

The Biorefiner

Annual Magazine

2018



**India Workshop
Report**

**Anaerobic co-digestion
Research showcase**

UK-Mexico-Malaysia Workshop ♦ Electricity from Empty Fruit Branches in
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Editorial letter



After its foundation 3 years ago the growth of the IBEST has been sustained, adding new individual (100+ total) and organisational (80+ total) members. The various international events organised and the research projects undertaken have strengthened the links amongst Biorefiners, especially early career researchers. And now, IBEST has even more expanded by the UK-India Newton-Bhabha Researcher Links Workshop “Energy for Economic Development and Welfare: Promoting International Collaboration, Innovation and Sustainability” at the Indian Institute of Petroleum 23-27 October 2017 (page 5-7). We are grateful for the continuous support from the Newton Fund through the British Council Researcher Links programme and the partner funding organisations in Mexico, Malaysia and India. The Royal Society of Chemistry has also supported the aforementioned workshop in India.

An international collaboration workshop on biomass and waste valorisation was carried out at The University of Bath between Bath, Mexico and Malaysia partners on 25th May 2018 (page 8). The workshop is part of the ongoing “NO-Waster” project funded by the University of Bath’s Pathways to GCRF Scheme, also involved Mexican Institute of Petroleum, UNAM, and University Putra Malaysia.

We are also pleased to announce the successful PhD viva outcome of Ida Fahani Md Jaye article featured on page 9.

The New Biorefiner section once again has featured contributions from early career researchers. We warmly welcome to all our new members. The Biorefiner editors have also participated in other events such as the Introduction to the Biorefinery workshop at CIEMAD, IPN Mexico, 16 August 2018. This has featured in this issue. The report is a reminder that the dream of a Biorefiner to see a biorefinery concept becoming a reality is possible; with the right policies, scientific research and engagement with all stakeholders, and, of course, the right context and country.

Sincerely yours,

The editors

“Energy for Economic Development and Welfare: Promoting International Collaboration, Innovation and Sustainability” – End of project report

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The UK-India Newton-Bhabha Workshop “Energy for Economic Development and Welfare: Promoting International Collaboration, Innovation and Sustainability” 23-27 October, 2017, Indian Institute of Petroleum, Dehradun, was aimed at building research capacity in integrated sustainable energy systems for poor and vulnerable populations. India has a fast growing economy albeit is amongst the lowest per capital energy consuming nations in the world. Indigenous energy production and security by integrated solutions are imperative for economic development and welfare. The organising and participating institutions of the workshop have shown dedication in delivering high quality R&D in the highly important international agenda. They have shown strong commitments to tackle “the challenge of socio-economic welfare by sustainable alternative energy systems development, a strongly multi-dimensional challenge in India”, presented by Sadhukhan, also stressed, “Sustainable and renewable energy supply and security is one of them at the heart of the problems affecting economic development and welfare of poor and vulnerable populations.” “All prioritised energy mix and technologies can be exploited, but in an integrated manner, with the support of life cycle assessment and unified policy framework involving all stakeholders.” “It is the job of researchers to make sure that the research done at laboratory has a societal and economic benefit applying whole system concept.” “This workshop should share visions to make a progress through the scale.” “The system has to be integrated, multi-process, multi-product, multi-sector and cyclical.” This workshop has been supported by the highly successful track-record of two British Council Researcher Links Workshops i) UK-Mexico "Biorefinery Research - Promoting International Collaboration for Innovative and Sustainable Solutions", Instituto Mexicano del Petróleo, 18-22 May 2015 and ii) UK-Malaysia "Bioenergy, Biorefinery, Bioeconomy: Promoting Innovation, Multidisciplinary Collaboration and Sustainability", Kuala Lumpur, 30 May-3 June 2016.

The widespread post-workshop news can be found in the following links:

<https://www.surrey.ac.uk/features/surrey-leads-uk-indian-workshop-sustainable-development>

<http://www.theibest.org/apps/blog/show/44885241-a-successful-uk-india-collaboration-towards-sustainable-development>

<http://epaper.livehindustan.com/epaper/Uttarakhand/Dehradun/2017-10-24/135/Page-7.html>

http://epaper.jagran.com/ePaperArticle/24-oct-2017-edition-Dehradun-city-page_6-3086-7292-104.html

<http://www.dailypioneer.com/state-editions/dehradun/workshop-begins-at-iip.html>

<http://www.rashtriyasahara.com/epapermain.aspx?queryed=14>)

The moments of the workshop were captured here: <https://photos.google.com/share/AF1QipP-JESfdFxCdse7d5inB0eQK7belwMjDLyrB2rVzuDHzt01v1GfYWr8bLB6jhOSdQ?key=RmRTVEhpt3oxQ3doX010Z1FULXJzdmdJeVZCMWV3>

Technical contributions are available here:

<http://www.theibest.org/the-biorefiner-2017>

<http://www.theibest.org/india-workshop-material>

A week long British Councils and Royal Society of Chemistry funded Researcher Links Workshop “Energy from Economic Development and Welfare”, 23-27 October, 2017, under the Newton Bhabha Programme has been concluded with remarkable success committing to bi-lateral cooperation between early career researchers in the UK and India. This workshop is supported by a Researcher Links grant under the Newton Bhabha Fund. The grant is funded by the UK Department of Business, Energy and Industrial Strategy (BEIS) and the Royal Society of Chemistry and delivered by the British Council. The workshop was coordinated by Dr Jhuma Sadhukhan of the University of Surrey and Dr Thallada Bhaskar of the Council for Scientific & Industrial Research (CSIR) lab, Indian Institute of Petroleum (pic below).



Through the week, several researchers from the two nations made presentations on their research areas and projects. The UK researchers emphasised the importance of source segregation of waste and System/Process Integration in order for effective valorisation into platform chemicals with multiple usages of their derivatives. The possibilities spanned a wide range of alternatives such as biofuels, cosmetics, pharmaceuticals, specialty chemicals, food ingredients, agrochemicals, pigments, biosurfactants, bioplastics, nutrients, sustainable energy such as solar and hybrid systems, energy storage systems, biodiversity and bioelectrochemical systems for resource recovery from wastes and CO₂ reduction. Research impact and output were linked with the UN Sustainable Development Goals. Presentations from the UK also included sustainable toilet systems with energy generation, and resource recovery from industries in the UK for circular economy. The Indian researchers presented thermochemical, biochemical, biotechnological and chemical systems for waste valorisation into multiple products, fuel additives, biofuel testing in real-time driving conditions and life cycle assessment. They also showcased a range of innovations in catalytic systems, several of which have been patented. There was good synergy between various presentations showing complementary skills and expertise. Researchers from the two nations have reached to a conclusion of applying whole system sustainability analysis to study performance of any technical system.

The workshop also included laboratory visits at CSIR-IIP to share complementary facilities, expertise and technologies having export potential with the UK researchers. Each day was concluded with a round table

discussion that eventually led to seven exciting project concepts in the area of waste valorisation for circular economy, hybrid energy systems, economic growth and sustainability, all presented by consortia evolved during the Workshop at the Valedictory session. The researchers showed serious commitments towards cooperation between two nations.

Last but not the least, an exhilarating cultural performance from the School OMM School of Dance and Music, which consisted of Kathak, Odissi and mixed dance styles and enriching experience of a tour at the Forest Research Institute, Dehradun, rounded off the week-long event. These were also essential components that contributed to the international camaraderie and collaborative spirit of the workshop. Some presentations from the workshop are included in this issue.



UK-Mexico-Malaysia Workshop Report

Biomass and Waste Valorisation Workshop

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An international collaboration workshop on biomass and waste valorisation was carried out at The University of Bath between Bath, Mexico and Malaysia partners on 25th May 2018. The objective of the workshop was to explore potential for collaborative research projects for an integrated approach to tackle the biomass and waste related problems in cities and rural areas in Mexico and Malaysia while leveraging UK's expertise. The workshop is part of the ongoing "NO-Waster" project funded by the University of Bath's Pathways to GCRF Scheme, led by Dr Sheila Samsatli from the Department of Chemical Engineering. The international partners included Dr. Jorge Aburto and

Elias Martinez from the Mexican Institute of Petroleum, Dr Alfonso Duran Moreno from Faculty of Chemistry of UNAM, and Dr Wan Azlina Ghani from University Putra Malaysia. From Bath there was participation from Dr Chris Chuck and Dr Sheila Samsatli and also counted with participation from the industry by Dr Rashmi Patil from Anaero Technology, Ltd. and Dr. Dhivya Puri from Fiberight Ltd. which can be strategic partners to deploy investigated technologies and models.

The workshop was well attended by Bath researchers and PhD students who listened to the wide variety of presentations on current waste situation in developing countries and the technologies that are being investigated. The topics of the presentations was on biochemical, thermochemical and integrated pathways to convert biomass and waste into useful products such as biofuels, chemicals and energy, and the related process modelling, policies, value chain optimisation, economic and environmental assessment. After the presentations, a discussion was carried out on common topics of interest. The discussion was supported by the introduction of the various international funding schemes by Tina Schilbach, International Partnerships Manager of the International Relations Office. Clear steps to follow for next GCRF call and other opportunities were identified among the collaborators.



Electricity Generation Potential from Empty Fruit Bunches in Peninsular Malaysia

Ida Fahani Md Jaye, Jhuma Sadhukhan, Richard J. Murphy

Palm Oil Industries in Peninsular Malaysia

Malaysia is the second largest producer of crude palm oil (CPO) globally after Indonesia and the world's largest PO exporter. In 2017, approximately 2.7 million hectares of oil palm were planted across the peninsular yielding an average of 1.6 tonnes of oil palm fresh fruit bunches (FFB). There are 235 palm oil mills operated to produce crude palm oil (CPO). The production of one tonne CPO requires 5.2 tonnes of FFB and generates about 5.2 tonnes residues. The production of CPO in 2015 generated roughly 94.2 million tonnes of residues which are the combinations of empty fruit bunches (EFB), mesocarp fibres (MF), palm kernel shell (PKS) and palm oil mill effluent (POME). These large quantities of residues have been perceived as a 'wastes' and are presently underutilized, bringing little or no economic value. The MF and PKS are currently being used as the feedstock for the boiler in the mills for internal heat and electricity consumption. However, the process has been made intentionally of a lower efficiency more as a means of disposal of these residues than as a way of optimally using them to generate more electricity and to curb carbon emission. To date, there are no specific utilization routes have been designated for EFB. EFB has commonly been dumped to undergo natural biodegradation since the ban on the incineration process by the Malaysian government in 2000, with the minimal amount being returned to the plantation area for mulching and as a bio-fertilizer.

Electricity Generation Potential from EFB

EFB accounted for 15% of the total accumulated residues from the milling process of CPO. It is estimated that 1.2 tonnes of EFB are produced from the production of one tonne CPO. Based on this abundant quantity and suitable chemical composition, EFB has been ascertained as having 520 MW electricity generation potential thereby reducing carbon emissions from the electricity generation sector. From this assertion, this research aims to estimate the actual electricity generation potential from the available EFB putting into consideration the technical and implementation constraints.

EFB is a solid residue produced after the removal of the palm fruits during the sterilization process in the mills. It is highly saturated with water from the sterilization process. The moisture content in EFB is estimated around 67%, a pre-treatment process to reduce the moisture content is necessary before it can be used as a feedstock for the boiler in the conventional steam-based electricity generation as shown in Figure 1.

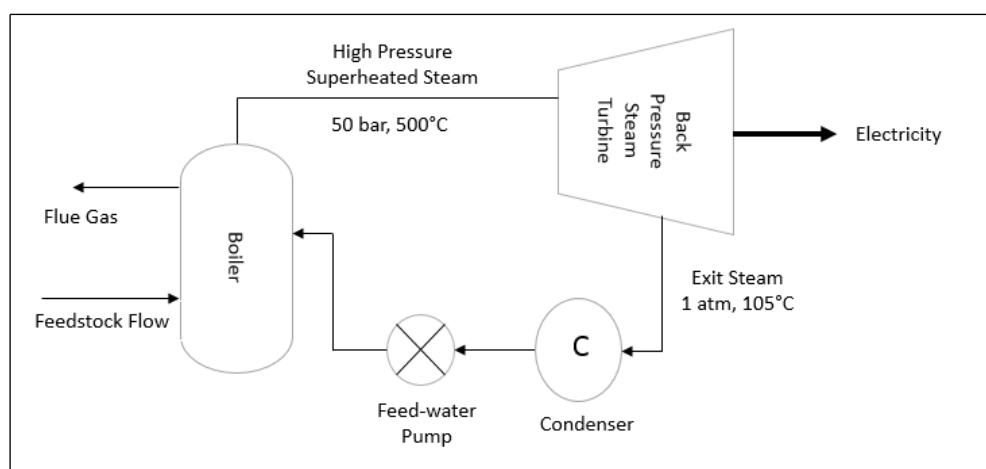


Figure 1. EFB-based Power Plant

The EFB-based power plant works in the sense that the EFB is combusted in the boiler to generate high-pressure superheated steam (HPSHS) to drive the back pressure steam turbine and rotary generator to generate electricity. Before being

used as the feedstock in the boiler, the moisture content of the EFB has to be reduced to 10-45% to minimize the effect of incomplete combustion. Mechanical drying is the most common pre-treatment process adopted to improve the combustible properties of EFB. Mechanical drying involving shredding the EFB into a smaller size and pressing to remove water in EFB are able to reduce the moisture content to 45%. The mechanical drying process can decrease the mass of the EFB by 23%, and the calorific value (CV) of semi-dry EFB is estimated at 8.5 MJ/kg. The conservative assumptions of 80% boiler efficiency and 35% electricity generation efficiency were used to evaluate the electricity generation potential of the EFB. Table 1 presents the electricity generation potential from the available EFB in the mills in Peninsular Malaysia.

Table 1. Electricity Generation Potential from EFB

EFB Available (t/yr)	Generation Potential from semi-dried EFB (MW)	Generation Potential from dried EFB (MW)
12,000	0.9	1.0
24,000	1.8	2.0
36,000	2.7	3.0
48,000	3.6	4.0
60,000	4.4	5.0
72,000	5.3	6.0
84,000	6.2	7.0
96,000	7.1	8.0
108,000	8.0	9.0
120,000	8.9	10.1
132,000	9.8	11.1
144,000	10.7	12.1

Further reduced the moisture content of EFB for instance to 11% will increase its energy density and subsequently the overall heat recovery efficiency. These are achievable through elevation of the CV of EFB and the effectiveness of the combustion process. With 11% moisture content, the CV is assumed to increase to 18.8 MJ/kg and boiler efficiency is at 90%. Higher electricity generation potential was projected from dried EFB (Table 1); however, approximately 0.6 – 5.3 MW of heat was required to dry the EFB. The tabulated electricity generation potential presented above confirmed the massive electricity generation potential from EFB. Based on this estimation, approximately 940 MW of electricity from EFB could be made available throughout Peninsular Malaysia which can accommodate about 13% of the national grid demand with a substantial amount of carbon emission reduction.

About the author



Ida Fahani is a doctoral researcher in the Centre of Environmental and Sustainability. She has a strong research interest in assessing the technical and techno-economic feasibility and environmental benefits of renewable electricity and promoting the sustainable transition towards low carbon future. This includes conducting the integrated assessment for new renewable energy technology adoption, developing investment mechanism, fostering institutional support and policy advice, and creating an advocates program to escalate the awareness on low carbon across the social metabolism.

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Research Showcase



This section is dedicated to organisations and members showcasing their latest biorefinery research. It is useful for presenting your group or team at your organisation working on biorefinery related topics. After the successful biorefinery workshops in Mexico and Malaysia, the number of IBEST members have significantly grown to more than 80 organisations. This number is constantly growing as more and more researchers, engineers and technologists get to know the IBEST and its activities. Undoubtedly, spreading the word by active members have also contributed to an increase in the number of organisations that have become members.

Microwave Vacuum Pyrolyzer (MVP): An Innovative Biomass Waste Transformer

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Abstract (50 words)

Microwave Vacuum Pyrolyzer (MVP) is a prototype incorporating microwave radiation, pyrolysis & vacuum condition to convert biomass and waste materials into useful products. The MVP shows advantages in providing fast heating (up to 100 °C/min), extensive pyrolysis cracking capacity, short process time (< 40 min), and low process temperature (< 500 °C).

Introduction

The palm oil industry constitutes about 8% of the gross domestic product (GDP) in Malaysia and this results in the production of about 80 million tons/year of biomass wastes containing empty fruit bunches, mesocarp fiber and palm kernel shell. It is estimated that the production of these biomass waste will achieve 85-110 million tons/year by 2020. Thus, efforts have been made by Malaysia government via policies such as 11th Malaysia Plan, Malaysia Biomass Industry Action Plan 2020, and National Biomass Strategy 2020 to either reuse these biomass waste for composting, or convert them into value-added products such as fuel, bio-based chemicals and activated carbon (AC). Thus, our research aims to support these policies by developing microwave pyrolysis process to transform these biomass waste into biofuel products (bio-oil, syngas) and activated carbon that can be used in multi-applications.

Biomass recovery using microwave pyrolysis represents a promising solution to divert the waste from increasingly impractical disposal methods such as landfilling and combustion. Microwave pyrolysis is a thermo-chemical decomposition process performed in an inert condition using microwave radiation as the heating source. It offers a rapid and selective heating mechanism over other thermal decomposition processes using conventional heating source such as oven and furnace in which the microwave radiation

targets mainly to material with good microwave absorbency. The heat energy is rapidly generated from the frictions between the atoms and molecules within the material which subsequently leads to rapid heating of the material, thus a relatively shorter process time is required to heat up the material to achieve a desired high temperature in order for extensive pyrolysis to occur. Other advantages shown by microwave pyrolysis include better process control in terms of quick start-up and shutdown, a more uniform heat distribution and increased production rate.

Recently, our team have improved the microwave pyrolysis process by eliminating the use of nitrogen gas to maintain the inert pyrolysis condition and this is replaced with the use of a vacuum condition to perform pyrolysis reaction (termed 'microwave vacuum pyrolysis'). The use of vacuum condition can reduce the production cost since the constant use of nitrogen gas is no longer needed. On top of that, the vacuum condition provides advantages in preventing uncontrolled heating inside the reactor and avoiding adverse chemical reactions such as re-condensation of volatiles that can subsequently affect the quality of product, while simultaneously allowing the control of the residence time of the pyrolysis volatiles in the reactor.

Our research group is formed by 10 team members whom have been actively researching on microwave pyrolysis. Our works since 2008 have led to patent filing for the pyrolysis method, publication in high impact journals, awards in research and innovation exhibitions such as *Special Award* in International Conference and Exposition on Inventions by Institutions of Higher Learning (PECIPTA) 2017, *Grand Price* in Seoul International Invention Fair (SIIF) 2016, *Best Community Project Award* in Novel Research and Innovation Competition (NRIC) 2016. Up to 14 research grants worth nearly RM 1.7 million have been secured involving collaboration with scientists from various institutions (Cambridge University, Monash University, University of Tianjin, RMIT, University of Exeter, Southampton University) for prototype development and optimization. In addition, partnerships and investments have been received from the industries (e.g. Pollution Engineering Sdn Bhd) for prototype development and up-scaling, product distribution and application.

Description of MVP

Figure 1 shows the schematic diagram of the microwave vacuum pyrolyzer, comprising four main components: i) microwave oven to provide microwave radiation as heating source, ii) temperature controller to monitor, record and control the process temperature, iii) condensation system for cooling and collecting liquid product, and iv) vacuum pump to create inert environment for pyrolysis reaction. To the best of our knowledge, no research has been reported on microwave vacuum pyrolysis of biomass and waste materials except some of the recent work published by

our group. Hence, our work represents an original approach to apply microwave vacuum pyrolysis in converting biomass waste into value-added products.

Table 2 shows the comparison of process features between our lab-scale prototype with the other microwave pyrolysis equipment reported in the literatures. In general, our method shows higher heating rate (up to 100 °C/min) and shorter process time (≤ 30 mins) than the method reported by other literatures, indicating that MVP can be a potentially time-saving approach.

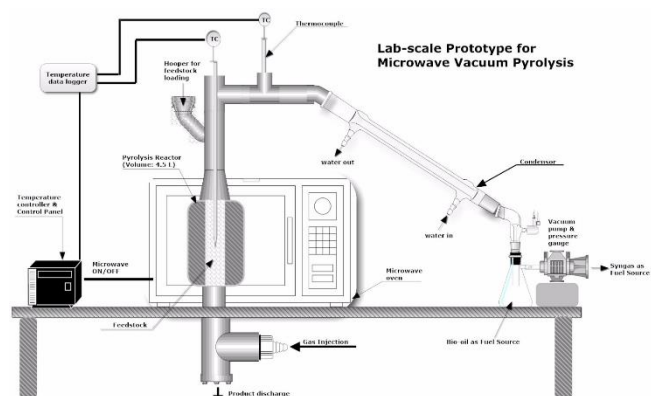


Figure 1 Schematic diagram of microwave vacuum pyrolyzer.

Research Impact

Microwave vacuum pyrolyzer (MVP) represents a promising approach in promoting the use of renewable resources and also diverting wastes from current yet increasingly impractical and environmentally-harmful disposal techniques such as combustion (with associated toxic emissions and greenhouse gas release) and landfilling (with considerably long decomposition times and the risk of undesirable leachate leaking out to the surrounding environment). MVP also serves an effort to support the needs of K-economy and the New Economic Model of Malaysia by developing an innovative pyrolysis technology to sustain growth of skilled human resources in Waste Treatment and Recovery, while simultaneously aims to sustain the growth and increase the generation of revenue of the palm oil industry in Malaysia by using the pyrolysis technology to not only

treat the biomass wastes or residues generated from the palm oil mills, but to transform them into value-added materials.

Table 1. Process Features and Comparison

Process Features	MVP	Literature reported
Microwave power	≤ 700 W	300 – 1000 W
Process temperature	≤ 500 °C	400 – 1200 °C
Heating rate	up to 100 °C/min	5 – 30 °C/min
Process time	≤ 30 minutes	2 – 8 hours

Recent Publications

1. Liew RK, et. al., Microwave pyrolysis with KOH/NaOH mixture activation: A new approach to produce micro-mesoporous activated carbon for textile dye adsorption. *Bioresour. Technol.*, 2018, 266, 1-10.
2. Wan Mahari WA, et. al., Microwave co-pyrolysis of waste polyolefins and waste cooking oil: Influence of N₂ atmosphere versus vacuum environment. *Energy Convers. Manage.*, 2018, 171, 1292-301.
3. Nam WL, et. al., Production of bio-fertilizer from microwave vacuum pyrolysis of palm kernel shell for cultivation of Oyster mushroom (*Pleurotus ostreatus*). *Sci. Total Environ.*, 2018, 624, 9-16.
4. Liew RK, et. al., Oil palm waste: an abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-applications. *Process Saf. Environ. Prot.*, 2018, 115, 57-69.

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Sustainable Future Bio-plastic through Co-pyrolysis biomass and plastic wastes.

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- c. Dep. Chemical Eng. University of Bath, UK.

Abstract

In-situ co-pyrolysis of bagasse pith and poly-ethylene-terephthalate (PET) were performed over mixture HZSM-5 (Si/Al ratio of 23) and Na₂CO₃/γ-Al₂O₃. Optimization of process showed the maximum production of aromatics (22%) and BTXE (19%) were obtained the biomass to plastic ratio of 5. Moreover, the reduction of GHG emissions (CO₂ and CO) while sodium based catalyst mixed with HZSM-5 catalyst.

Introduction

Current world shows that 300 million tonnes of plastics in the waste upstream, with more than 25 million tonnes/year disposals in the European Union, which 39% was landfilled (Ratnasari et al, 2017). The plastic wastes make serious problems to the environment and has determined impact on human health. Although incineration or landfilling of plastics may produce energy, but it cause to release the toxic compounds such as SO₂, NO_x, dioxins, and furans into the atmosphere.

Although many studies have conducted the thermal and catalytic co-pyrolysis of the biomass-plastic mixture over zeolite catalysts, but most of them has challenged with short life-time of zeolite catalysts and coke formation during the process. In addition, the optimizations of co-pyrolysis process, optimal biomass to catalyst ratio on the yield of aromatic and olefin compounds are not well understood.

The objective of this paper is to study on the role of Na₂CO₃/γ-Al₂O₃ mixed with HZSM-5 on the life-time of catalyst. In addition, the effects of the PET to biomass ratio and reaction temperature were investigated to ascertain the optimal reaction conditions for maximizing the aromatic (BTX) yield from fast co-pyrolysis of biomass and PET.

Catalytic Co-pyrolysis

Catalytic pyrolysis of pith over HZSM-5 predominantly converted the oxygenated compounds into aromatic hydrocarbons. The compounds identified over HZSM-5

were furan, benzene, toluene, xylenes, ethylbenzene, indenes, and naphthalene completely totally different from non-catalytic fast pyrolysis (Figure 1).

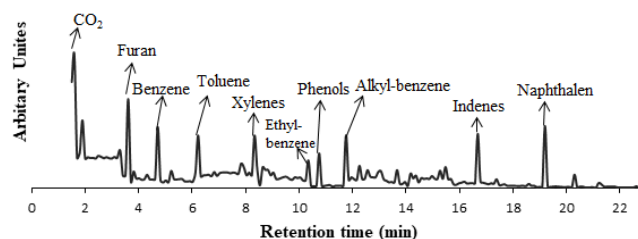


Figure 1. Catalytic pyrolysis of Pith of bagasse with HZSM-5

In fact, catalytic fast pyrolysis of biomass is a method to produce deoxygenated pyrolysis liquids, but it is still a low-efficiency process because catalytic mechanisms lead to loss of hydrogen from the biomass consequently coke formation and short life-time of catalyst. This loss can compensate by mixture the plastic as hydrogen-enrich reactant. In addition, The meaningful changes CO₂ formation (18%) has shown the γ-Na₂CO₃ displays toward deoxygenation without decreasing the aromatics and olefins at HZSM-5 to γ-Na₂CO₃ ratio of 4 (Figure 2).

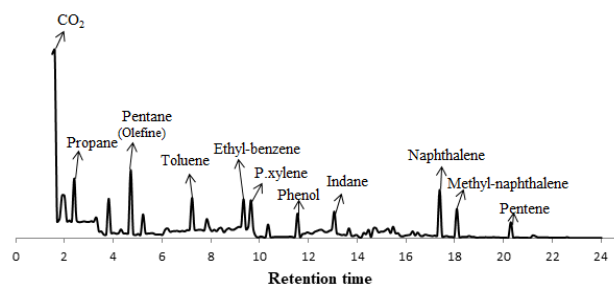


Figure 2. Co-pyrolysis of Pith of bagasse with PET over HZSM-5/γ-Na₂CO₃ catalyst.

Results and discussion

The effect of HZSM-5 addition was established within the range from 1 to 5 ratios in this study. The phenols showed the most significant effects on co-pyrolysis products by adding the HZSM-5, whereas the BTXE showed less significant effect. The best HZSM-5 to γ-Na₂CO₃ ratio was detected at around 4 (Figure 3).

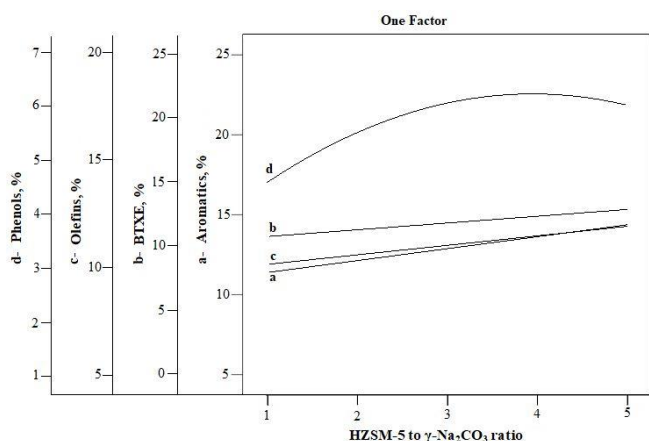


Figure 3. The independent effect of HZSM-5 to γ -Na₂CO₃ on a) Aromatics, b) BTXE, c) Olefins, and d) Phenols.

In comparison of HZSM-5 to γ -Na₂CO₃ ratio, the biomass to PET ratio showed a greater effect on the co-pyrolysis valuable products (Fig 7). For instance, the BTXE was increased by increasing the biomass to PET ratio, while an increasing HZSM-5 to γ -Na₂CO₃ did not show significant affect it. The optimal biomass to PET was detected at ratio of 5 when the maximum aromatics, BTXE, olefins and phenols were obtained (Figure 4).

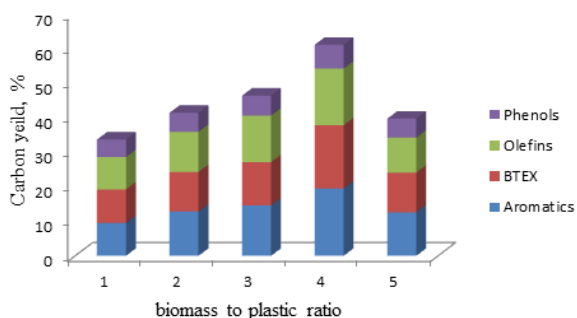


Figure 4. The effect of biomass to plastic ratio on the co-pyrolysis products distributions

Moreover, the temperature of 700 °C was selected as optimum temperature for maximum production of bio-based products during co-pyrolysis process (Figure 5).

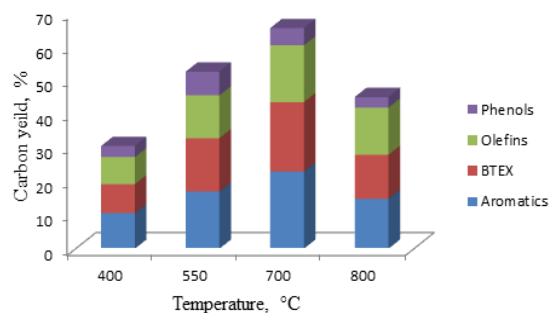


Figure 5. The effect of temperature on the co-pyrolysis products distributions

Research Impact

The view and research works of the authors expressed herein can reduce the disposal of these waste polymers in landfills, reduce our dependence of fossil fuels, and move toward to sustainable bioplastic production through co-pyrolysis of biomass and plastic wastes.

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Microwave Steam Activator

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Abstract

Microwave steam activator, is a prototype combining the use of microwave heating and steam activation to produce high grade activated carbon continuously from waste palm shell. The prototype provides a fast heating rate of up to 150 °C/min, short process time (15 min) and high steam activation temperature (above 500 °C).

Introduction

Steam activation is commonly employed for pilot scale and mass production of activated carbon in high temperature rotary kiln. However, the existing technology uses conventional heating and reactor that are less efficient, requires high maintenance cost and energy consumption, low heat transfer efficiency, and shows difficulty to fulfil the stringent legal requirements on the gas emissions to the atmosphere during the production process.

Microwave steam activator shows potential as an alternative to overcome the limitations shown by conventional heating. The use of microwave heating provides rapid and volumetric heating mechanism by inducing dipole rotation in atomic scale that creates a frictional force between atoms and molecules within the material. It shows better process control in terms of quick start-up and shutdown compared to conventional heating that requires a certain time to heat up or cool down. Thus, the application of microwave steam activator in the production of AC could potentially lead to

an energy-efficient, shorter process time, and improved yield of AC product.

The production of activated carbon from waste palm shell was conducted in a self-purging atmosphere, representing a cost-effective approach for both carbonization and activation due to no extra cost for nitrogen gas purging is needed along the process. The steam activation was performed to convert the biochar derived from waste palm shell into AC over a range of activation temperature (400-700 °C), activation time (5-15 min) and steam flow rate of 5 g/min in order to determine the yield and adsorption capacity of the resulted AC.

The resulting AC was characterized for its porous characteristics, surface morphology, proximate analysis and elemental compositions. The recovery of AC with desirable properties suggests the great potential of the microwave-steam activation as a promising technology to produce high grade adsorbent for dye removal. The optimization results showed that AC with the maximum efficiency of methylene blue (38.5 mg of methylene blue / g of AC) can be obtained by performing steam activation under 10 min of microwave heating at 550 °C.

Description of MSA

Figure 1 shows the schematic diagram of the microwave steam activator, comprising five main components: i) microwave generators ii) thermos sensor controller to monitor the process temperature, iii) condensation system, iv) mini boiler to generate steam for feedstock activation and v) auger system for sample feeding and discharge purpose.

Figure 2 shows the surface morphology of produced activated carbon with uniform and well-developed porous structure with larger pore sizes observed on the surface of AC in which small pores were formed on the larger pores.

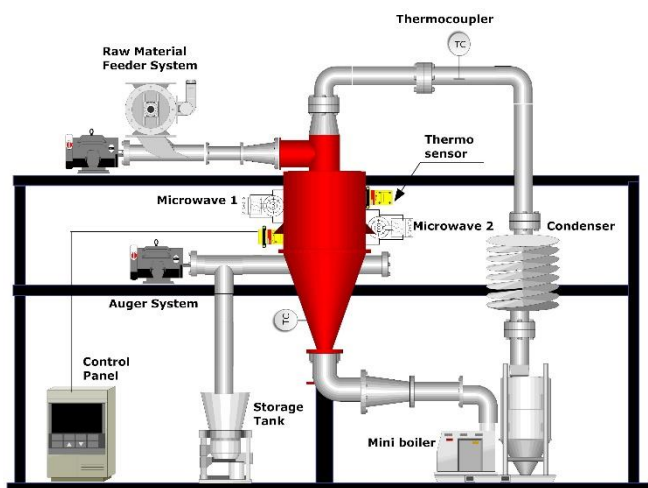


Figure 1 Schematic diagram of microwave steam activator.

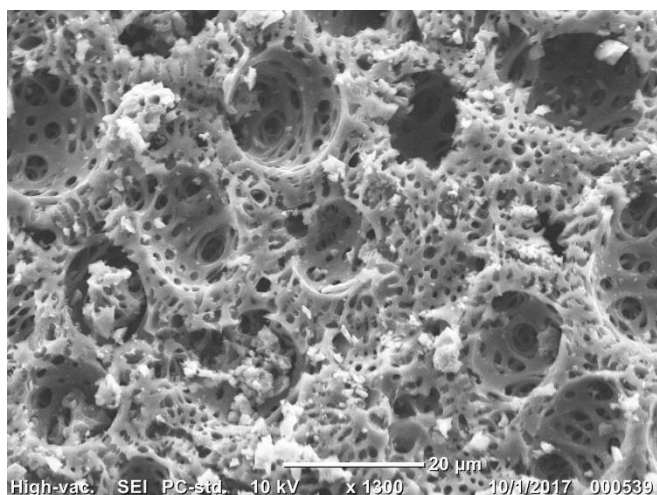


Figure 2 Surface morphology of activated carbon

Optimum condition of microwave steam activator to produce activated carbon (AC):

- Reaction temperature: 550 °C
- Reaction time: 10min
- Steam Flow rate: 5 g/min

Results analysis

- Fixed carbon of AC: (73 wt%),

-BET surface area of AC: 571 m²/g

-Microspore surface area of AC: 763 m²/g

- Surface morphology of AC: hard texture, uniform and well-developed porous structure

- Estimated production cost of AC: RM 2.90/kg

Research Impact

Microwave steam activator shows better process control which lead to an energy-efficient, shorter process time, and improved yield of AC product. This prototype can potentially produce AC at cheaper cost and with desirable microspores for use as adsorbent for wastewater and flu gas treatment. or residues generated from the palm oil mills, but to transform them into value-added materials.

Recent Publications

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Anaerobic co-digestion of the organic fraction municipal solid waste with liquid cheese whey: integrated management and calorific value

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Abstract

The main aim of the study was to evaluate the codigestion performance of the organic fraction municipal solid waste (OFMSW) with liquid cheese whey (LCW). An extra effort was made to calculate the calorific value of the OFMSW, BCW, and the mixture codigested.

Introduction

Organic waste varies as a function of affluence in each country however; it can be account for slight more than 50% of the total waste generation rate and are broadly classified in several waste streams.^[1] In this study, 60% average waste composition in Mexico is categorized as organic matter from the municipal solid waste and 37% from dairy industry, representing a source of valuable substrates for anaerobic digestion and addressing a clean alternative renewable energy source instead of being a public safety issue if not managed accurately.^[2-5]

Materials and methods

The experiment was carried out until final production of biogas in batch assays at 35 °C. The maximum biogas potential of the co-substrates (LCW and BCW) was assessed by setting up a biochemical methane potential (BMP) test using the Bioprocess Control System. In the proposed methodology there are four stages.

Obtaining and preparing samples

Sampling was performed using the coning and quartering method, based on and in accordance with the Mexican standard (NMX-AA-015-1985).^[6]

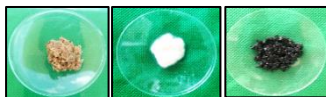


Figure 1. Samples left: OFMSW, middle LCW and right sludge

Characterization of substrates

The reactors were sampled once, being shaken vigorously to ensure complete homogenization of the medium and prior to being sealed with rubber stoppers. All analyses were performed in triplicate for the characterization of the OFMSW, and LCW Elemental

analysis (dry base), volatile solids (VS), and chemical oxygen demand (COD) were analysed (using fresh material) according to standard procedures.^[7]

Operational conditions

A total of three treatments of the organic fraction of municipal solid waste (OFMSW) were prepared based on the cosubstrate liquid cheese whey (LCW).^[3, 5]

Reactor capacity: 500 mL
Workload: 400 mL
Temperature: 35 ° C
Time: 21days



Figure 2. Operational conditions

Calorific value

Based on the results obtained from the characterization of the substrates used in this study, first, the values of the elemental content (CaHbOcNd) were used to calculate the molecular weight of the substrate to be evaluated (Eq. 1).

$$\text{Substrate formula } C \left[\frac{a \div 12}{d \div 14} \right] H \left[\frac{b}{d \div 14} \right] O \left[\frac{c \div 16}{d \div 14} \right] N_{[1]}$$

Results and discussion

The biogas and methane production from the organic fraction of municipal solid waste (OFMSW) co-digested with liquid cheese whey (LCW) and beef cattle waste (BCW) was assessed for each of the different treatments.

Characteristics of the substrate

Chemical analysis was performed for the tested substrates to identify trends in degradation behavior according to assumptions of carbohydrate, lipid, and protein contents. The characterization of the substrates (wet matter) in terms of pH, TS and VS contents are summarized in Table 1.

Table 1. Characteristics of the tested digestion substrates and sludge.

Parameter	Unit	OFMSW	LCW	Sludge
pH		5.05	3.67	6.71
COD	gO ₂ /kg	50	72	47
TS	g/kg	130	64	61
VS	g/kg	125	54	59
NH ₄ -N	g/kg	0.2	0.3	-
Nitrogen*	g/g	2	2	-
Carbon*	g/g	44	36	-
Hydrogen*	g/g	5	6	-

Monodigestion vs Codigestion

Biogas is mostly a mixture of methane (CH₄) and inert carbonic gas (CO₂), it is described based on its chemical composition and the physical characteristics, which result from it. Cumulative methane production yields related to the different experiment, are reported in Figure 3. A parallel anaerobic codigestion carried with the mix of OFMSW + LCW was performed under identical conditions so to compare the performances of the monodigestion processes with the ones mixed.

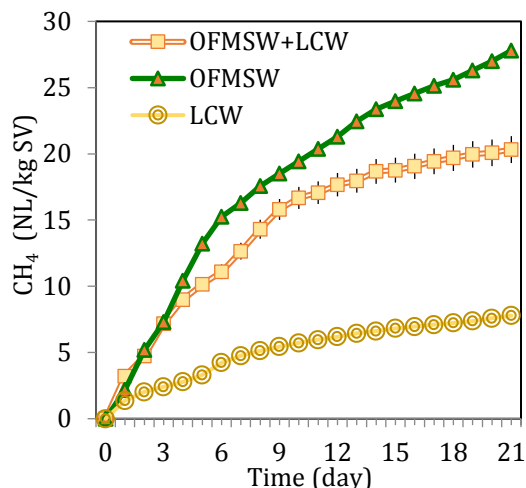


Figure 3. Daily accumulated methane production rates in the anaerobic digestion of the organic fraction of municipal solid waste (OFMSW), alone and mixed with liquid cheese whey (LCW).

Calorific value

In this study, the chemical thermodynamics of the substrates combustion reaction were modelled. Table 2 shows the most closely approximated empirical formula of the mix from the evaluated substrates. These molecular formulas correspond to that of organic compounds. All reactions were highly exothermic.

Table 2. Characteristics of substrates

	OFMSW	LCW	OFMSW +LCW
Moisture (%p/p)	86	94	93
Approximate empirical formula	C ₂₆ H ₃₅ O ₁₆ N	C ₂₁ H ₄₂ O ₂ N	C ₂₄ H ₃₇ O ₁₆ N
MW	613	573	600
Δhc (MJ/mol)	-9.54	-8.01	-1.57
Δhr (MJ/mol)	-4.88	-5.3	-43.23
C/N	22	18	21

Research Impact

This work aims to advance the understanding of the anaerobic digestion of the OFMSW that occur during the mixing with LCW. Therefore, all reactors were kept in a water bath at 35 °C (±0.5 °C) and continuously mixed to

minimize mass transfer limitations. To compare the degradation of the organic substrates in the anaerobic reactors, three critical parameters were considered: TS, VS, and COD. Anaerobic conditions in the reactors were established by flushing the headspace with nitrogen gas. The reactors were started under similar operational conditions. Moreover, the calorific value of the substrates and their mix were calculated systematically under specific operating conditions and using the modified Dulong formula.

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Material Flow Cost Account (MFCA)-based Approach for Synthesis and Optimization of Wastewater Treatment Plant

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Abstract

Wastewater treatment (WWT) is a mandatory process in every biorefinery process. However, with countless WWT technologies prevailing in the market, the selection of WWT technologies are usually based on vague assumptions which results in subsidiary remittance and extra disbursement to the company. Therefore, this research aims to develop a novel MFCA-based approach as a primary decision-making tool in selection of WWT technologies which meets the constraint of treated effluent quality while maximising the recovery of investment cost.

Introduction

Material Flow Cost Accounting (MFCA) is a management tool which quantifies material flows across a production process in both physical and monetary values. As MFCA tracks the monetary value in the streamline of a process, this concept was proposed to be incorporated into waste recovery prioritization by Wan et al. [1]. Most conventional accounting practices in industrial manufacturing process only consider operating cost such as material cost, power cost and system cost. The novel parameters such as hidden cost (HC) and carry forward cost (CFC) proposed by Wan et al. [1] were always overlooked. Hidden costs are the incurred cost that was embedded in each stream. Elsewhere, carry forward cost (CFC) is the HC that are carried forward along the stream and will be incurred in the next stage of process. As hidden costs are costs associated to the stream, it projects an overview of the breakdown of working capital investments within the streams which allows monitoring of flowrates in a process. Hence, hidden costs in waste streams or waste generation cost (WGC) should be kept to minimum to prevent lost in profit. With similar concept, this approach can be adapted into optimization of wastewater treatment process in this work since wastewater entering the WWT process would generate treated water that would be recycled back to the manufacturing process and sludge cake waste that will eventually be disposed to the environment which is an unrecoverable cost. Therefore,

the optimization objective in this work is to minimize sludge cake generation cost.

Methodology

Generic superstructure is established to project all possible pathways that could be generated based on interlinks between wastewater treatment technologies at different treatment stages as shown in Figure 1.

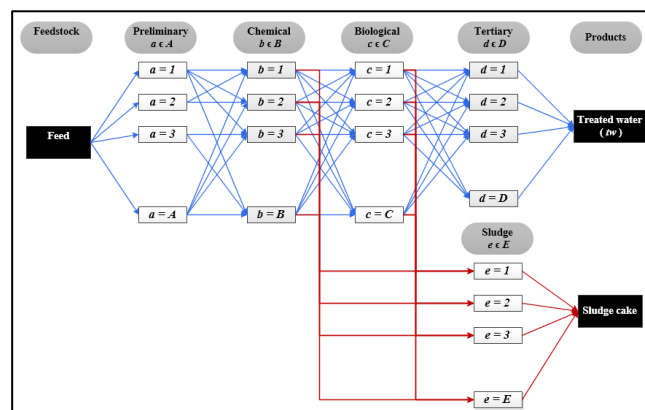


Figure 1. Generic superstructure of conventional wastewater treatment process.

Next, a MFCA-based approach is developed to identify a wastewater treatment pathway route which complies with the constraint as well as meeting the objective for optimization process. The constraint in the developed approach is the contaminant concentration of treated wastewater which must comply to the government standard effluent discharged regulations. Meanwhile, the optimization objective in this work is to minimize the waste generation cost. To develop the approach, a series of equations are formulated based on the generic superstructure which includes volumetric flowrate balance ($\frac{m^3}{day}$), contaminants (e.g. COD, BOD, TSS, OG) mass balance and cost computations (e.g. material cost, power cost, hidden cost, carried forward cost). These equations are the core principle of this developed approach where the formulation of these equations produces a framework which determine the optimized wastewater treatment pathway. To illustrate the approach, an industrial case study superstructure on organic wastewater treatment plant for a biorefinery process has been developed as shown in Figure 2. Subsequently, the series of formulated equations are then coded into a commercial optimization software, LINGO Version 17, with computer specification of Intel® Core™ i5-6402P @ 8 Gb RAM, x64-based processor for process optimization according to the superstructure of industrial case study.

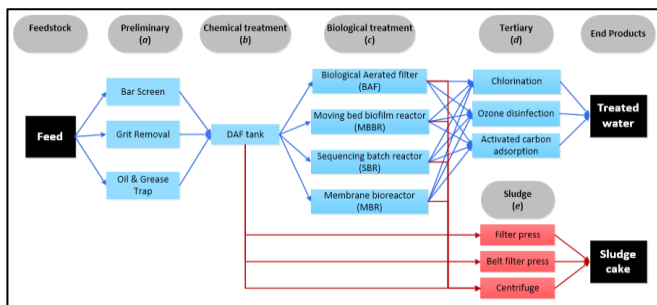


Figure 2. Case study superstructure of organic wastewater treatment plant for a sago-based biorefinery.

Results and discussion

The obtained solution is a global optimized solution by solving the proposed mathematical model which is a mixed integer nonlinear programming (MINLP). Based on the global optimum solution results, the optimum wastewater treatment pathway for the proposed case study is included oil and grease trap, dissolved air floatation (DAF) biological aerated filter (BAF) and belt filter press as shown in Figure 3 along with the contaminant concentration. The concentration of contaminants in the treated water complies with ENVIRONMENTAL QUALITY ACT, 1974, the Malaysia Environmental Quality (Industrial Effluents) Regulations 2009: Standard A. The hidden cost (RM/day) which are associated to each stream can be computed based on the operating unit cost as shown in Figure 4. As illustrated, the hidden cost which are embedded in each stream are consecutively accumulated and carried forward to the next stage. In this case, for every RM 16,661/day spent on the wastewater treatment process, minimum of RM 814/day value of sludge cake will be disposed which is approximately 5% from the investment. Meanwhile, the remaining 95% of the investment will be utilised back into the sago biorefinery process. Therefore, it is concluded that the developed MFCA approach is able to determine the pathway with minimum waste generation cost (sludge cake cost).

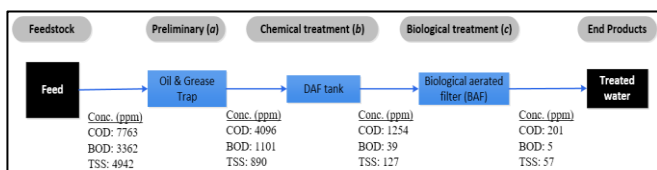


Figure 3. Case study results for optimum pathway.

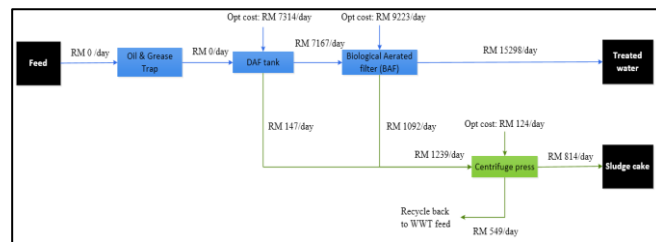


Figure 4. Case study results on cost computation.

Research Impact

This research work contributes a MFCA-based approach for optimization and synthesis of wastewater treatment pathway. Material flow cost accounting (MFCA) was adapted to access the monetary values embedded in the streamlines. In terms of sustainable development, the developed approach had incorporated the economic aspect by minimizing the waste generation cost of the wastewater treatment process which are rarely included by the current published research work. Furthermore, the treated wastewater generated with this approach will comply with the environment regulation, minimizing water pollution. Subsequently, reducing water pollution will benefit to all human welfare in terms of social aspect. Therefore, this provides a promising mathematical model to industry decision makers as a guide in selecting the wastewater treatment technologies for their WWTP and also helps in verifying the feasibility of their respective processes. Consequently, industrial decision makers would be able to synthesize a cost-effective wastewater treatment pathway to maximize the profit gain of company, at the same time, ensuring the discharge treated water will always comply with the discharge standard regulation.

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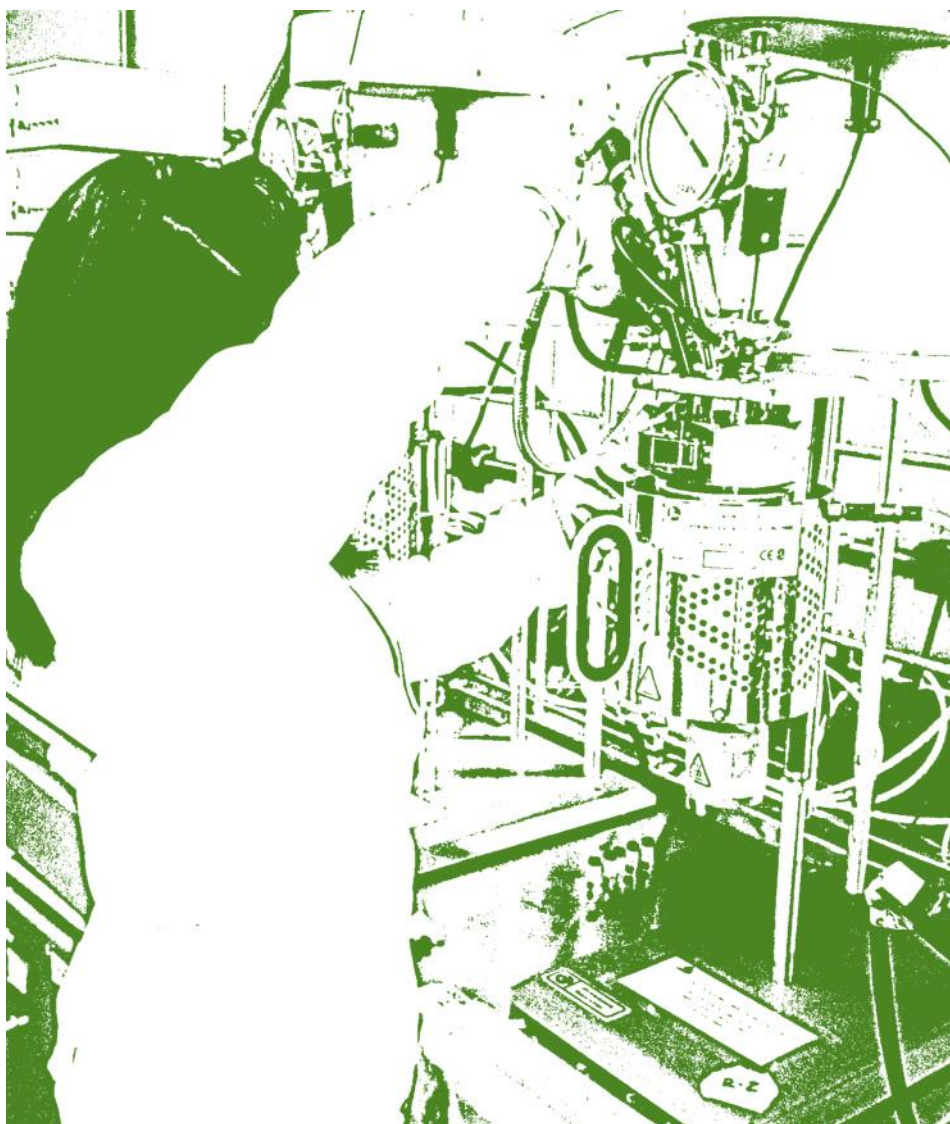
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New Biorefiner

This section is dedicated to members presenting their profile as a **New Biorefiner** by either doing research, as process engineer, chemist, biologist, and any background. Like all the IBEST members, a New Biorefiner is committed to advance the field and translate knowledge into real impact to help biorefineries deliver their full potential as an enabler of better economic opportunities and social welfare.





Numerical modeling of bioelectrochemical systems

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My work is currently focussed on development of numerical models for bioelectrochemical systems (BESs). BES such as microbial fuel cell or microbial electrosynthesis system use microorganisms to facilitate oxidation/reduction processes through the release/capture of electrons from an electrode. These systems have drawn great attention in recent years as an emerging technology for energy-efficient wastewater treatment, desalination, electricity generation, and chemical production.

Significant amount of energy and billions of pounds are spent every year to treat the industrial/domestic/municipal wastewater. However, this wastewater which typically contains a lot of organic compounds can actually be used as a valuable resource using BESs. BES, like any other electrochemical cell (e.g. Battery), consist of an anode, cathode and a separating membrane (optional), but the difference lies in how the electrochemical reaction is catalysed. In BES, at least one or both of the electrode reactions are catalysed with the help of microorganisms. By combining living biological systems with electrochemistry, BES makes it possible to utilize the chemical energy from wastewater and generate electricity (microbial fuel cells, MFCs), hydrogen (microbial electrolysis cells, MECs) or value-added chemicals (microbial electrosynthesis, MES)¹.

The type of bacterial population, electrodes and substrates used at the anode and cathode and many other biological and design parameters determine the total cell potential (E_{cell}) of BES, which if positive ($E_{cell} > 0$), the BES can be used to generate electricity and when negative ($E_{cell} < 0$), additional external power may be required to reduce the electron acceptor at the cathode. These two scenarios are described in the schematic of BESs as shown in Fig. 1.

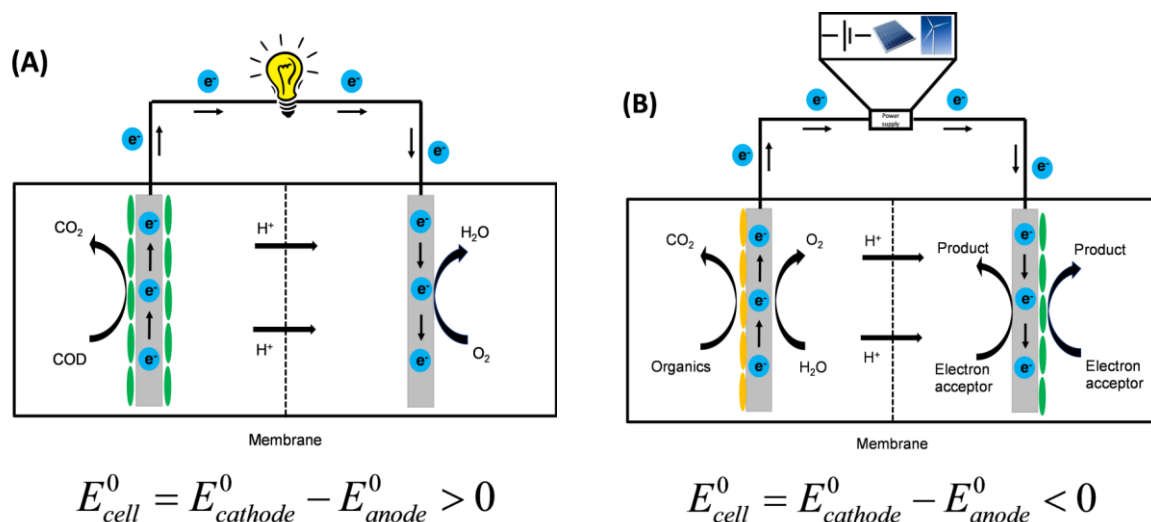


Fig. 1. Schematic of bioelectrochemical systems for two scenarios, (A) Cell potential if positive, typical microbial fuel cell (B) Cell potential is negative (requires additional voltage).

Past research on BES has extensively focused on experimental studies, while mathematical modelling has remain neglected. The development of mathematical models will be critical to the optimization and scaling of

BES systems in future. In my research work, am developing comprehensive mathematical models that can not only provide insight on the governing mechanisms of BES but also on how such systems will affect the environment. Such numerical models will compliment experiments and help to develop this technology towards commercialisation at a reduced cost and time.

Our team has recently developed a novel framework, integrating dynamic simulation (DS), life cycle assessment (LCA) and techno-economic assessment (TEA) of a BES to study the wastewater treatment by removal of chemical oxygen demand (COD) by oxidation in anode and thereby harvesting electron and proton for carbon dioxide reduction reaction or reuse to produce products in cathode (using formic acid synthesis as a case study)². Dynamic simulation (DS) results showed that increase in initial COD concentration and applied potential increases COD removal and product formation (in this case formic acid) rates. DS correlations were used in LCA and TEA for holistic performance analyses.

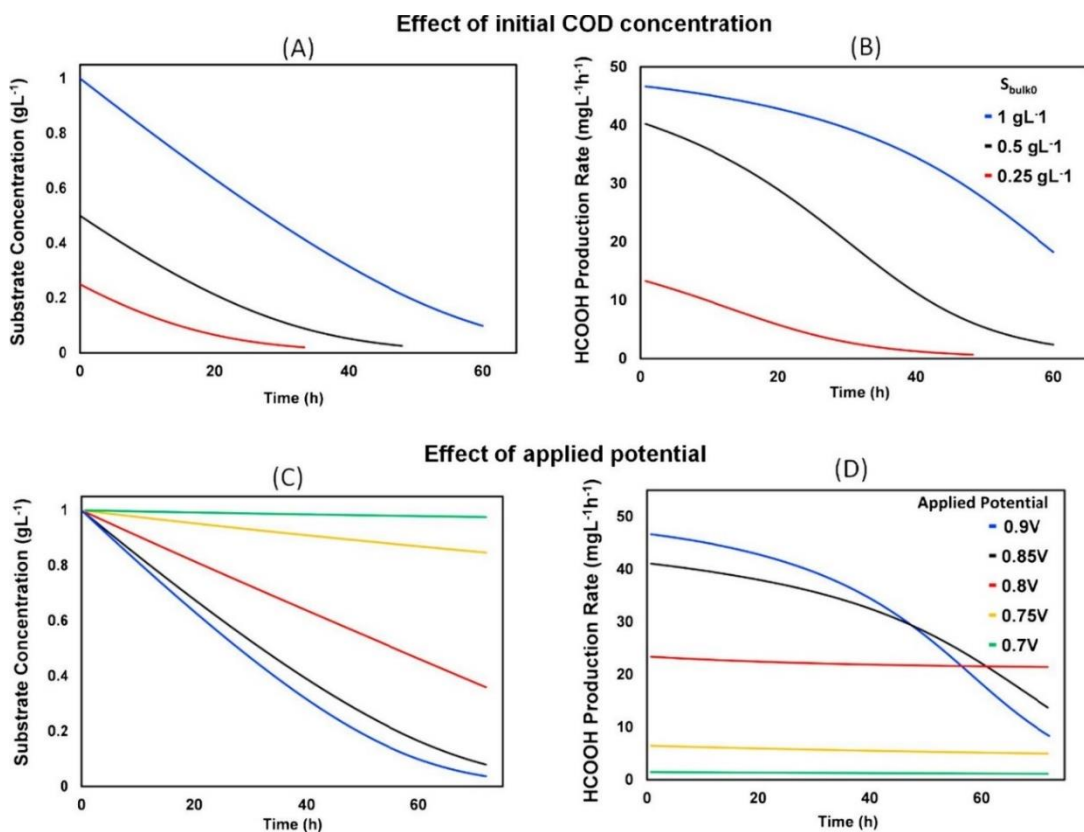


Fig. 2. Change in substrate concentration (gL⁻¹) and HCOOH production rate (mgL⁻¹ h⁻¹) as a function of time for three different values of initial COD concentration (A & B), and for five different applied potential values (C & D).

In future, we are planning to develop more comprehensive 2D/3D mathematical models of BES to gain a deeper understanding of the biological, physical-chemical and electrochemical processes that influence BES performance. The research outcomes will contribute directly towards popularizing such sustainable technologies for bioproduction of wide range of chemicals (MES, MEC) as well as generation of renewable electricity (MFC) from wastewater.

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Hydrothermal Treatment of Organic Residues

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The Department of Chemical, Industrial and Food Engineering in Universidad Iberoamericana Ciudad de México has been conducting cutting edge research into biorefining for several years. These works have been led by M.C. Lorena Pedraza and have focused primarily in the study of fermentative processes mainly to recover high value products with application in the food industry like xylitol. Turning waste into fuel and value added products is key to ensure that we head into a cleaner and more sustainable future. In this sense, we are expanding the scope of our research into the application of hydrothermal processes to upgrade biomass and organic waste.

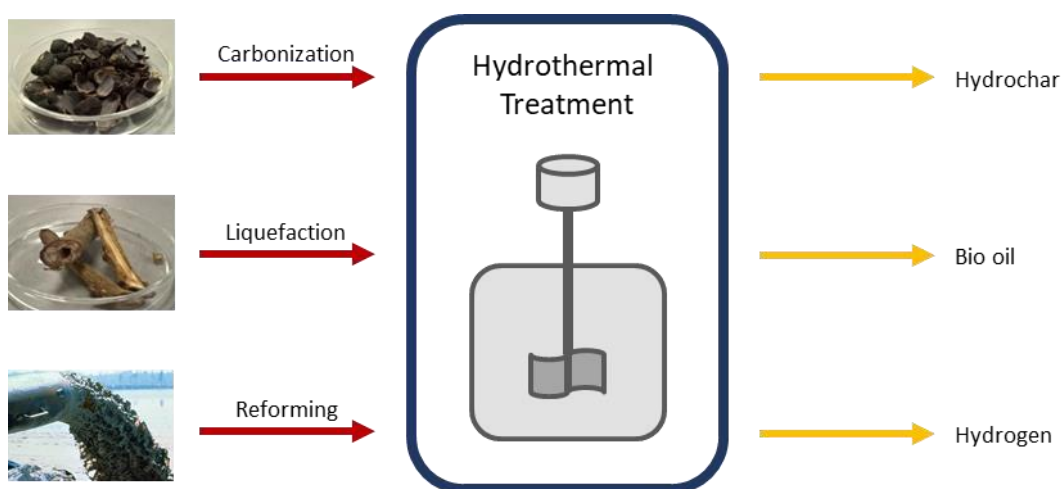


Figure 1. Hydrothermal treatment of organic residues to produce fuel.

Hydrothermal processes are those where water at high temperature is used as reaction medium. These are particularly interesting as water is regarded as a green, non-toxic and environmentally friendly solvent that can change its properties with small changes in reaction temperature and pressure.

Therefore, reaction conditions will determine the nature of the products obtained from the process as shown in figure 1. Hydrothermal carbonization (180-250 °C and autogenous pressure) to obtain preferentially an upgraded solid fuel, hydrothermal liquefaction (280-370 °C and 10-25 MPa) for a high quality bio oil and catalytic reforming (aqueous 200-250 °C and 1-5 MPa, vapor 700-800 °C and 0.1 MPa) to produce hydrogen. In the group we are interested in exploring hydrothermal treatment of organic waste from different angles depending on its nature: Experimental hydro treating of residues and studies with model compounds, development of active, resistant and selective catalysts and kinetic modeling for process optimization.

Research Group

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Software showcase



TESARREC™: A bespoke software for life cycle sustainability assessment of resource recovery technologies

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In order to remain within a safe space for human prosperity, a shift from a linear economy, where resources are used and disposed of as waste, to a circular economy, where resources are recovered from waste for further utility, is crucial. This pertinent paradigm shift has propelled investment in research and development of several flexible resource recovery from waste technologies (RWTs) to complement or possibly replace existing waste treatment technologies. Several RWTs have been successfully trialled to date; however, a couple of hurdles need to be crossed before they can gain parity with the existing waste treatment infrastructure. These

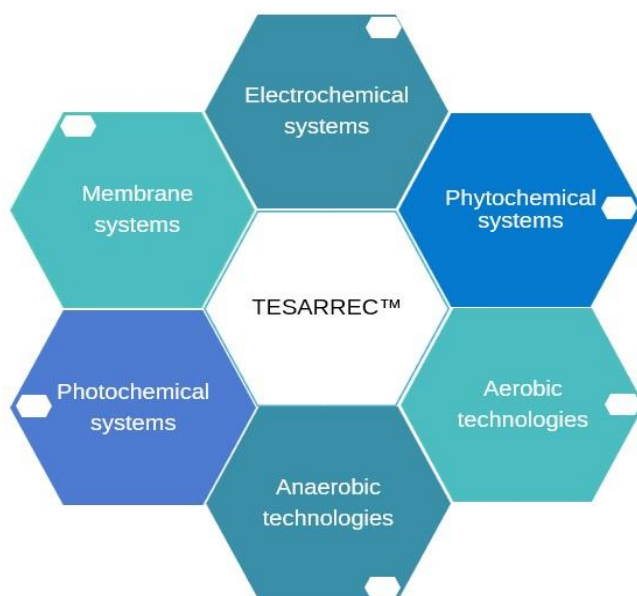
challenges

include operational performance problems at large scales and sustainable inventory selection issues. Therefore, there is a need for the holistic sustainability assessment of these RWTs in order to ensure that they are scaled up towards Technology Readiness Level (TRL) 9 in a sustainable manner.

TESARREC™, a first of its kind software application for assessing the life cycle sustainability of RWTs, has been developed to address these challenges. The software is targeted towards three sectors plagued with adverse wastewater treatment and resource recovery challenges: the food, distillery and wastewater treatment sectors. The potential triple-bottom-line benefits of resource recovery from these sectors can be assessed in TESARREC™. Precisely, user inputs, such as wastewater concentration, wastewater disposal capacity and materials of construction etc can be used to evaluate the relative financial, environmental and social benefits of various RWTs.

Two case studies have been conducted thus far based on TESARREC's development philosophy.

The first examines the environmental and economic sustainability of bioelectrochemical systems (BES) (a TRL 3-4 microbe-aided electrochemical device) for wastewater treatment and formic acid production



[1]. The second explores the social risk associated with the importation of requisite raw materials for BES construction and operation for formic acid synthesis from CO₂ reduction and copper recovery from spent lees in the UK [2].

The software is still at the prototyping stage. Nevertheless, some progress is being made towards its commercialisation. Works in the pipeline include improvement to software functionality and migration to the cloud in order to allow a wide range of access across different client platforms. We envisage that TESARREC™ will be the ‘go-to app’ for how to generate the best sustainable ‘value’ from wastewater.

Watch TESARREC’s demonstration video: <https://www.youtube.com/watch?v=MR1HmiJOuH4>

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Supplementary material

Introduction to the Biorefinery

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This workshop aims to develop basic understanding of sustainable biorefinery design challenges, gaps in research and skillsets needed for successful development of biorefineries. The workshop has a flexible and interactive structure, where attendees are welcome to interrupt and discuss pain points.

The workshop begins with an introduction to www.theibest.org a network of biorefinery professionals and the Annual Magazine *The Biorefiner* ISSN: 2398-0575 reporting internationally leading research and development activities in *Advanced biorefinery engineering; Waste-stocks and resource recovery; Sustainability and circular-economy*. The outreach of *The Biorefiner* ISSN: 2398-0575 is maximised by circulating to the Government and funding bodies.

At the outset, also, discussed collaboration opportunities between the UK and Mexico bringing appropriate track record examples that include the following:

- University of Surrey hosted PhD researcher from the University of Nottingham Malaysia that resulted in two publications on techno-economic analysis of CHP and bioethanol processes utilising palm oil milling waste
- Newton Institutional Collaboration Grant (Royal Academy of Engineering) – completed in 2017 between Surrey, Imperial College London, IMP and INIFAP
- Newton Early Career Researcher Links Workshop (British Council / CONACYT) – held at IMP 2015
- One week intensive CPD course on: Life cycle assessment, Energy efficiency, Techno-economic analysis, Life cycle sustainability assessment, Biomass Processing Technology, offer by the University of Surrey. Biorefinery options will be used as example cases. Problem and project based learning approaches are embraced.
- Tutors can be hired as project consultant
- Dual degree offering between the University of Surrey and overseas institution (embed cost of time spent at Surrey, ideally a year)

The workshop then starts with the explanation of the definition of biorefinery. In the most advanced sense, a biorefinery is a facility with integrated, efficient and flexible conversion of biomass feedstocks, through a combination of physical, chemical, biochemical and thermochemical processes, into multiple products [1,2]. The concept was developed by an analogy to the complex crude oil refineries adopting the process engineering principles applied in their designs, such as feedstock fractionation, multiple value-added productions, process flexibility and integration [1]. This definition of biorefinery evolved from the earlier works of the National Renewable Energy Laboratory (NREL) [3] and the Department of Energy (DOE) of the USA [4]. Biorefinery could be of three types “according to their phases of development defined by their degree of complexity and flexibility.

- I. Single feedstock, fixed process and no product diversification. Examples include dry-milling bioethanol plants using wheat or corn and biodiesel plants using vegetable oils which have no process flexibility and produce fixed amounts of fuel and co-products.
- II. Single feedstock, multiple, and flexible processes and product diversification. An example is a wet milling plant using corn and various processes with capability to adapt production depending on product demand and market price.

III. Multiple, highly integrated and flexible processes allowing the conversion of multiple feedstocks of different or same nature and shift between feedstocks or processing of a blend of similar feedstocks. Highly diverse product portfolio.

The biorefinery Type III corresponds to the biorefinery concept in its broader extension. Various schemes for this type of biorefineries are under extensive research and development. The most workable one is the lignocellulose feedstock based biorefinery for the processing of agricultural residues, straw, wood; wastes such as sewage sludge and municipal solid wastes or refuse derived fuels, etc. Other developments include the two-platform biorefinery which combines biochemical with thermochemical processes and more recently, the algae biorefinery. Materials and tools involved for sustainable designs of these processes are shown in [1]. A biorefinery must produce at least one added value product with niche market for sustainability [1]. In chronological order from high value low volume to low value high volume products are food and pharmaceutical ingredient, chemical and material, biofuel and energy, respectively [1]. At least one high value low volume product must be targeted alongside high volume low value products.

Explored, in collaboration with Malaysia and Mexico, a bioethanol producing biorefinery configuration of type II. It comprises pretreatment, enzymatic hydrolysis, fermentation and bioethanol purification; wastewater treatment with anaerobic digestion; and combined heat and power (CHP) generation system [5-6]. The study with and for Mexico comprises techno-economic and environmental footprint analyses of 19 forestry and 13 agricultural residues including pinus and wood species, agave, sugarcane and apple bagasse, rice and barley husks, wheat straw, grass species, coffee pulp, and sweet sorghum stalk, etc. For a cost of lignocellulose of 34 \$/t (USD/tonne) and a delivered cost of equipment varying between 209.5 (rice husk) and 220.3 (rubber wood) million \$ for 2000 t/d dry lignocellulose processing capacity, the minimum ethanol selling price (MESP) obtained is in the range of 1.89–2.39 \$/British Imperial gallon.

A type III biorefinery could be the one utilising heterogeneous waste. The state-of-the-art material recovery facilities (MRF) are configured to recover recyclables and refuse derived fuel (RDF) from municipal solid waste (MSW). Furthermore, biological treatment, anaerobic digestion, of organic components gives biogas and fertiliser. MRF and biological treatment together make a mechanical biological treatment (MBT) plant. Moreover, chemical valorisation of lignocelluloses present in MSW integrated to MBT / MRF makes a complex optimal biorefinery configuration coined as mechanical biological chemical treatment (MBCT) system [7-8]. A novel configuration employs a mechanical biological chemical treatment (MBCT) system, including MRF liberating recyclables, metals and RDF from MSW, followed by a pulping process for extracting lignocellulosic fraction of MSW, a chemical conversion section producing a chemical from the lignocellulosic fraction of MSW, a biological section to release fertiliser and biogas from the effluent and a total site CHP system utilising RDF, char and biogas [7-8]. These publications have investigated levulinic production from MSW and shown that levulinic acid production (only by 5 wt% of the mass of MSW) can increase the economic margin of the MBCT system by 110–150% and can offset negative margins caused by the other products. Target niche chemicals are referred as 'sleeping giants' owing to their vast potentials in the emerging biobased economy due to their key positions in the production of biomass-derived intermediates and transition from fossil based to bio-based economy [7-8]. For newer biorefinery businesses, targeting such chemicals as bio-based products alongside a bulk chemical or bioenergy or biofuel product with large market potential is the safest and low risk option, because demands for such chemicals are expected to increase due to versatility in their applications. Application areas and examples of levulinic acid derivatives include: Pharmaceutical (e.g. δ -aminolevulinic acid) > Specialty chemical (e.g. γ -valerolactone) > Agricultural (e.g. diphenolic acid) > Solvent and bulk chemical (e.g. pyrrolidones) > Chemical (e.g. succinic acid as antifreeze agent) > Fuel and additive (e.g. levulinate esters, 2-methyl tetrahydrofuran). Other 'sleeping giant' chemicals investigated are 5-hydroxymethylfurfural (5-HMF), furan-2,5-dicarboxylic acid (FDCA), lactic acid and succinic acid.

Biorefineries are only successful when multiple feedstock and product options were holistically analysed for optimal investment. Fermentation / anaerobic digestion (AD) / transesterification can be considered for one type of feedstock availability at small scale; storage or immediate utilisation options should be evaluated thoroughly to accommodate feedstock supply intermittency.

Biorefineries type III will cost three times more than the simple fermentation / AD / transesterification option; only be worthwhile when at least one high value niche product is produced [1]. Design and selection of biorefinery type can be heuristics based as follows [1].

- Energy crops
 - o CHP generation
- Oily wastes and residues
 - o Biodiesel by (trans)esterification
- Forestry / Agricultural / grass silage (or lignocellulose)
 - o Moisture content <10% by mass and also presence of ash: Thermochemical
 - o Moisture content >10% by mass or biomass drying is expensive: Biochemical
- Aquatic
 - o High value product for food / pharmaceutical / healthcare sector, protein extraction, heavy metal reduction (Sargasso algae)
- Wastewaters
 - o Effluent treatment
 - o Resource recovery (electrochemical system) o Anaerobic digestion o Also, see Aquatic
- Municipal solid waste
 - o MRF, MBT, MBCT

Lignocelluloses are of more interest due to availability, and are made up of three main polymer types: Lignin encasing cellulose in cell walls provides rigidity of cell walls; hemicelluloses cover the cellulose and strengthen cell walls by interaction between lignin and cellulose; while encased cellulose microfibrils give tensile strength of cell walls [7]. Celluloses and hemicelluloses are polysaccharides of C6 and C5 monomers, respectively, connected by β -(1-4)-glycosidic linkages [7]. The main lignin compounds are polymers of para-hydroxyphenyl (H lignin), guaiacyl (G lignin) and syringyl (S lignin) alcohol [1]. Pretreatment for decomposition of biomass into cellulose, hemicellulose and lignin is needed for lignocellulosic or second generation feedstock, such as MSW, due to its heterogeneous nature [7]. The various methods of pretreatment broadly fall into two categories: addition of extraneous agent and application of energy. The former incurs higher cost of chemical and downstream separation and purification and the latter incurs higher cost of energy and capital cost of pretreatment. Hydrolysis (acid or alkali), organosolv (extraction using organic solvent) and ionic liquid extraction use extraneous agents for biomass decomposition, while ultrasonication and microwave irradiation technologies make use of energy for biomass decomposition. Steam explosion and supercritical water extraction technologies (also known as pulping as well as hydrothermal liquefaction, up to 450°C and 250 bar) are a flexible method for biomass decomposition, because moisture is naturally present in biomass reducing the amount of steam requirement. Pretreatment liberates hemicelluloses first because these are hydrolysed at a faster rate. Liberation of hemicellulose separates lignin and cellulose. β -(1-4)-glycosidic linkages are broken down by pretreatment, liberating glucose from celluloses. Upon pretreatment, a lignocellulosic platform can give rise to three phases, which can be easily separated and then valorised to added value products: an aqueous solution of C6 and C5 sugars generated from decomposition of cellulose and hemicellulose; an insoluble (or soluble in organic solvent) lignin containing black liquor; a solid phase of cellulose microfibrils. Thus, three platforms are generated for further processing. These would have certain market values. But to enhance their economic margin, they must be processed into added value products, in so called biorefinery systems.

Chemicals derived from biomass can be of two types, one that can directly displace a petrochemical, usually having the same chemical formula; the other offers the same functionality (but with different chemical formula) as a petrochemical and thus can displace the petrochemical [1]. The former usually would have an advantage of established market, while the latter would have to find a new market. Sugar platform is the most popular platform so far, giving rise to both the types of chemicals.

Some chemicals offer many functionalities of petrochemicals and can be a precursor to numerous added value products with applications in pharmaceutical, specialty chemical, agricultural, solvent, platform chemical, fuel (additive) and energy sectors. These chemicals are referred as 'sleeping giants'. For newer biorefinery businesses, targeting such chemicals as bio-based products alongside bioenergy or biofuel product with large market potential is the economic proposition, because demands for such chemicals are expected to increase due to versatility in their applications. Five such 'sleeping giant' priority chemicals include levulinic acid, 5-HMF, FDCA, succinic acid and lactic acid from lignocelluloses, for resource efficient sustainable biorefinery and bioeconomy development. These are the popular target chemicals from the sugar platform.

"The lignin fraction ($C_9H_{10}O_2(OCH_3)_n$) consists of complex phenolic polymers. The dominant monomeric units in the lignin polymers are benzene rings bearing methoxyl, hydroxyl and propyl groups that can be attached to other units. Lignin has the potential to unlock the market for high functional material and chemical production, thus making biorefinery commercially an attractive proposition. Of the highest importance is the need to extract lignin early from lignocellulose. Unless lignin fraction is routed to value-added chemical production, a biorefinery is unlikely to be economically and environmentally sustainable. Lignin value addition is an important stumbling block, unveiling of which can unlock the sustainability of biorefineries. The potential applications of lignin go from simple combustion for heat and power production to the production of aromatics typically produced from crude oil (phenols; benzene, toluene and xylene: BTX chemicals) or other highly functional chemicals used in the food and flavoring industry (e.g., vanillin). The productions of BTX derivatives are well established from the petrochemical industry. The sequence from the most mature technology to the furthest-from-market technology utilizing lignin is as follows: BTX derivatives > phenol and guaiacol derivatives > vanillin derivatives > dimer and syringol derivatives" [1].

Process Integration or Process Systems Engineering is essential for optimal biorefinery design from numerous possible configurations, combining feedstock, process and products. Systems life cycle sustainability assessment is needed much beyond a chemical plant's boundary. System thinking is imperative for overall environmental, economic and social sustainability. Environmental life cycle assessment (LCA) includes impact assessments due to emissions to the atmosphere, water and land. LCA and techno-economic analysis are essential for feasible biorefinery design. The final session of the workshop includes hands-on with a tool for techno-economic and life cycle assessments of MBCT system [7-8] ©<http://www.theibest.org/eubce-workshop-material>

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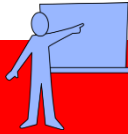
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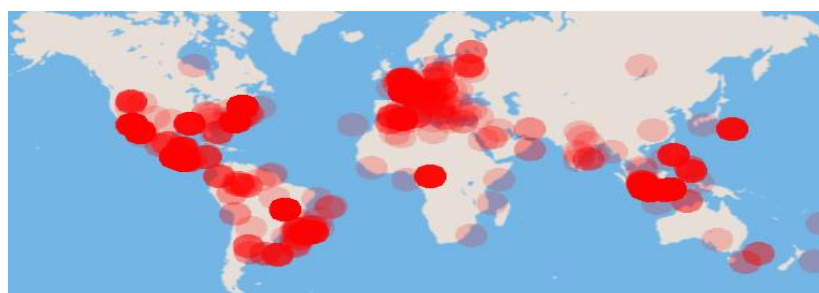
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