M., Scholz, M. and Białowiec, A. (2021): Opportunities and Challenges of High-Pressure Fast Pyrolysis of Biomass: A Review. Energies, 14: 5426

[19] Ibrahim H.A. Recent Advances in Pyrolysis. Print ISBN978-1-78984-063-6; 2020.

[20] Santos, J. H. S., Gomes, J. T. S., Benachour, M., Medeiros, E. B. M., Abreu, C. A. M., Lima-Filho, N. M. (2020): Selective hydrogenation of oxalic acid to glycolic acid and ethylene glycol with a ruthenium catalyst. Reaction Kinetics, Mechanisms and Catalysis, 131: 139–151

[21] Jaibiba, P., Vignesh, S.N. and Hariharan, S. (2020): Working principle of typical bioreactors. Editor(s): Singh, L., Yousuf, A. and Mahaputra, D. M. Chapter 10 - In Sustainable Design and Industrial Applications in Mitigation of GHG Emissions, Bioreactor, pp 145-173.

[22] Chang S. H. (2023): Plastic waste as pyrolysis feedstock for plastic oil production: A review. Science of The Total Environment, 877: 162719.

[23] Tech-Team (2024): What are the advantages of fixed-bed batch reactor? Available from What Are The Advantages Of Fixed Bed Reactor? - Kintek Solution (kindle-tech.com) (Accessed 15 June 2024).

[24] Hafeez S., Pallari E., Manos G., and Constantinou A. (2019). Catalytic Conversion and Chemical Recovery, In Plastics Design Library, Plastics to Energy, William Andrew Publishing, 147-172.

[25] Fadele, O. A., Otieno, M., Omojola, S. O., and Adeyemi, M. (2022): The use of palm kernel shell as a partial replacement for coarse aggregate in concrete. 18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022). https://doi.org/10.5281/zenodo.6603486

[26] Ogunkanmi, J. O., Kulla, D. M., Omisanya, N. O., Sumaila, M., Obada, D. O., and Dodoo-Arhin, D. (2018): Extraction of bio-oil during pyrolysis of locally sourced palm kernel shells: Effect of process parameters. Case Studies in Thermal Engineering, 12(1): 711-716.

[27] Asadullah, M., Ab Rasid, N. S., Syed A., and Azdarpour, K. A. (2013): Production and detailed characterization of bio-oil from fast pyrolysis of palm kernel shell. Biomass and Bioenergy, 59: 316-324.

[28] Chan, Y. H., Quitain, A. T., Yusup, S., Uemura, Y., Sasaki, M. and Kida, T. (2018): Liquefaction of palm kernel shell in sub- and supercritical water for bio-oil production. Journal of the Energy Institute, 91(5): 721–732.

[29] Varma A. K., Lokendra S.T., Shankar R. and Mondal P. (2019): Pyrolysis of wood sawdust: Effects of process parameters on products yield and characterization of products. Waste Management, 89(1): 224-235

[30] Danso, H. and Appiah-Agyei, F. (2021) Size Variation of Palm Kernel Shells as Replacement of Coarse Aggregate for Lightweight Concrete Production. Open Journal of Civil Engineering, 11: 153-165.

[31] Adeoye, A. O., Quadri, R. O. and Lawal, O. S. (2022): Assessment of biofuel potential of tenera palm kernel shell via fixed bed pyrolysis and thermal characterization. Results in Surfaces and Interfaces 9: 100091

[32] Mohammed S. P., Roshan T. M. S., Ragesh, P., Karthik C. T., Minhaj M. K., and Poolakkal M.F. (2018): Design and Fabrication of Pyrolysis Unit. International Journal of Innovative Science and Research Technology, 3(5): 799–801.

[33] Veiga, P., Schultz, J., Matos, T., Fornari, M., Costa, T., and Meurer, L. (2020): Production of high-performance biochar using a simple and low-cost method: optimization of pyrolysis parameters and evaluation for water treatment. Journal of Analytical Applied Pyrolysis, 148: 104823.

[34] Wang, W., Gu, Y., Zhou, C., and Hu, C. (2022): Current Challenges and Perspectives for the Catalytic Pyrolysis of Lignocellulosic Biomass to High-Value Products. Catalysts, 12:1524

[35] Chen T., Hsiao Y.W., Baker-Fales M., Cameli F, Dimitrakellis P., and Vlachos D.G. (2022): Microflow chemistry and its classification for sustainable chemical manufacturing, Chemical Science, 13(36): 10644–10685

[36] Bharathi, M., Prasad Mohan S. H., Santhosh S. M., Karthikeyan. S M. and Rajkamal M.D, (2017): Design and Fabrication of Shell and Tube Heat Exchanger. International Journal of Latest Engineering Research and Applications, 2(4): 35-39.

[37] Bashiru A., Ayoade A. M., Buhari O. O., Olatunde A. R., and Olaniyi F. J. (2020): Design, Fabrication, and Performance Evaluation of a Shell and Tube Heat Exchanger for Practical Application. European Journal of Engineering Research and Science, 5(8): 835-845.

[38] Oyebanjo O., Ekosse G. and Odiyo J. (2020): Physico-chemical, Mineralogical, and Chemical Characterisation of Cretaceous–Paleogene/Neogene Kaolins within Eastern Dahomey and Niger Delta Basins from Nigeria: Possible Industrial Applications. Minerals, 10: 670; doi:10.3390/min10080670

[39] Abdullahi N., Sulaiman F., and Safana A. A. (2017): Bio-oil and Biochar Derived from the Pyrolysis of Palm Kernel Shell for Briquette. Sains Malaysiana, 46(12): 2441–2445.

[40] Bridgwater T. (2018): Challenges and Opportunities in Fast Pyrolysis of Biomass: Part I. Introduction to the technology feedstocks and science behind a promising source of foods and chemicals. Johnson Matthey Technol. Revolution, 62(1): 118–130.

[41] Veiga, P., Schultz, J., Matos, T., Fornari, M., Costa, T., and Meurer, L. (2020): Production of high-performance biochar using a simple and low-cost method: optimization of pyrolysis parameters and evaluation for water treatment. Journal of Analytical Applied Pyrolysis, 148: 104823.

[42] Ojolo S.J., Adelaja A. O., and Sobamowo G. M. (2012): Production of Bio-Diesel from Palm Kernel Oil and Groundnut Oil. Advanced Materials Research, 367: 501-506

[43] Onochie, U. P., Itoje, H. J., Itabor, N., Akhator, P., and Ojariafe, G. (2015): Calorific Value of Palm Oil Residues for Energy Utilisation. International Journal of Engineering Innovation & Research, 4(4): 664-667.