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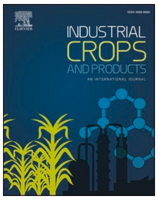

New perspectives on biomass conversion and circular economy based on Integrated Algal-Oil Palm Biorefinery framework for sustainable energy and bioproducts co-generation

Mohd Azmuddin Abdullah [a,*], Muhammad Shahid Nazir [b], Hanaa Ali Hussein [c], Syed Muhammad Usman Shah [d], Nizakat Azra [b], Ramsha Iftikhar [e], Muhammad Saqlain Iqbal [b], Zeenat Qamar [b], Zulfiqar Ahmad [f], Muhammad Afzaal [g], Ahmad Daud Om [h], Mohd Idris Shaharah [h], Aweng Eh Rak [i], Yung-Tse Hung [j]

[a] *SIBCo Medical and Pharmaceuticals Sdn. Bhd., No. 2, Level 5, Jalan Tengku Ampuan Zabedah, D9/D, Seksyen 9, Shah Alam, Selangor 40000, Malaysia*
[b] *Department of Chemistry, COMSATS University Islamabad, Lahore Campus, Punjab 54000, Pakistan*
[c] *College of Dentistry, University of Basrah, Basrah, Iraq*
[d] *Department of Biosciences, COMSATS University Islamabad, Park Road, Islamabad 44000, Pakistan*
[e] *Department of Chemistry, Government College University Faisalabad, Faisalabad 38000, Pakistan*
[f] *Department of Civil and Environmental Engineering, College of Engineering, A'Sharqiyah University, Ibra 400, Oman*
[g] *Department of Sustainable Development Study Center (Environmental Sciences), GC University, Lahore, Punjab, Pakistan*
[h] *Fisheries Research Institute, Tanjung Demong, Kampung Raja, Besut, Terengganu 22200, Malaysia*
[i] *Faculty of Earth Science, Universiti Malaysia Kelantan, Jeli Campus, Jeli, Kelantan 17600, Malaysia*
[j] *Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH 44115, USA*

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ABSTRACT

The concept of bioenergy co-generation with environmental remediation has gone through tectonic paradigm shift with the perspective that wealth and economic activities can be created through biomass utilization and conversion and waste valorization. In this review, the concept of Integrated Algal-Oil Palm Biorefinery as a cost-

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Abbreviations: AOP, Advanced Oxidation Process; BGPS, Biomass Gasification Power Generation System; BHD, Bio-Hydrogenated Diesel; BMIM, 1-Butyl-3-methylimidazolium; BOD, Biological Oxygen Demand; BSS, Biofilm Support System; CA, Cellulose Acetate; CAGR, Compound Annual Growth Rate; CDs, Carbon Dots; CDM, Clean Development Mechanism; CMS, Carbon Molecular Sieve; CNG, Compressed Natural Gas; CNT, Carbon Nanotubes; COD, Chemical Oxygen Demand; CPO, Crude Palm Oil; CSTR, Continuous Stirred-Tank Reactor; Cur, Curcumin; DDS, Drug Delivery Systems; DES, Deep Eutectic Solvents; DHA, Docosahexaenoic acid; DMF, Dimethylformamide; DMSO, Dimethylsulfoxide; DoxHCl, Doxorubicin hydrochloride; DS, Degree of Substitution; EFB, Empty Fruit Bunches; EMIMAc, 1-Ethyl-3-methylimidazolium acetate; EMIMCl, 1-Ethyl-3-methylimidazolium chloride; EPA, Eicosapentaenoic acid; ETBE, Ethyl tert-Butyl Ether; FAs, Fatty Acids; FAME, Fatty Acid Methyl Ester; FFB, Fresh Fruit Bunches; GO, Graphene oxide; GQDs, Graphene Quantum Dots; GHGs, Green House Gases; HHx, Hydroxyhexanoate; HQ, Hydroquinone; HRT, Hydraulic Retention Time; HUFAs, Highly Unsaturated Fatty Acids; HV, Hydroxyvalerate; IL, Ionic liquids; ImHCl, Imipramine hydrochloride; ISPO, Indonesian Sustainable Palm Oil; IUMAS, Integrated Ultrasonic Membrane Anaerobic System; LEDs, Light Emitting Diodes; LNG, Liquefied Natural Gas; LNPs, Lignin- nanoparticles; MCL, Medium-Chain Length; MF, Mesocarp Fibers; MSPO, Malaysian Sustainable Palm Oil; MT, Metric Tons; NP, Nanoparticle; OPA, Oil Palm Ash; OPF, Oil Palm Fibre; OPL, Oil Palm Leaves; OPS, Oil Palm Shells; OPT, Oil Palm Trunk; PAC, Polyaluminum chloride; PAN, Polyacrylonitrile; PBR, Photobioreactor; PCL, Polyε-caprolactone; PFAD, Palm Fatty Acid Distillate; PHA, Polyhydroxyalkanoate; PHB, Polyhydroxybutyrate; PKC, Palm Kernel Cake; PKS, Palm Kernel Shell; PLA, Polylactic acid; POLE, Palm Oil Leaves Extract; POME, Palm Oil Mill Effluent; POMS, Palm Oil Mill Sludge; PPF, Palm Pressed Fibers; PrHCl, Procaine hydrochloride; PTT, Polymer Trimethylene Terephthalate; PUFA, Polyunsaturated Fatty Acids; RC, Regenerated Cellulose; RGO, Reduced Graphene oxide; RSPO, Roundtable on Sustainable Palm Oil; SCL, Short-Chain Length; SDDV, Scale Drop Disease Virus; SDGs, Sustainable Development Goals; SFE, Supercritical Fluid Extraction; SHF, Separate Hydrolysis and Fermentation; SSF, Simultaneous Saccharification and Fermentation; TetHCl, Tetracycline hydrochloride; TN, Total Nitrogen; TOC, Total Organic Carbon; TSS, Total Suspended Solids; UASB, Up-Flow Anaerobic Sludge Blanket; UASFF, Up-Flow Anaerobic Sludge Fixed Film; UV, Ultra-violet; VNN, Viral Nervous Necrosis; VS, Volatile Solid.

[*] Corresponding author.

E-mail addresses: joule1602@gmail.com, joule1602@yahoo.com (M.A. Abdullah), shahid.nazir@cuilahore.edu.pk (M.S. Nazir), hanaazahraa85@gmail.com (H.A. Hussein), usman.kazmi@comsats.edu.pk (S.M.U. Shah), azranizakat@gmail.com (N. Azra), ramsha.mohsan@gmail.com (R. Iftikhar), saqlainiqbal942@gmail.com (M.S. Iqbal), zeenatqamar90@gmail.com (Z. Qamar), zulfiqar@whu.edu.cn (Z. Ahmad), afzaalbhatti.utp@gmail.com (M. Afzaal), daudom@dof.gov.my (A.D. Om), shaharah@dof.gov.my (M.I. Shaharah), aweng@umk.edu.my (A.E. Rak), y.hung@csuohio.edu (Y.-T. Hung).

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effective and innovative solution to address the Climate-Energy-Food-Water-Socio/Economy Nexus for sustainable energy production, and developments of bioproducts are elaborated. Different types of oil palm biomass and mill effluent generated are highlighted, and the technologies for environmental remediation with clean/bioenergy co-generation based on biodiesel, bioethanol, biomethane, biohydrogen, bio-oil, and jet biofuel with energy storage and supercapacitors are discussed. The conversion of biomass and effluent into biopolymer, graphene, biocomposites and MXene, and into biochemicals and for biomedical applications are highlighted. The importance of utilizing green and eco-friendly processes is detailed out. Finally, economical integrated algal cultivation within oil palm industrial setting for aquaculture application, with inclusive community development programs based on HEESBA philosophy to meet the agenda of global sustainable development goals is promoted.

1. Introduction

Industrial Biotechnology sector is forecasted to reach USD546.8 billion (Globenewswire, 2022), and the global biorefinery market is expected to reach USD1.1 trillion by 2027, increasing at 9.8% CAGR (Compound Annual Growth Rate) over the period of 2020–2027. Biorefineries make use of variety of animal and plant-derived biomass feedstock for conversion into valuable bioproducts. In a biorefinery, there are 4 major classification systems which are further divided into groups and subgroups – the Feedstocks (dedicated feedstocks and residues); Processes (thermochemical, biochemical, chemical, physical/mechanical; Platforms (C5/C6 sugars, oils, bio/electrical/heat energy, organic effluents, lignin); and Products (energy/materials). Table 1 shows the feasible bioenergy/clean energy and bioproducts from the perspectives of circular economy, waste valorization and biorefineries. Algal biorefinery has been classified as the “New--Biorefinery-Kids on the Block” but its rapid development is hindered mainly by the prospect for commercialization, attributable to the high investment cost to cultivate the feedstock, and the availability of suitable technologies for scaling-up (International Energy Agency Bioenergy, 2022). As shown in Fig. 1, based on publications between 1996 and 2022 in Scopus database for “Algae” and “Biorefinery” keywords, the publications have started to increase significantly from 2010 especially in energy, environmental science, and chemical engineering-based publications. There are still a lot more to be explored especially the fundamental aspects in engineering, biochemistry, green processes, and medical and agricultural applications.

Algal biorefinery has great potential as a cost-effective and innovative solution that could meet the Climate-Energy-Food-Water-Socio/Economy Nexus. The location of a biorefinery platform is critical to make it economically viable, especially in utilizing the waste streams and flue gases from industrial plants as the media to grow algae. This is where the Integrated Algal-Oil Palm Biorefinery framework comes in as a workable and practical solution to consider, not only to remediate all the wastes generated from the mill, but more importantly to valorize the wastes into value-added products, to generate new and green economy (Abdullah and Hussein, 2021). Palm oil industry is one of the leading industries in Malaysia and Southeast Asia, with oil palm (*Elaeis guineensis*) as the oil crop for more than 100 years. Malaysia currently is the second world’s largest producer of palm oil (27.9%), behind Indonesia (56.5%). Both countries produce a combined total of 64.2 million metric tons (MT) of palm oil (Index Mundi, 2019). Malaysia alone accounts for 34.3% of the global palm oil export (MPOC, 2020). Crude palm oil (CPO) is refined into a wide range of food and non-food products. Oil palm has made tremendous achievement as a premier crop with marked genetic improvement made for better quality planting materials, improved agronomic practices and plantation management, and increased utilization of oil palm resources for energy and waste valorization in meeting the agenda of global sustainable development goals (SDGs) (Wahid et al., 2005; Abdullah, 2021; Mardiharini et al., 2021).

Palm oil mills produce variety of wastes, estimated at RM 6.38 billion in energy per year (Jaafar et al., 2003). The challenge is to utilize cost-effective and green methods to harness the abundant solid wastes for conversion into value-added products, and to remediate the wastes such as removing the pollutants including residual oil and heavy metals from the Palm Oil Mill Effluent (POME). To reduce over reliance on fossil-based energy sources, biodiesel, biogas, biomethane, bioethanol, bio-oils and bioelectricity have been touted as one of the alternative solutions (Chin et al., 2013; Chen et al., 2015; Ali et al., 2024). These can be produced from the oil palm and algal biomass. Algae can be cultivated on non-agricultural land, and harvested throughout the year, with the flexibility to increase output, wherever and whenever required, utilizing minimal resources for various products in the biorefinery set-up. Microalgae and cyanobacterium have been grown on POME with great potentials to produce bioenergy, biomolecules, and biopolymers (Nur and Burma, 2019; Abdullah and Hussein, 2021; Nur, 2022). Utilization of algae for aquaculture could provide answers to global food security, to fight poverty, and to reduce pressure on wild populations and avoid overfishing whilst maintaining the fish supplies.

The rapid development of palm oil industry promotes not only the economy of developing countries like Malaysia and Indonesia, but also being blamed for rain forest clearing, destruction of wildlife habitat and environmental pollution. The unrelentless anti-palm oil campaign, especially in the West, prods the big oil palm companies and small holders to take the issue of sustainability seriously and to be ever more vigilant in reducing the negative perception on deforestation and impact on wild-life habitat. Land clearing and land use change such as the use of croplands for biofuels actually increases Green House Gases (GHGs) emission and the carbon debt (Searchinger et al., 2008; Fargione et al., 2008). The awareness on meeting the standards established such as that based on Roundtable on Sustainable Palm Oil (RSPO, 2014), Malaysian Sustainable Palm Oil (MSPO) (Intertek, 2022) and Indonesian Sustainable Palm Oil (ISPO) (Wilmar, 2022), suggest the concerted efforts made to move things in the right direction. To date, there has not been any comprehensive review on Integrated Algal-Oil palm Biorefinery to meet the agenda of global sustainable development goals to address the Climate-Energy-Food-Water-Socio/Economy Nexus. The existing review is either emphasizing micro/macroalgal biorefinery, or oil palm products or environmental control and remediation, separately and on individual basis.

The objectives of this review are to elaborate the concept of Integrated Algal-Oil Palm Biorefinery framework for sustainable energy with environmental remediation, and waste valorization based on circular economy implemented in oil palm plantation and palm oil mill for value-added products co-generation. Different aspects of oil palm biomass and mill effluent with algal cultivation for bioenergy, biomaterials, biochemicals and aquaculture application are elaborated. The progress involving biodiesel, bioethanol, biomethane, biohydrogen, bio-oil, jet biofuel and energy storage and supercapacitors are discussed. The conversion of biomass and effluent into biopolymer, graphene, biocomposites, and MXene, and into biochemicals and for biomedical applications are highlighted. Special emphasis on utilizing green and eco-friendly processes, and aquaculture application with inclusive community development programs based on HEESBA concept, to meet the agenda of global sustainable development goals, are proposed.

Table 1
Feasible bioenergy/clean energy and bioproducts from environmental remediation, waste valorization, and biorefineries.

Product Classification	Process description	Performance / Yield / Productivity	References
1. Bioenergy / Environmental remediation			
Biogas/Biomethane, dewatered sludge as biofertilizer.	Anaerobic ponding system with optimum depth ranges from 5 to 7 m for 30–45 days hydraulic retention time (HRT).	Methane of 1043 kg/d released to the atmosphere	Yacob et al. (2006)
	Mild steel open digesting tank volumetric capacities ranging from 600 to 3600 m^3 for 20–25 days hydraulic retention time (HRT)	No mechanical mixing to reduce the energy cost; 518.9 kg/d methane released to the atmosphere; Continuous removal of the solids build-up at the bottom for consistent treatment efficiency.	Tong and Bakar (2004); Yacob et al. (2006); Poh and Chong, (2009).
	Closed digesting tank with HRT of 18 days, utilizing pump-aided circulation and gas lifting mixing, gas collector, safety valves, and monitoring and control systems	Total biomethane of 1407 tonnes/year; 29547 tonnes/year of CO_2 equivalent reduction	Hassan et al., (2004); Sulaiman et al., (2009)
	Anaerobic digestion of POME for 3 and 7 days, with *Chlorella* sp. and *N. oculata*, and without microalgal addition.	Removal of BOD (83–95%) and COD (87–98%) with *Chlorella* sp; and 90–98% BOD and 83–97% COD removal with *N. oculata*; Only 83–86% BOD and 69–96% COD removal without microalgae	Ahmad et al. (2014); (2015)
		EFB at 0.12 g/mL POME, sludge inoculum at 3 mL/mL POME; the highest methane yield of 5256.8–5295.8 mL CH_4/L POME/day of *Chlorella* sp.; 4606–5018 mL CH_4/L POME/day of *N. oculata*; With 2 mL/mL POME of *Chlorella* sp. ~2367.8–3336.0 mL CO_2/L POME/day; 2789.4–3228.2 mL CO_2/L POME/day with 2 mL/mL POME of *N. oculata*;. No biohydrogen detected.	Ahmad et al. (2014); (2015)
	Natural and magnetic biosorbent based on oil palm fibres, cellulose and kapok fibres for oil and heavy metal ion removal from aqueous system and POME). Column filtration under gravity at 0.08 g/cm3 packing of raw kapok fibers (RKF), NaOH-treated kapok (SKF), and HCl-treated bentonite (HTB).	All configurations exhibit more than 95% oil and heavy metal ion removal efficiency. SKF exhibits higher POME sorption at 82 g/g, while the HTB attains 69 g/g. RKF achieves high removal efficiency of BOD, COD, TOC, and TN of POME at 74–98%, and bentonite clay at 72–94%, higher than the SKF at 66–80% and HTB at 64–80%	Abdullah et al. (2010); (2015); Daneshfozoun et al. (2017)
High efficiency remediation	The UASFF bioreactor for the treatment of POME, dairy, sugar and wood fiber wastewater, and the wash waters from virgin olive oil purification.	Higher biomass retention, and higher operability at high OLRs, and stability at the shock loadings. Overcome the clogging and biomass washout problems encountered in the anaerobic filter and UASB	Borja and Banks, 1994a,b; Ayati and Ganjidoust (2006); Najafpour et al. (2006); Wu et al. (2010); Najafpour et al. (2006); Lorestani (2006)
	For POME treatment, high ratio of effluent recycle enhances internal dilution to reduce the effects of high Organic Loading Rate (OLRs) and the internal packing of the column. Effectively retain and prevent wash out of the biomass	The anaerobic treatment at COD of 42,500 mg/L and 4 days HRT based on the UASFF reactor reduce 95% COD at an average OLR of 15 g COD/L/d, and 96% COD removal at an OLR of 10.6 g COD/L/d. The mesophilic condition at 38 °C and 3 days HRT of the UASFF produce 0.346 L CH_4/g COD removed, with 97% COD removal efficiency	
Recycled water, POME treatment	Membrane technologies in combination with coagulation/flocculation as pre-treatment	Achieves 78% water recovery from POME. The reclaimed water meets the drinking water standard set by the USEPA. Membrane fouling, from cake formation, is reversible. The treated effluent can be recycled or used as boiler feed water or as the source of drinking water.	Ahmad et al. (2003); (2006)
	The feasibility of membrane separation technology evaluated at 450 L/h capacity		Ahmad et al. (2003); (2005d)
	A pilot plant where the first stage involves coagulation, sedimentation, and adsorption, and the second stage involves the combination of ultra-filtration and reverse osmosis.	The sequence of treatment with significant reduction in turbidity, COD, and BOD upto 99–100%, at final pH of 7. The pre-treatment and ultrafiltration membrane treatment suggest the combination of filtration–ultrafiltration to attain a reduction of 93.4% for TN, suspended solids, turbidity, and colour content.	Wong et al. (2002)
	Polyvinyl fluoride ultrafiltration membrane incorporated with zinc-iron oxide nanoparticles to reduce the dark brownish color of aerobically treated POME, from high concentration of tannins, melanoidin and lignin	70% colour removal, but with the potential of structure collapse after several cycles of washing	Tan et al. (2017).
Sludge for biofertilizer, recycled water and feeds for animals and aquaculture	A holistic treatment for POME incorporating anaerobic-aerobic-wetland sequential system and a convective sludge dryer.	At the lowest HRT of 21 days, the biogas production increases from 1442 to 11,028 kg d^{-1} with increased organic loads from 0.46 to 2.2 kg m^{-3} d^{-1}. The COD, VSS and VFA removal are 99%, while the SS and TN removal are 96% and 72%, respectively	Farid et al. (2019)
	Sludge cake converted into compost through aerobic microorganisms or via vermicomposting using earthworms to produce humic acid-like substances, vermicompost or earthworm compost. The earthworm biomass further processed into proteins for animal and aquaculture feeds		Hartenstein and Hartenstein (1981); Singh et al. (2010); Edwards and Bohlen (1996)

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Table 1 (*continued*)

Product Classification	Process description	Performance / Yield / Productivity	References
2. Bioenergy / Clean Energy			
Biodiesel	Biodiesel production from *Spirulina* sp. in a batch, stirred reactor using palm oil as a co-solvent of methanol, catalyzed by KOH at 1 wt% (w/w of palm oil)	Biodiesel yield of 85.28% (99.01% of partial biodiesel yield from palm oil and 16.69% of partial biodiesel yield from dry microalgae).	Pradana et al. (2020)
	Self-flocculating *Chlamydomonas* sp. BERC07, grown on urban wastewater	2-fold increase in biomass, and complete removal of TN, 94% TP, but only 56% COD, and 41% BOD. The biomass yields 480 mg/g lipids, transesterified to produce EU and US standard of biodiesel,	Malik et al. (2022)
Biogas/Biomethane	Anaerobic digestion of EFB with sludge inoculum and POME, without microalgae, at high temperature of 47.8 °C	25.6% methane yield	Saleh et al. (2011)
	Anaerobic co-digestion of Empty Fruit Bunches (EFB) (0.12 g/mL POME) with *Nannochloropsis oculata* and *Chlorella* sp. (at 1 mL/mL POME)	Lipid content of *N. oculata*, and *Chlorella* at 27.5, and 30.4%, respectively, with 4651.9 mL CH_4/L POME/day and the specific biogas production rate of 0.124 m3/kg COD/day	Ahmad et al. (2016)
Biohydrogen	Biohydrogen production by dark fermentation of POME in an anaerobic sequencing batch reactor (ASBR) using enriched mixed culture	2.99 mol H_2/mol-sugar	Maaroff et al. (2019)
	Anaerobic digestion POME and sludge inoculum, without *Chlorella* or *N. oculata*	Undetectable methane, low CO_2 (80–300 mL CO_2/L POME/day), and hydrogen of 32–124.4 mL H_2/ L POME/day	Ahmad et al. (2014); (2015).
Biohydrogen/Biomethane	Two stage anaerobic digestion of *Chlorella* sp. residual biomass	CH_4 yield of 81 mL/g Volatile solid (VS), and H_2 of 12.5 mL/g VS, equivalent to the total energy yield of 3.03 kJ/g VS or 4.6% energy recovery, based on residual biomass heating value	Lunprom et al. (2019)
	Two-stage thermophilic digestion of POME	Biogas mixture of biomethane, biohydrogen and carbon dioxide with H_2 to CH_4 ratio in the range of 0.13–0.18	Seengenyoung et al. (2019)
	Palm oil decanter cake and crude glycerol employed in two-stage thermophilic anaerobic processes	Significant H_2 of 23 L/kg after 4 days, and CH_4 of 44 L/kg after 13 days	Kanchanasuta and Sillaparassamee (2017)
Bioethanol	Whole oil palm tree, pre-treatment, hydrolysis and fermentation, distillation, and finally formation bioethanol	142.25 tonnes per each hectare of oil palm farm	Islam et al. (2021)
	Fungal and phosphoric acid pretreatment of EFB	89.4% theoretical ethanol yield with phosphoric acid pretreatment, 62.8% ethanol with the combined fungal and phosphoric acid pretreatment, and 27.9% ethanol with fungal pretreatment	Ishola and Taherzadeh (2014)
	Simultaneous Saccharification and Fermentation (SSF) and Separate Hydrolysis and Fermentation (SHF) process of EFB	0.281 g/g of bioethanol based on SSF, 0.258 g/g of bioethanol based on SHF with 0.584 g/g of reducing sugars are produced.	Sukhang et al. (2020)
Biothanol and biodiesel	Extractive reaction process with transesterification of *in situ* ethanol from EFBs and Palm Press Fibers	3.4% reduction in unit energy costs from material flow integration, 39.8% cost reduction from material and energy flow integration	Gutiérrez et al. (2009)
Bio-CNG	Compressed purified biogas ($>$ 97% CH_4, $<$ 2% O_2) at 20–25 MPa.	Bio-CNG requires less than 1% of the volume that it occupies at standard atmospheric pressure	Yang et al. (2014)
Jet biofuel	Algae in a mixture with *Jatropha* has been evaluated up to 50% of the biojet fuel content in flight tests		Wang and Tao (2016)
	High pyrolysis temperature above 800 °C is required to convert the cobalt phosphide (Co2P) phase to CoP phase, for higher cracking activity of palm oil, and selectivity to bio-jet, due to the improved acidity of the catalyst		Kaewtrakulchai et al. (2020)
	De-oxygenation of palm oil fatty acids to C15 and C18 alkanes by decarbonization and decarboxylation, catalytic cracking into C8-C14 alkanes, and cyclic alkanes as well as aromatics into aromatic hydrocarbons		Basir et al. (2021)
Energy storage / Supercapacitor	PKS-based porous carbon utilizing KOH as activation agent via two-step activation processes; O, P, S self-doping with hierarchical porous carbon preparation	Dominant mesopores at high mass ratio; superior energy density (11.38 W/kg), power density (500 W/kg), higher specific surface area (2521 m^2/g), and higher specific capacitance (360 F/g) than one-step method	Li et al. (2023).
	PKS-lignin and PAN blended in DMF at different PKS-lignin:PAN ratios; fiber formation via electrospinning; the PKS-lignin:PAN ratio of 10:6 parts per hundred volume (phv) thermally stabilized without any crosslinking agent; carbonized at 900, 1000, and 1200 °C with no physical/chemical activation.	The PKS-lignin/PAN CF mats with 0.3–1.1 µm fiber diameter, high surface area (577–1330 $m^2\ g^{-1}$), micropore volume (V_{micro}) (0.97–2.94 $cm^3\ g^{-1}$), and total pore volume (V_{total}) (1.03–2.97 $cm^3\ g^{-1}$); high electrical conductivity (20–106 S cm^{-1}) and total heteroatom (nitrogen (N) and oxygen (O)) content (20–24 wt%); electrode preparation at 1000 °C attains the highest specific capacitance (C_s) $\cong$ 148 F g^{-1}, energy (35 W h kg^{-1}), power densities	Thongsai et al. (2021)

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Table 1 (*continued*)

Product Classification	Process description	Performance / Yield / Productivity	References
		(860 W kg^{-1}), and capacitance retention (C_R) of ~ 90% over 10,000 cycles	
	PKS-based pAC and cAC; coin type CR2032 cells with glass separator; 1 M H_2SO_4, 1 M Na_2SO_4 and 6 M KOH electrolytes	Varied operating potential in H_2SO_4 (1.0 V), KOH (1.2 V) and Na_2SO_4 (2.0 V); the highest energy density (7.4 Wh kg^{-1}) in Na_2SO_4 electrolyte at 300 W kg^{-1} power density; stability cycle of 3500 times and 78–114% capacitance retention; low current density (0.5 A g^{-1})	Misnon et al. (2019)
	Cleaned PKS carbonized by pyrolysis and activated by physical and chemical methods; pAC has uniform pores (1.5 nm); cAC has wider pore distribution (1.4–9.3 nm).	cAC attains high areal capacitance (~45mF cm-2); specific capacitance (C_S) (210 F g^{-1}) using 1 M KOH electrolyte at 0.5 A g^{-1}; ~95–97% of C_S after 1000 cycles; low series resistance ($< 0.6\ \Omega$) and relaxation time (~0.69 s)	Misnon et al. (2015)
Lithium-ion capacitors	Fabrication in the Carbon//LiPF6//Li configuration; surface modification of porous PKS-based carbon with Mn_2O_3 or cobalt thin film; filling-up the voids using hierarchical $MnCo_2O_4$ or TiO_2 nanoflowers	Nominal increment in specific capacitance; remarkable increase in potential window and rate capability; largest capacitance and capacity retention for $MnCo_2O_4$ flowers filled electrode; lower lithium ion transfer resistance	Vijayan et al. (2023)
3. Biomaterials			
Biosorbent	PKS as biosorbent; Cellulose extracted from the EFBs, magnetic biosorbents from EFBs, cellulose (extracted from EFBs), and *Ceiba pentandra*	Adsorbent for water treatment plant; Cellulose-polypropylene composite material biosorbent for diesel desulphurization; heavy metal ion removal from water samples	Baby et al. (2019); Abdullah et al. (2016a); Nazir et al., (2018a),b); Daneshfozoun et al. (2017).
	Oil palm-based biosorbents and biofilters including the porous oil palm ash (OPA); Chitosan-coated charcoal derived and carbon molecular sieve (CMS) from OPS	Removal of nitrogen oxide and sulfur oxide; heavy metal especially chromium from industrial wastewater; adsorption of gases	Mohamed et al. (2006); Saifuddin and Kumaran (2005); Ahmad et al. (2008)
Biofiller, Composite materials	Fillers of the natural rubber vulcinates; OPF added in natural rubber, polypropylene, polyvinyl chloride, phenol formaldehyde, polyurethane, epoxy, or polyester, to form biocomposites; fillers in thermoplastic and thermoset composites	High demand in furniture and vehicle parts	Shuit et al. (2009); Shinoj (2011); Abbas et al. (2019);
	Light weight aggregate/composites in the concrete beam	Higher moment capacity by about 3%, PKS-concrete beams more ductile than the normal concrete beams, suitable to give ample warning before failure happens, and as early warning sign for concrete beam failure; higher compressive strength of OPF-concrete than the normal concrete, increasing proportionally with the amount of the OPF in the concrete	Alengaram et al. (2008); Lee et al. (2018).
Cellulose acetate	One-step heterogeneous acetylation of EFB cellulose; no need for hydrolysis; optimization of reaction time and acetic anhydride/cellulose ratio (RR)	Acetone soluble EFB-CA; DS of 2.52; highly amorphous EFB-CA; 6.41% degree of crystallinity; higher tensile strength and Young's modulus than commercial CA	Daud and Djuned (2015)
Biosensor	EFB-based cellulose-hydroxyapatite carbon composite electrode	High selectivity and sensitivity for heavy metal ions detection in blood serum, POME, and water sample	Ajab et al. (2018); (2019)
Functionalized carbon dots	PKS-based CDs synthesized via solvothermal method with N-N dimethylformamide (DMF)	CDs of 2.5 nm average diameter; exhibit fluorescence emission at 520 nm from surface functional groups; superior photo, ionic and thermal stability; utilizable as fluorescent ink; invisible during daylight but emits bright green fluorescence under UV at 365 nm	Ganesh et al. (2023)
Biopolymer/Bioplastic	Bacterial *Rummeliibacillus pycnus* Strain TS8 cultivation on POME	P(3HB-co-3HV-co-3HHx) composed of (mol%) 42.8 3HB, 34.9 3HV, and 22.4 3HHx.l, and lipid (59.5% CDW of oleic acid) can be processed into biodiesel	Junpadit et al. (2017)
	An alkaliphilic *Halomonas alkalicola* Ext for the production of PHAs	Optimal PHA of 1.42 g/L, 41.8% of PHA content; 3.397 g/L of biomass after 72 h, pH 10, 35 °C, 2.5% (w/v) NaCl; 1.44 g/L of PHA, 45.6% content after optimization. The PHA extracted is a poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) with two copolymer subunits of 3-hydroxyvaryrate (3-HB) and 3-hydroxybutyrate (3-HV)	Muigano et al. (2024)
	Cyanobacterium *Arthrospira platensis* cultivation on POME with UV-C radiation exposure	Accumulation of the PHB along with C-phycocyanin	Nur (2022)
Bio-rigid polyurethane foam, Bio-based-polyurethane and polyester polyols	Residual palm oil in POME and algal oil at different ratios; Conversion of inedible residual palm oil from the EFBs and POME sludge, with the addition of algal oil and jatropha oil.	One-pot process, algal oil content at 50% attains the required thermal and tensile strength along with the biodegradability property, potential as a material for sandwich panels and insulation; One-pot process with epoxidation, hydrolysis, and isocyanation of thydroxyl groups of polyols, addition of polyunsaturated oils improves thermal stability and biodegradability	Gomez et al. (2020); Gomez et al. (2021)

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Table 1 (*continued*)

Product Classification	Process description	Performance / Yield / Productivity	References
Graphene	Palm oil wastes as the precursor of carbon, and graphene grown on the nickel substrate via double thermal chemical vapor deposition.	At 10 µl, appreciable amount of carbon aggregate; precipitates on the nickel surface to produce multilayered graphene, considerable amount of GO and amorphous carbon obtained	Mamat et al. (2018)
	A single step, green transformation of palm oil fuel ash into highly porous graphene nanosheets	Yield > 25 wt%, graphene nanosheets of 1–8-layer thickness and 1506.06 m^2 g^{-1} surface area	Ayub et al. (2021)
	Bio-inspired modified graphene anode for the fabrication of biochemical fuel cells for energy production from wastewater.	Energy output of 135.96 mA m^{-2}, almost 8 times more efficient than the unmodified conventional graphene anodes with energy output of 15.65 mA m^{-2}, the fabricated anode can remove Cd (II) with 99% removal efficiency	Yaqoob et al. (2021)
	Oil palm leaves (OPL), PKS and EFBs for the production of rGO from GO synthesized from carbonized materials	A green and environmentally friendly palm oil leaves extract (POLE) as reducing agent to transform GO into rGO, increases the carbon to oxygen ratio from 1:1–3:1	Nasir et al. (2017); Faiz et al., (2020);
MXene	MXene nanoparticles suspended in the palm oil methyl esters to form a homogeneous nanofluid	Improved thermophysical properties of the methyl esters; Higher heat transfer efficiency as heat transfer fluids; for energy storage applications, water purification, and gas sensor, and nanofluids	Mashtalir et al. (2014); Ren et al., (2015); Rahmadiawan, et al. (2021)
4. Biochemicals			
Lipid, Protein, Pigment	*Chlamydomonas* cultivation on urban wastewater as a low-cost growth media. All solvents are returned back to the primary waste water	Yields 1.83 mg/g of carotenoids, and the 75–100 g/l of algal biomass residue is fermented with *Aspergillus oryzae* to produce 131.6 U/mL of α-amylase, 375–384 mg/g of mycoproteins.	Malik et al. (2022)
	Two-stage cultivation of *Chlorella vulgaris* by varying light intensity, salt stress with or without medium replacement, and by utilizing light intensity with different combination of salt stressors	Simultaneous production of lipid (15.6 mgL^{-1}d^{-1}) and carotenoids and antioxidant compounds. High total carotenoids (4.4 µgmL^{-1}) with 10 gL^{-1} NaCl supplemented. PUFAs at 7.25–25.1% with palmitic, stearic and oleic acids as the major fatty acids for biodiesel; Different salt combinations to attain the highest antioxidant activity (86.2%) and protein content (35.3%).	Ali et al. (2021); El-fayoumy et al. (2023)
Bonding and gum resins		Surface covering, plywood, coatings, insulators, and rough coating, and sand molds and cores in foundry industries	Md. Kawser and Farid Nash (2000)
Bio-oil		Flavouring compounds, slow-release fertilizers and balms	Venderbosch et al. (2005)
Biochar	Pyrolysis of the biomass at 300–1000 °C, under low or zero oxygen to produce stable organic compound	Soil conditioner	Kahar et al. (2022)
Ruminant/Animal feed	PKC rich in crude fibers (6–25%) and crude protein (14–20%); OPTs in disk, chipped, squeezed, washed and powder form		Abdeltawab and Khattab (2018); Uke et al. (2021)
Bio-flocculant	Enzymatic hydrolysis of POME using POME-isolated *Bacillus marisfavi* NA8 to release sugars as substrates to be transformed into bio-flocculant BM-8 containing polysaccharides, proteins, and nucleic acids	Bioflocculant BM-8 precipitates out *Chlorella vulgaris* with 90% biomass recovery in 30 min	Bukhari et al. (2020)
Drug delivery system	Lignin- nanoparticles (LNPs), xylan nanoparticles, cellulose nanocrystals; lignin-based biomaterials	As DDS for curcumin, resveratrol, ovalbumin, benzazoline, irinotecan, sorafenib, and doxorubicin, not very high loading capacity but high efficiency of encapsulation; High loading capacity of hydrophilic drugs such as tetracycline hydrochloride (TetHCl), hydroquinone (HQ), procaine hydrochloride (PrHCl), doxorubicin hydrochloride (DoxHCl), and imipramine hydrochloride (ImHCl); Embryo pretreatment technologies	Zhou et al. (2019); Wijaya et al. (2021); Kumar et al. (2021)
	The electrospun fiber cloths composed of 90% CA and 10% PCL; smooth and bead-free; with 0.5 and 1 wt% Cur	Enhanced hydrophilicity improves swelling behavior of the scaffolds by 700 and 950%, in phosphate-buffered saline (PBS); cumulative drug release of 60% for 0.5 Cur/CA/PCL and 78% for 1.0 Cur/CA/PCL; higher actin level in fibroblasts than those without Cur; applicable for wound healing	Suteris et al. (2022)
	Tamoxifen (TMX)-microalgal extracts applied against MCF-7 and 4T1 breast cancer cells and non-cancerous Vero cells	The ethanol and water algal extracts with TMX attain high cytotoxicity against MCF-7 (IC_{50} 15.8–29.5 µg/mL) and 4T1 cells (IC_{50} 13.8–31.6 µg/mL), but with reduced cytotoxicity against Vero cells (IC_{50} 24.5–85.1 µg/mL)	Hussein et al. (2022)
	Chitosan-alginate nanoparticles encapsulating Amoxicillin-docosahexaenoic acid as prepared by ionotropic gelation method	Enhanced biocidal activities against *Helicobacter pylori* infection with improved aspirin-induced ulcer healing in rats' stomachs	Khoshnood et al. (2023)

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Table 1 (*continued*)

Product Classification	Process description	Performance / Yield / Productivity	References
Biofactories, Biopharmaceuticals and Biomedical applications	EFBs for nanocellulose hydrogel production	Drug delivery, wound dressings, food packaging, tissue engineering, additive manufacturing, and biosensing	Padzil et al. (2020); Wang et al. (2021)
	Algae as biological factories; Algal polysaccharides eg ulvan, alginate, fucoidan, and carrageenan; Fucoidans from brown algae, carrageenans from red algae and ulvans from green algae; Ulvan, with 3-sulfated rhamnoglucuronan as the essential component rich in L-rhamnosa, D-glucuronic acid, and L-iduronic acid; Ulvan-based hydrogels	Production of metallic NPs; Immunomodulatory abilities, drug delivery, tissue engineering and therapeutic potential; Rheology modifiers, conditioners, wound-healing agents; skin whitening agents;	Fawcett et al. (2017); Wang et al. (2015); Muhamad et al. (2019); Aditya et al. (2016); Sulastri et al. (2021)
5. Aquaculture			
Algal cultivation and aquaculture	*N. oculata* and *T. suecica* cultivation in 1–15% POME in seawater media	Higher maximum specific cell growth of 0.17–0.21/day, and lipid content of 20.71–39.14%; at 10% POME in sea water, high palmitic acid in *N. oculata* (28.22%) and *T. suecica* (36.48%)	Shah et al. (2016)
	Outdoor large-scale cultivation of *Arthrospira platensis* in 1% v/v fresh POME	Higher maximum specific growth rate (0.25/d) and biomass productivity (0.211 g/L.d) than the Control culture; Level of chlorophyll (1.05%DW), carotenoid (0.57%DW), phycocyanin (12% DW) comparable to Control	Sukumaran et al. (2014)
	Rectangular photobioreactor for high density *Nannochloropsis* sp. cultivation	More surface for light illumination to achieve the cell density of 1.0 $\times 10^8$ cell/mL, 10–20 times higher than the outdoor culture tank, need only 15 L of green water in tiger grouper larvae culture tank (5 tonnes of water in 10 tonne tank) to achieve 0.3 $\times 10^6$ cell/mL cell density	Teoh et al. (2021)
6. Bio-solvent			
Bio-solvent/Co-solvent	Based on 2-methyl tetrahydrofuran and isoamyl alcohol (at 2:1 ratio (v/v)); Terpenes for microalgal oil extraction	Lipid extraction with 78% selectivity and 88.2% efficiency, compared to the conventional solvent; Comparable efficiency and selectivity to n-hexane	de Jesus et al. (2018); Dejoye Tanzi et al. (2012); Mahmood et al. (2017)
	Imidazolium-based IL with methanol co-solvent	Lipids extraction from microalgae along with trans-esterification; The ILs achieve oil extraction efficiency higher than 70%	Shankar et al. (2017); Wahidin et al. (2018)
	IL-EFB mixture prepared at 100 °C, 270 rpm, followed by dry-jet wet spinning using water coagulation bath.	Smooth surface RCF; with a round and rigid structure; hard to break characteristic at 160.45 ± 0.699 MPa tensile strength, 8.774 ± 0.699 cN/tex tenacity, 83.245 ± 1.183 MPa Young's modulus, and 12.92% elongation at break.	Hassin et al. (2022)
	Choline chloride-oxalic acid at optimal ratio, water addition and temperature, wit ultrasound assisted extraction of polyphenols from *Aegle marmelos*	Reduction in viscosity, with enhanced H-bonding between the DES and the components, enhanced yield and capacity by more than 60% as compared to the conventional solvents	Saha et al. (2019)
	Switchable solvent based on N-ethylbutylamine through the application of stress and multiple stages of extraction	Enhanced lipid yield from *Neochloris oleoabundans*	(Du et al., 2015, 2017)
	Transesterification of glycerol triolate catalysed by basic IL for biodiesel preparation	Lipid extraction, followed by transesterification, triglycerides react with methanol and converted to monoglycerides, diglycerides, and biodiesel	Zhou et al. (2012)
	Palm oil and methanol as co-solvent	Simultaneous extraction-transesterification process based on potassium hydroxide-catalyzed single-step synthesis of biodiesel from *Spirulina* sp.	Pradana et al. (2020)

2. Palm oil mill processes and wastes

Fig. 2 shows the typical oil palm plantation, palm oil mill, fruits and wastes generated. Approximately 181 billion tonnes of biomass wastes are produced annually across the globe (Dahmen et al., 2019). In 2022, an estimated of 182.6 million tonnes of biomass are generated in Malaysia, of which 89.8% (164 million tonnes) come from plantation biomass, and others are contributed from agricultural biomass (2.3%), woody biomass (2%), livestock industry waste (5.6%), and fisheries industry waste (0.4%). Palm oil industry in Malaysia processes an estimated of 94.8 million tonnes of fresh fruit bunches (FFB) in the mill, producing large number of wastes such as (million tonnes) empty fruit bunches (EFB) 7.3, mesocarp fibers (MF) 7.68, palm kernel shell (PKS) 4.43, palm kernel cake (PKC) 2.47, and POME 63.5 (Ministry of Plantation and Commodities, 2023). Other wastes include palm pressed fibers (PPF), decanter cake, palm oil mill sludge (POMS), and flue gas emission; and from the plantation area are the fronds, and trunks (Rupani et al., 2010).

The accumulation of wastes is contributed mainly by the processing stages during the extraction of CPO from the FFBs. The first stage is sterilization where freshly harvested FFBs are subjected to a high-pressure steam (120–140°C at 3 bar) for 75–90 min to inactivate lipolytic enzymes and prepare the mesocarp for subsequent processing (Thani et al., 1999, Ma et al., 2000, Sivasothy et al., 2005). During stripping, the fruits are mechanically stripped to produce EFBs. The separated fruits are reheated during digestion using 80–90°C hot water to rupture the oil bearing cells, and prepare for oil extraction (Noerhidajat et al., 2016). Whilst the twin screw presses out the oil under high pressure, more hot water is added. The CPO now consists of a mixture of palm oil (35–45%), water (45–55%) and fibrous materials at different proportions (Thani et al., 1999). In clarification tank, the oil is continuously skimmed-off from the top and passed through a high-speed centrifuge and a vacuum dryer before being sent to the storage tanks (Thani et al., 1999). The press cake which is made up of oily fiber, nut, and the moisture, is sent to a depericarper to separate out the nuts and the fibers (Borja and Banks, 1994a; Borja et al., 1996; Thani et al., 1999). The nuts are sent to a rotating drum where the remaining fibers are removed. The nuts later will go through a nutcracker to get the palm kernel. The kernels and the shells are further separated out by hydrocyclone, and the discharge provides additional source of wastewater stream (Ng et al., 1987). Palm kernel can be sold for the extraction of palm kernel oil. At the end of the oil extraction process, the solid waste materials and by-products generated are the EFBs (23% of FFB), potash (0.5% of FFB), palm kernel (6% of FFB), PKS, PKC, and the fibers (Thani et al., 1999).

A metric tonne of FFB produces 14 m^3 of POME or 25 kWh of energy on average (Basiron and Weng, 2004). At 16.3 million tonnes of CPO production, approximately 2.5–3.5 tonnes of POME/tonne of CPO is generated (Ahmad et al., 2005a; Shavandi et al., 2012a). POME is contributed by the steam condensate (36%), main clarification (60%), and hydrocyclone (4%) units (Thani et al., 1999, Ma et al., 2000). It is a thick brownish, colloidal suspension containing water (95–96%), oil and grease (0.6–0.7%) and total solids (4–5%), including 2–4% of suspended solids (Wong et al., 2009). These are mainly the cell walls, organelles, short fibers, different types of carbohydrates, a range of nitrogenous compounds, free organic acids and organic and mineral constituents (Ugoji, 1997). POME is discharged at 80–90 °C, at pH of 3.4–5.2 with (mg/L) 16000–100000 Biological oxygen demand (BOD); 23000–61994 Chemical oxygen demand (COD); 4000–7550 Total organic carbon (TOC); 80–1400 Total nitrogen (TN); 5000–54000 Total suspended solids (TSS); and 150–18000 Oil and grease (Thani et al., 1999; Rupani et al., 2010; Saleh et al., 2012; Shavandi et al., 2012a).

Palm oil mills are normally located near rivers to facilitate the supply of water. This has caused POME to become one of the major sources of aquatic pollution, especially when discharged indiscriminately (Ma, 2000; Singh et al., 2010). The characteristics of POME and effluent discharge standards limit (mg/L) are pH 5–9, BOD 100; COD -; TOC -; TN 150; TSS 400; Oil and grease 50 (DOE, 1999). The permissible limits of iron, manganese and zinc are 179.1, 14.4 and 28.0, respectively (Shavandi et al., 2012a,b). Heavy metals especially Cu(II) and Zn(II) and phenol 2,6-bis (1,1-dimethylethyl) are regarded as the major toxicants in POME final discharge (Hashiguchi et al., 2020). The Malaysian Environmental Quality Act 1974 and Environmental Quality (Prescribed Premises) (Crude Palm Oil) regulations (1977) make it mandatory for industrial players to provide efficient management and mitigation procedures to avoid environmental catastrophe (Thani et al., 1999). Environmental Quality Regulations 1977 is promulgated under Section 51 Environment Quality Act 1974 for environmental control of palm oil mills discharge. The mill must obtain a license to operate, and to allow the enforcement of the effluent standards based on the demands of the prevailing environmental conditions (DOE, 1999).

3. Environmental remediation with bioenergy co-generation

The abundance of wastes from palm oil processing and operations provides great opportunities for waste re-utilization and commercialization by the industries. Table 1 shows waste valorization and bioenergy co-generation with environmental remediation via biorefinery routes. For old mills, EFBs and decanter cake are applied in the plantation as fertilizer, mulched, or burned in the incinerator to produce potash (Chavalparit et al., 2006). Land application of POME and biomass wastes is practised but over-applied could lead to organic matter coating on the soil surface, resulting in anaerobic conditions (Zakaria et al., 2000; Keu, 2005). Due to its eutrophying nature, POME is one of the biggest sources of methane and carbon dioxide emission (Tan and Lim, 2019). Effective POME treatment involves the combinations of physical, chemical and biological methods to remove suspended solids and residual oil (Abdullah and Ahmad, 2016). The selection of any system ultimately hinges upon the cost, and ease of operation in the large-scale plantation and mill setting. Due to low costs, more than 85% of the mills use only ponding systems for effluent remediation (Yeoh, 2004), and opt for the sequence of anaerobic and facultative pond system, and open tank digester with extended pond aeration (Bello and Raman, 2017). Conventional techniques require less energy due to limited mechanical mixing, operational control, and monitoring (Yacob et al., 2006), low operating costs and capable of supporting high rate of organic loading. However, these may need large area to accommodate the ponds, with long retention time, low nitrogen and phosphorus removal efficiency,

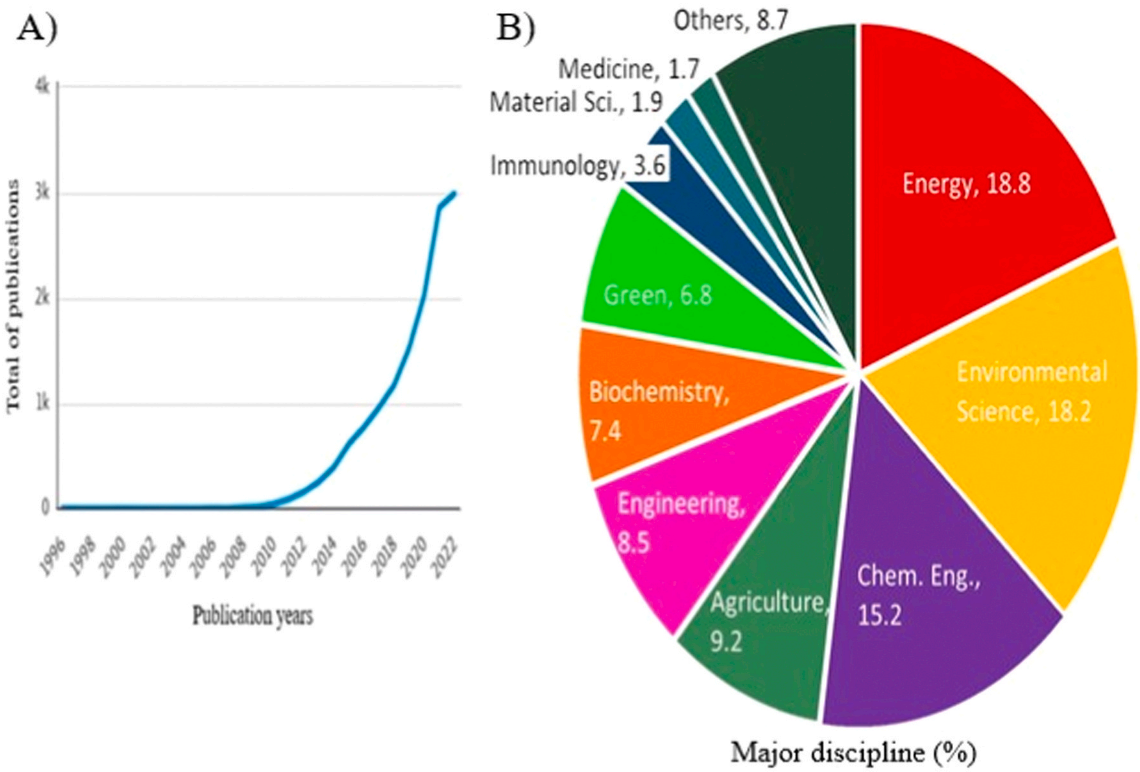

Fig. 1. Publications based on "Algae" and "Biorefinery" keywords - A) Trends in publications between 1996 and 2022 in Scopus database; and B) Major discipline.

Fig. 2. A) Typical oil palm plantation with palm oil mill; B) Palm Oil Mill; C) Piles of Oil Palm Empty Fruit Bunches waiting to be transported, C1: Fresh Fruit Bunch, C2: Fruit, C3: Empty Fruit Bunch; D) Effluent in treatment lagoon.

and high amount of sludge produced. Aerated lagoons use artificial aeration where the high temperature of the pond increases substrate removal (Environmental Management Guideline for the Palm Oil Industry, 1997). The drawback is that large open pond system leads to indiscriminate release of methane.

Clean development mechanism (CDM) promotes total GHGs emission from open systems to be substantially reduced using closed anaerobic reactors, where biogas is captured, or used for flaring, boiler fuel or power generation (Tong and Bakar, 2004; Yacob et al., 2005; 2006). The problem is, flaring releases CO_2, methane, nitrous oxide, and black soot into the atmosphere (International Energy Agency, 2023). During anaerobic treatment, dissolved organic substrates are mostly converted into biogas (a mixture of around 60% CH_4 and 30% CO_2), and very little substrate is converted into biomass. The treated POME however may be incomplete with greater risk of releasing GHGs from subsequent treatment (Lam and Lee, 2011). The steel structures may get corroded from prolonged contact with hydrogen sulfide (Yacob et al., 2006). Other conventional pretreatments of POME include flocculation by aluminum sulphate, and polyaluminum chloride, followed by solvent extraction and adsorption (Ng et al., 1987; Ahmad et al., 2005a, 2006). The trend is increasing towards physical treatment (Ahmad et al., 2005c,d) using biosorbent (Embrandiri, et al., 2012), and biocoagulant such as chitosan (poly D-glucosamine) (Ahmad et al., 2005b). With the aid of a flocculator, the colloidal and suspended organic matter could effectively be removed although this may be less efficient on dissolved organic matter (Ahmad et al., 2005a,b). Agro-based adsorbents are low cost, with excellent hydrophobic-oleophilic properties, large specific surface area and modifiable surface for tunable properties to sorb organic and oily wastes (Abdullah et al., 2015; Daneshfozoun et al., 2017).

There is greater attention for process control to prevent spillage and product losses utilizing equipment with low energy and water consumption. The lab scale Continuous Stirred-tank Reactor (CSTR) could achieve 94–98% COD removal from POME (Ugoji, 1997), but the CSTR in actual palm oil mill setting may attain lower COD removal efficiency and methane production. The incorporation of a biofilm support system (BSS) into the CSTR, enhances biomass growth and efficiency (Ramasamy and Abbasi, 2000). Membrane technology, up-flow anaerobic filtration, up-flow anaerobic sludge blanket (UASB), and up-flow anaerobic sludge fixed film (UASFF) (a hybrid based on the integration of the UASB reactor and anaerobic filter) bioreactors are the alternatives to enhance the performance and efficiency of treatment. The long Hydraulic Retention Time (HRT) can be rectified by using high-rate anaerobic bioreactors, while the long start-up period can be shortened by using granulated seed sludge (Wu et al., 2010; Lam and Lee, 2011). Of great importance is to maintain high-rate anaerobic bioreactor at optimal pH and temperature to promote microbial growth (Lorestani, 2006; Wu et al., 2010). In the treatment of POME using the UASB reactors under high OLR of 9.5 g COD/L.d and transitioning from mesophilic to thermophilic (57 °C) conditions, acceptable COD removal and biogas production are achieved from the more diverse microbial population of hydrolytic, acidogenic, and acetogenic bacteria. Under mesophilic (37 °C) condition, significant biomass washout is reported (Khemkhao et al., 2012). These suggest the importance of optimal OLR and operating temperature on the microbial diversity and performances of the UASB reactors in treating highly polluting wastewater such as POME. A mixture of 100% molasses used as a start-up, with 10% increment of POME over a period of 59 days until 100% POME, have been treated under continuous mode in the UASFF bioreactor. At 30% molasses and when POME is increased from 70% to 100% on day 57–59, the amount of hydrogen is between 53% and 70%, while methane is at 90–95%. With 100% raw POME added, 83.7% of total COD removal is achieved with a total gas production of 5.29 L H_2/d at 57.1%, and 9.6 L CH_4/d at 94.1%. These are comparable to the results from the treatment of 100% molasses. For over 2 months start-up period, the two-stage UASFF operates optimally at 4 h HRT and 43 °C, to produce more stable biogas on day 56–59 (Zainal et al., 2019).

4. Integrated Algal-Oil Palm Biorefinery

Conventional approaches to waste treatment have not fully reaped the economic benefits of waste valorization, conversion, and utilization. Biorefineries have become viable alternatives not only in promoting circular bioeconomy (Banu et al., 2020), but more importantly in achieving the agenda of Global SDGs to produce bioenergy, biochemicals and bioproducts, with socio/economic framework for holistic community development and extreme poverty eradication (Budzianowski, 2017; Abdullah, 2021; Abdullah and Hussein, 2021; Cheng et al., 2022). Despite big potential for immediate use in the mill itself, large amount of solid wastes remain underutilized (Hamzah et al., 2019). The spirit is when there are no passive wastes released to the environment, either before or after treatment, there will be no environmental pollution. Achieving "Zero wastes" is a step forward towards sustainable development of a palm oil mill (Haan et al., 2021). The simultaneous promotion of circular economy, with eco-friendly approaches for resource optimization, conservation of biodiversity, and environmental rehabilitation (Abdullah, 2021; Talebi et al., 2022) pave the way to address the 5 pillars of global security - the Climate-Energy-Food-Water-Socio/Economic Nexus. Integrated Algal-Oil Palm Biorefinery, as illustrated in Fig. 3, is positioned as a unique model system by making use of the most well-managed plantation system in the world based on oil palm, in combination with smart algae cultivation system for high-value added products.

Waste recycling, and utilization from palm oil processing to produce other products or for different applications in the factory or externally, could significantly reduce the operational cost, and increase the profit margin. The residual biomass such as EFBs, MF, PKS, and POME are feedstocks for fuel, fibers, fertilizers, or composite materials (Chiew and Shimada, 2013; Garcia-Nunez et al., 2016; Abdullah et al., 2016a). The fibers are cheap sources of biopolymers especially as cellulose, hemicellulose and lignin (Nazir et al., 2013; Abdullah et al., 2017b). The multi-product algal bio-refinery model is the route to produce pharmaceuticals and high-value natural products; feed and food supplements; bioenergy, biomaterials and biochemicals; and for wastewater treatment (Fabris et al., 2020). The integration of CO_2 or flue gas biofixation with wastewater treatment allows microalgae to absorb CO_2, and capture wastewater nutrients such as those in POME (Abdullah and Ahmad, 2016). POME is an economical medium for algal cultivation especially for specialty chemicals such as lipid, astaxanthin, biofertilizer, and bioplastic (Shah et al., 2014; 2016; Kamarudin et al., 2015; Nur and Burma, 2019; Fernando et al., 2021; Hussain et al., 2021; Nur, 2022). The different routes for bioenergy co-generation may involve combustion of residual algae, biogas production from POME, the production of biochar, bio-oil, and green diesel (Hamid and Lim, 2019), bioethanol and biohythane (Abdullah and Hussein, 2021); and bioelectricity (Ng et al., 2021). With sustainable energy production, the value-added biomaterials and biochemicals can be implemented with smart aquaculture system within the plantation and palm oil mill eco-system.

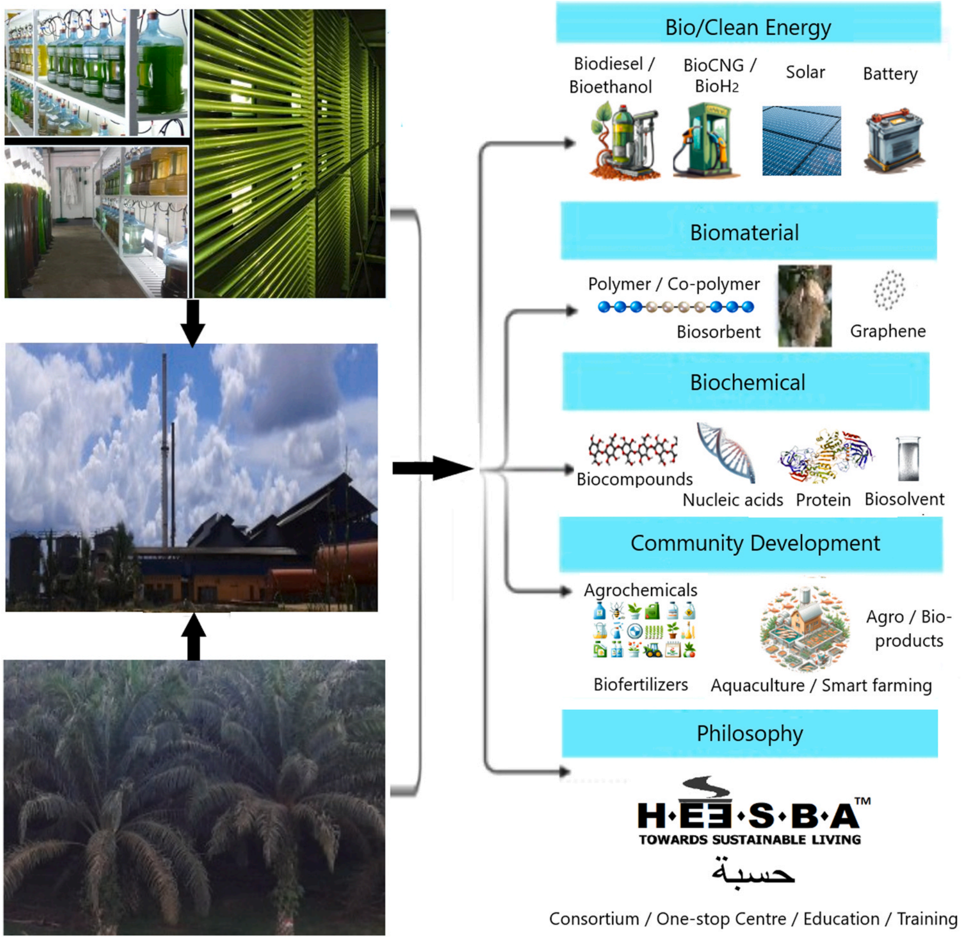

Fig. 3. Integrated Algal-Oil Palm Biorefinery for bioenergy and bioproducts co-generation with value-added environmental remediation and waste valorization (Microalgal Culture Facilities and PBR courtesy of Centre for Sustainable Aquatic Research, University of Swansea, United Kingdom, with permission).

4.1. Bioenergy production

Oil palm industry remains viable as the production house of economical heat, power, and electricity generation (Ludin et al., 2009). The mills are self-sufficient in terms of energy requirements as the amount of fibers generated are adequate as solid fuels in the steam boiler for power generation. The combustion of 0.3–0.4 kg of wastes may produce steam to electricity of about 20 to 1 ratio (Husain et al., 2003). This meets major portion of electrical and energy needs in the mill, with backup diesel generator (Mahlia et al., 2001; Yusoff, 2006). However, the boiler and turbine used may have low thermal efficiencies as compared to those in the conventional power plants, attributable to the non-uniformity of the fuel quality used. At the extraction rate of around 0.188 for the co-generation system utilizing biomass residue as fuel in the boiler, the power output can be increased by 60% even at just 65% utilization factor, by replacing the back pressure turbine with a condensing turbine (Husain et al., 2003). One tonne of EFB with 65% moisture is estimated to deliver 418.6 kWh electricity, giving economic return of RM 49.81, almost 3.5 times higher than the returns when EFB is used for mulching (Menon et al., 2003).

The issue with direct biomass combustion in the boiler and incinerator is that incomplete combustion can be the source of gaseous emission (Thani et al., 1999). The release of methane from POME treatment through open pond and lagoon is one of the major sources of gaseous pollution (Shirai et al., 2003). POME remediation and disposal can be integrated in the pretreatment plants to increase biogas production and optimized for industrial applications (Aziz et al., 2019b; Khadaroo et al., 2021). Integrated biogas production system involves pumping of POME into the storage tank (reception tank), before POME being flowed into the digester and post digester tank. The two digester tanks must be optimized for biogas production. The biogas will go through desulphurisation stage to reduce sulphur content, and later the compression unit, to compress the gas before going to the storage tank (MPOB, 2011). The biogas is used for heat and electricity, and for use in engines, microturbines, and fuel cells; or the biomethane can be upgraded into vehicle fuel. Both sludge and wastewater will be produced as wastes, and the treatment unit must be included in the process flow. The treatment of wastewater is normally carried out by bacterial consortium or a mixture of microbial community (Oswal et al., 2002; Lanciotti et al., 2005). It will be difficult for just one organism to metabolize all the polluting components of different effluent characteristics, and to treat them into acceptable discharge level (Asses et al., 2009). The inocula from activated POME sludge and different types of compost have been evaluated in the anaerobic fementation of artificial wastewater with 10 g glucose in a batch process. The anaerobic microflora produce biogas containing 66–68% H_2 and 32–34% CO_2 without methane being generated (Fakhru'l-Razi et al., 2005). This may suggest the importance of high organic content wastewater to enhance methane productivity.

Although the combustion of biofuels eventually leads to CO_2 emission, the cultivation of biomass feedstocks could offset the CO_2 generated and therefore is not considered in the GHG inventories (Energy Information Administration, 2022). Palm oil biodiesel has been touted as the cleaner fuel than petroleum diesel due to lower GHG emission during combustion (Ganjehkaviri et al., 2016). The GHG emission of bio-hydrogenated diesel (BHD) produced from palm fatty acid distillate (PFAD) is lower than that produced from fatty acid methyl ester (FAME), but the energy consumption is higher and the overall environmental impact of BHD-PFAD is 3.58 greater than the BHD-FAME (Boonrod et al., 2021). The viable options to simultaneously produce valuable liquid and gaseous biofuels are through pyrolysis and gasification of the biomass (Aziz et al., 2019a). Pyrolysis of EFB or Oil Palm Trunk (OPT) (Sakulkit et al., 2020; Mahmud and Zakaria, 2020), and fast pyrolysis of oil palm shells (OPS) (Abnisa et al., 2011), produce bio-oil, biochar (Kong et al., 2014) or pyrolysis gases. Bio-oil is easy to use, store, and transport as an alternative to petroleum fuel (Bridgwater and Peacocke, 2000). Co-pyrolysis of OPT and rubber wood sawdust at 50:50 (wt%) ratio, at 400, 450 and 500 °C and specific reaction conditions, in an agitated bed pyrolysis reactor, improve the quality and yields (wt%) of bio-oil (38−47), pyrolysis gas (30−37), and biochar (22−29). The biochar has high C and low O content and exhibits Higher Heating Value (HHV) of 26–30 MJ/kg, as compared to 16–21 MJ/kg for bio-oil, and 3–7 MJ/m^3 for pyrolysis gas (CO, CO_2, H_2 and CH_4) (Sakulkit et al., 2020).

Hydrothermal gasification of biomass produces syngas and hydrogen (Nirmala et al., 2022). The basic principle of Palm Waste Biomass Gasification Power Generation System (BGPS) is to convert the EFB, PKS, or Oil Palm Fibre (OPF) into combustible gas. The high temperature exhaust gas can be reused by the waste heat boiler to generate steam, or hot water for civil or industrial use, or used as fuel in gas engine to generate electricity. The process involves conversion of biomass into syngas in the first stage; syngas purification in the second stage to remove dust, coke, or tar (Calvo et al., 2012); and power generation in in the third stage. With high content of volatiles (>82%) and more than 90% decomposition achieved at 700 °C, the reactivity of EFBs is suitable for gasification. However, having moisture content greater than 50%, and oxygen content more than 45%, the calorific values of EFBs are low (Mohammed et al., 2012). Compared to the biochar with the HHV of 26–30 MJ/kg (Sakulkit et al., 2020), gasification of OPF produces the HHV of 0.24–0.41 MJ/m^3, and for *Koompassia malaccensis*, or Kempas biomass (forest residues) with the HHV of 0.75–0.93 MJ/m^3. The Equivalence Ratio (ER) and Cold Gas Efficiency (CGE) of OPF are also lower at 0.3 and 2.18 MJ/m^3, respectively, than Kempas at 0.35 and 4.98 MJ/m^3, respectively. When the gasification temperature is increased from 700 to 900 °C, the gas composition changes with higher levels of H_2 and CO produced, and lower CO_2 released from Kempas (Ismail et al., 2019). Biomass gasification is advantageous as it requires small land to operate and is environmentally friendly (Bhoi et al., 2018). To increase total efficiency, steam turbine can be incorporated as a Gas-Steam Combined Cycle Power Plant (Singh et al., 2017). Power plants are increasingly utilizing Gas/Steam Combined Cycles for better energy consumption and performance than the individual Gas turbine or Steam turbine plant. In a study using a gas turbine with closed loop cooling of gas turbine blades and multiple approaches of the bottoming cycle, effective use of energy in the topping cycle could determine the variation in the bottoming cycle based on steam cycle or ammonia water cycle or its combination. Maximum work output of 638 kJ/kg of air for simple gas turbine is attained by having the bottoming cycle with reheated ammonia water turbine and steam turbine (Maheshwari and Singh, 2019).

Oil palm biomass conversion to bioethanol can replace gasoline and fossil fuels. With abundance of hemicellulose and cellulose components (Laosiripojana et al., 2018), bioethanol production from oil palm biomass is a competitive option to biodiesel and biogas generation. It is estimated that 142.25 tonnes of bioethanol can be produced from oil palm biomass per hectare. The EFBs show the highest potential as the substrate as compared to the leaves, frond and the OPT (Islam et al., 2021). The conversion to bioethanol requires pretreatment and delignification steps, before processing to hydrolysis step (Sukhang et al., 2020), and fermentation of sugars into bioethanol using *Saccharomyces cerevisiae* (Adela et al., 2014; Kumneadklang et al., 2015). The overall yield is affected by the pretreatment method such as the acid-alkali treatment which produces hydrolysed sugar for fermentation (Sukhang et al., 2020). During Simultaneous Saccharification and Fermentation (SSF), phosphoric acid pretreatment of EFB results in 89.4% theoretical ethanol yield (Ishola and Taherzadeh, 2014). The SSF process under optimal conditions produces 0.281 g/g of bioethanol, while the Separate Hydrolysis and Fermentation (SHF) process under optimal conditions, where sugar production via hydrolysis is kept separated from fermentation, results in 0.258 g/g of bioethanol along with 0.584 g/g of reducing sugars.

Hemicellulose and cellulose can be the raw material to produce Ethyl tert-Butyl Ether (ETBE) where xylose is fermented to ethanol, and glucose is fermented to *i*-butene. Both ethanol and *i*-butene is required for ETBE production (Galán et al., 2019). The composition of biomass is important to determine the resulting byproducts. Dilute acid is the preferred pretreatment method over a novel ammonia fiber explosion (AFEX) due to high sugar yield and the flexibility to modify both ethanol and *i*-butene production to suit the requirements of ETBE. The economic analysis suggests that at a cost of 0.61€/kg for 90 kt/year of ETBE, an investment of 160 M€ must be made (Galán et al., 2019). Integrating ethanol and biodiesel production based on extractive reaction process with transesterification of *in situ* ethanol from EFBs and Palm Press Fiber (PFF) could possibly lower the unit energy costs, and material and energy costs (Table 1) (Gutiérrez et al., 2009). The oil from FFB is the feedstock for biodiesel, and an extractive reaction is for the transesterification based on in situ ethanol from EFB and PFF residues. Material flow analysis suggests that the integration could reduce the unit energy costs down to 3.4%, and material and energy costs to 39.8% reduction. The integration however may not yet be feasible as the technology has not reached maturity where ethanol production from biomass will be more comparable economically to the production from grain or sugarcane (Gutiérrez et al., 2009). Based on Life Cycle Assessment (LCA), the addition of bioethanol to the process of biodiesel production reduces the Net Energy Ratio (NER) by 27.5%, the Net Carbon Emission Ratio (NCER) by 66.6%, and the Carbon Emission Savings (CES) by 21.9%. The overall production of bioethanol from palm oil industries has shown some positive environmental impact, but it still requires large energy input as well as resulting in GHGs emission. This eventually results in producing a net negative environmental impact more than the energy output obtained from the use of bioethanol itself. Minimum conversion of larger than 60% to bioethanol is needed for greater energy and GHG emission ratio than the processes for biodiesel, with biogas recovery put in place, and no new expansion of the plantation into the primary forest or peatland (Lim and Lee, 2011).

The controversy surrounding the fuel versus food debate in relation to palm oil utilization, makes algae the natural choice to replace palm oil. Biodiesel production using microalgae is advantageous, not only due to similar profiles as that of plant-based biofuels, but also because of their higher photosynthetic potential as well as lipid content than plants (Sun et al., 2018; Catone et al., 2021). A novel biorefinery route, with complete biomass valorization, and zero-waste approach has been developed utilizing self-flocculating *Chlamydomonas* sp. BERC07 grown on urban wastewater as a low-cost growth media. Improved biomass production (1.24 g/L) by 2-fold, with removal of 41% BOD, 56% BOD, 94% P and 100% TN are reported. The use of potash alum as additional flocculant at 0.27 kg/1000 L dose enhances the flocs sedimentation by 240-fold, with 96–98% algal biomass recovery efficiency. The downstream processing of the biomass yields 1.8 mg/g of carotenoids, and 480 mg/g of lipids which are transesterified to produce biodiesel that meets the US/European standards. A total of 75–100 g/L of the residual biomass is further fermented with *Aspergillus niger* and *Aspergillus oryzae* to produce 131.6 U/mL of α-amylase and 375–384 mg/g of mycoproteins. The extracting solvents for product recovery are recycled to complete the biorefinery route (Malik et al., 2022).

The improved economics of microalgal biodiesel production is currently not yet sustainable. The reduction in costs with the recycling of water, nutrient and CO_2 remains challenging especially in attaining high algal culture quality (Patnaik and Mallick, 2021). This has shifted the interest towards the use of microalgae for wastewater treatment and biogas production. For microalgae culture grown on POME, *Chlorella* sp. is the most common species used due to its high oil-to-biomass ratio, and its capability to attain high growth rate, biomass productivity, saturated and unsaturated fatty acids, and ester content up to 68.9–71% (Resdi et al., 2016; Idris et al., 2017). The two-stage thermophilic fermentation, and solar-assisted bioreactor and the anaerobic algal co-cultivation with POME, sludge inocula and co-substrate addition such as the EFBs, kernel, shell, decanter cake and crude glycerol, are effective strategies to enhance the biogas yield (Table 1) (Saleh et al., 2012; Ahmad et al., 2014; 2015,; Kanchanasuta and Sillaparassamee, 2017; Mamimin et al., 2019; Zaied et al., 2020). Two stage anaerobic digestion of *Chlorella* sp. residual biomass produces both CH_4 and H_2 (Lunprom et al., 2019). The presence or absence of microalgae in the microflora could determine whether methane, hydrogen or CO_2 will be produced. Without microalgae, anaerobic digestion of EFB with sludge inoculum and POME at high temperature produces around 26% methane yield (Saleh et al., 2011). Optimal dosage and the combination of EFB, sludge inoculum and microalgal species could attain as high as 5256.8–5295.8 mL CH_4/L POME/day with *Chlorella* sp.; and 4606–5018 mL CH_4/L POME/day with *N. oculata* (Table 1) (Ahmad et al., 2014; 2015). Maximum removal efficiencies of BOD (83–98%) and COD (83–98%) with *Chlorella* sp. and *N. oculata* addition are also higher than without microalgal addition at around 83–86% BOD and 69–96% COD (Ahmad et al., 2014; 2015). With just POME in the anaerobic digester, and in the absence of *Chlorella* or *N. oculata* and sludge inoculum, low CO_2 and some amount of biohydrogen are produced but there is no methane.

Microalgae is feasible for biohydrogen production due to its high photosynthetic efficiencies (Dębowski et al., 2021). For co-production of bio-hydrogen and bio-methane, higher efficiency can be obtained through two-stage dark fermentation of the POME, thermophilic and mesophilic anaerobic sequencing, along with microbial electrolysis (Khongkliang et al., 2019; Maaroff et al., 2019). Two stage anaerobic digestion of *Chlorella* sp. residual biomass produces H_2 of 12.5 mL/g Volatile Solid (VS) and CH_4 yield of 81 mL/g VS, equivalent to the total energy yield of 3.03 kJ/g VS or 4.6% energy recovery (Lunprom et al., 2019). Biohythane production from POME can be a route for a more controllable H_2/CH_4 ratio especially in the range of 0.13–0.18 ratio, deemed suitable for vehicle fuel. A two-stage, pilot-scale thermophilic treatment of POME at 55 °C involving 2 days HRT and 27.5 g COD/L·d OLR in the first stage, and 10 days HRT and 5.5 g COD/L·d OLR in the second stage, has resulted in the biogas composition of 11% H_2, 52% CH_4 and 37% CO_2 at 1.93 L gas/L.day of biohythane. The H_2 stage is dominated by *Thermoanaerobacterium* sp., and methane stage by *Methanosarcina* sp. Optimal pH at 5–6.5 in the first stage is controlled by circulating the methane and mixed with POME at 1:1 ratio (Seengenyoung et al., 2019).

Biogas generation from POME makes use of feedstocks which are available at a low cost or may even generate a tipping fee, making it economically favourable as the source of sustainable, clean, affordable, efficient, and secure energy (Yang et al., 2014; Mohtar et al., 2017). The biogas plants based on POME may be in rural areas whose supply is most often exceeding the demand, with excess biogas highly likely flared. The biogas consisting of 60% methane needs scrubbing and compressing for transportation and distribution. Excess biogas can be transported as compressed gas, or via pipeline to a location with higher demand. For different storage systems and distribution by truck or pipeline, the specification may vary to meet the strict safety and quality standards (Mohtar et al., 2017). Compressed natural gas (CNG) or liquefied (LNG), is another alternative fuel to the petroleum-based transportation fuels proposed to reduce GHG emissions by more than 80% as compared to the gasoline (Bordelanne et al., 2011; Mohtar et al., 2017). LNG and CNG have low carbon footprint and low local emissions of NO_x and SO_x. The biogas-based Bio-LNG has roughly the same chemical formula as the relatively pure methane LNG, but without the higher hydrocarbons present in the LNG (Van Dael et al., 2014). The biogas-based CNG, Bio-CNG, is similar to regular CNG in terms of vehicle fuel economy and emissions. Conversion of biogas to Bio-CNG requires removal of water, N_2, O_2, H_2S, NH_3 and CO_2 impurities from the raw biogas. Bio-CNG is then made by compressing the purified biogas at high pressure, resulting in it requiring less than 1% of the volume that it occupies at standard atmospheric pressure (Yang et al., 2014).

Apart from land transportation fuels, of great interest in addressing global climate change issue is in finding replacement to the burning of jet fuels. Algal biomass provides a viable route in the production of jet biofuel such as through the hydrolysis of algal cell-wall into carbohydrates and simple sugars for conversion into alcohol to jet biofuel; or intermediates hydrocarbon, or methane or synthesis gas via catalytic hydrothermal gasification for algal biomass-to-gas to jet biofuel (Ewurum, 2018). Algae in a mixture with *Jatropha* has been evaluated up to 50% (the blend of 2.5% algal oil and 47.5% jatropha oil) of the jet biofuel content in flight tests (Wang and Tao, 2016; Wang et al., 2016). The reaction route to transform palm oil into jet biofuels include de-oxygenation of fatty acids to C15 and C18 alkanes by decarbonization and decarboxylation, catalytic cracking into C8-C14 alkanes, and cyclic alkanes as well as aromatics into aromatic hydrocarbons (Basir et al., 2021). High pyrolysis temperature above 800 °C is required to convert cobalt phosphide (Co2P) phase to CoP phase, for higher cracking activity of palm oil, and selectivity to jet biofuel, due to improved acidity of the catalyst (Kaewtrakulchai et al., 2020).

4.2. Supercapacitors and energy storage

High capacitive performances have been reported based on carbon fiber (CF) produced from PKS-extracted lignin (PKS-lignin) and polyacrylonitrile (PAN). The excellent performance is attributed to the enrichment of heteroatoms and excellent-wetting surfaces of the PKS-lignin/PAN CF electrode, even without any conductive additive (Thongsai et al., 2021). High performance electrochemical double layer capacitor (EDLC) fabricated from PKS-based activated carbon (AC) shows superior capacitance, low series resistance and relaxation time in comparison to other biomass-derived carbon electrodes, and therefore could provide high power density (Misnon et al., 2015). The coin type CR2032 cells with glass separator is fabricated using PKS-based AC which has been physically activated (pAC) and chemically activated (cAC) in 1 M H_2SO_4, 1 M Na_2SO_4 and 6 M KOH electrolytes for electrochemical charge storage (Misnon et al., 2019). PKS can be the source for the preparation of porous carbon for high performance symmetric supercapacitor with superior energy and power density, and higher specific surface area and specific capacitance. Two step activation method using KOH produces activated carbon of large specific area (2521 m^2/g) and higher specific capacitance (360 F/g). The hierarchical, predominantly mesoporous carbon attains self-doping of O, P, S at high mass ratio. The assembled symmetric supercapacitor exhibits much higher energy density (11.38 W/kg) and power density (500 W/kg) than previously reported values (Li et al., 2023). Lithium-ion storage in carbon electrodes is challenging attributable to limited storage capability and poor electrode kinetics. To improve the performance of energy storage and batteries, improvements such as surface and void modifications can be made to enhance the storage kinetics and rate capability. Modifications of electrode surface or voids with thin film of Mn_2O_3 or cobalt or filling up the voids with hierarchical $MnCo_2O_4$ or TiO_2 nanoflowers could improve the specific capacitance, the potential window, and the kinetics. The electrode filled with $MnCo_2O_4$ flowers specifically exhibits the largest capacitance and capacity retention, owing to lower transfer resistance of lithium. The electrode surface modification with 10 wt% metal/metal oxide/nanoflowers results in moderate improvement in lithium-ion storability, but significant enhancement in the kinetics (Vijayan et al., 2023).

4.3. Biomaterials and biocomposites

The oil palm solid biomass wastes such as the OPF and OPS are viable substitutes of the raw materials to produce commercial biomass briquettes (Husain et al., 2002; Nasrin et al., 2008). The OPF can be added in polymeric matrices such as natural rubber, polypropylene, polyvinyl chloride, phenol formaldehyde, polyurethane, epoxy, or polyester, to form biocomposites (Shinoj, 2011); or as fillers in thermoplastic and thermoset composites, which are in high demand in furniture and vehicle parts (Shuit et al., 2009). The PKS which exhibits sturdy and strong physical characteristics has great potential as filler of the natural rubber vulcinates (Abbas et al., 2019), or as additive material in concrete. The OPF-concrete has higher compressive strength than the normal concrete, and the strength increases proportionally with the amount of OPF in the concrete (Lee et al., 2018). The PKS-concrete beams show higher moment capacity and more ductile mode of failure than the normal concrete beams, suggesting that the former could give ample warning before failure happens, and therefore are suitable as early warning sign for concrete beam failure (Alengaram et al., 2008).

The EFB has high moisture content of approximately 55–65%, and silica content of 25% from the total FFB (Keu, 2005). It may be more suitable for papermaking due to its lower tensile strength and higher tearing resistance. Total chlorine-free processes have been developed to bleach the pulp for paper production (Singh et al., 2013a). To achieve good tensile and tear indices, the EFB pulps and aspen pulps can be blended (Wan Daud and Law, 2011). Single step acetylation of cellulose from EFB utilizing sodium bisulfate and sulfuric acid as a catalyst, without the need for hydrolysis, is carried out to synthesize acetone soluble cellulose acetate (CA) of high Degree of Substitution (2.52). The acetylation is attained by optimizing the reaction time and the acetic anhydride/cellulose ratio. The synthesized CA has higher tensile strength and Young's modulus than the commercial CA (Daud and Djuned, 2015). Cellulose extracted from the EFBs have been fabricated into cellulose-polypropylene composite material (Abdullah et al., 2016a; Nazir et al., 2018a), biosorbent for diesel desulphurization (Nazir et al., 2018b), and cellulose-hydroxyapatite carbon composite electrode for heavy metal ions detection in blood serum (Ajab et al., 2018), POME (Ajab et al., 2019), and water sample (Ajab et al., 2020). Other types of oil palm-based biosorbents and biofilters include the magnetic biosorbents from EFBs, cellulose (extracted from EFBs), and *Ceiba pentandra* for heavy metal ion removal from water samples (Daneshfozoun et al., 2017), the PKS adsorbent for water treatment plant (Baby et al., 2019), the porous oil palm ash (OPA) for the removal of pollutant gases such as nitrogen oxide and sulfur oxide (Mohamed et al., 2006), chitosan-coated charcoal derived from OPS for heavy metal removal especially chromium from industrial wastewater (Saifuddin and Kumaran, 2005), and carbon molecular sieve (CMS) from OPS for adsorption of gases (Ahmad et al., 2008).

There is a great demand for eco-friendly, and biodegradable plastics from low-cost materials to replace non-biodegradable plastics and polymers derived from petrochemicals to reduce global plastic pollution (Adeleye et al., 2020; Dalton et al., 2022). Polylactic acid (PLA), polyhydroxyalkanoate (PHA), polyhydroxybutyrate (PHB), trimethylene terephthalate (PTT) polymer, cellulose ester, soy-based and starch plastic, functional vegetable oil-based resin and thermoset, and elastomer biocomposites, are being developed as biodegradable polymers (Dungani et al., 2018). Both residual solid waste as well as POME containing short-chain and long-chain fatty acids are suitable substrates for microbial conversion into biopolymers. Residual palm oil has similar fatty acid composition to the crude palm oil, but with additional degraded free fatty acids (Gomez et al., 2015a,b). Volatile fatty acid-rich effluent serves as inexpensive carbon source for bacterial or algal growth which can be converted into energy storage compounds. PHAs are accumulated by microorganisms as intracellular granules or carbonosomes utilizing substrates under limiting specific inorganic nutrients. These later are extracted or released as biopolymers and co-biopolymers. PHAs, together with PHB and PHB co-polymer, are biodegradable polymers, possessing similar properties to the synthetic polymer such as polypropylene. The diverse properties and functionalities of PHAs are attributable to the composition of the monomers (Dalton et al., 2022).

Cultivation of *Rummeliibacillus pycnus* Strain TS8 on POME in 1 L bioreactor produces terpolymer PHA and biodiesel (Junpadit et al., 2017). At optimal C/N ratio (10), aeration rate (1 vvm) and P (0.1 g/L), the highest cell dry weight, P(3HB-co-3HV-co-3HHx) which is composed of (mol%) 42.8 3HB, 34.9 3HV, and 22.4 3HHx.l, and lipid (59.5%CDW of oleic acid). In 72 L bioreactor cultivation, the terpolymer PHA extracted exhibits the Glass transition temperature (T_g) of −21 °C, and Melting temperature (T_m) of 147 °C. The tensile strength, Young's modulus and elongation at break values are 27.7 MPa, 1260 MPa, and 11.7%, respectively. The FAME produced shows the heating value of 32.9 kJ/g (Junpadit et al., 2017). This is lower than the LHV standards of 37–38 kJ/g for vegetable oils, biodiesel, and processed fuels (Mehta and Anand, 2009), although the flash point (132 °C), and pour point (7 °C) are within the standards (US Department of Energy, 2023; McCormick and Moriarty, 2023). An alkaliphilic, moderately halophilic *Halomonas alkalicola* Ext can accumulate PHAs. Optimal PHA of 1.42 g/L or

41.8% of PHA content obtained from 3.397 g/L of biomass after 72 h at pH 10, 35 °C and 2.5% (w/v) NaCl. Further optimization leads to 1.44 g/L of PHA, or 45.6% content. The PHA extracted is a poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) with two copolymer subunits of 3-hydroxyvaryrate (3-HB) and 3-hydroxybutyrate (3-HV). Under high salinity and alkalinity, *H. alkalicola* Ext attains high conversion of 2% galactose, with 0.1% ammonium sulfate as N source, into PHBV (Muigano et al., 2024). Poly (3-hydroxybutyrate-co-3-hydroxyhexanoate) or P(3Hb-co-3HHX) is the co-polymer in PHA family. A new strain, *Cupriavidus necator* PHB-4/PBBR_CnPro-phaCRp, has been genetically-engineered to produce P(3HB-co-2 mol% 3HHx) utilizing crude palm kernel oil as carbon source. The concentrations of palm kernel oil and sodium hexanoate, with cultivation time are optimized, resulting in 3.6 g/L of P (3Hb-co-3HHX) having 4 mol% of 3HHx monomer. In 10 L bioreactor, the 3HHx composition is enhanced to 5 mol% (Trakunjae et al., 2023). The issue with this strategy is the use of edible oil to produce inedible material, when volatile fatty acids (VFAs) such as those from dark fermentative effluents of biohydrogen reactor can be converted to PHAs (Kumar et al., 2019). Cyanobacterium *Arthrospira platensis* cultivated on POME with UV-C radiation exposure could accumulate PHB with C-phycocyanin (C-PC). The batch mode cultivation on 50% POME with modified Zarrouk medium, under 5 min irradiation of UV-C at 20 W m^{-2}, yields 7 mg/L.d of PHB, and 16 mg/L.d of C-PC (Nur, 2022).

For the synthesis of polyurethane from POME, different strategies such as epoxidation, transesterification, and polycondensation are employed. The polymer contains both the petrochemical and palm oil polyols components that eventually affect biodegradation properties (Arniza et al., 2015; Ng et al., 2017; Prociak et al., 2018; Polaczek et al., 2021). By using residual palm oil in POME and algal oil at different ratios in one-pot process, bio-rigid polyurethane foams of the required thermal and tensile strength along with biodegradability, can be obtained (Gomez et al., 2020). The use of non-edible residual palm oil with 10% algal oil or 10% jatropha oil as additives in the production of bio-based polyurethanes could improve thermal stability and biodegradability (Gomez et al., 2021). The polymerization is carried out based on one pot epoxidation with peroxyacetic acid and alcoholysis, and later reacted with poly-isocyanate for isocyanation of the hydroxyl groups to produce polyurethanes. Residual oil has higher content of free fatty acids but lower Iodine value than Refined Palm Oil. Algal oil contains higher phospholipids and has a slightly higher Iodine value than jatropha oil, due to the predominantly longer C20:5 chain with more double bonds, while jatropha has predominantly C18:1 chain. Iodine value signifies the degree of unsaturation of oil and fat. The use of algal oil as additive to residual palm oil has doubled the number of hydroxyl groups in the polyols and resulted in higher thermal stability than that achieved with jatropha oil, potentially from the increased cross-linking from higher polyunsaturated fatty acid chain and due to the presence of phosphate groups which could enhance the fire-retardant properties of the polyurethanes (Gomez et al., 2021).

Due to increasing concerns for the environment and higher disposal costs, effective utilization of industrial wastes such as fuel ash to produce high value materials has become a priority (Yan et al., 2020). PKS is used for the synthesis of Carbon dots (CDs) of 2.5 nm average diameter, using N,N-dimethylformamide in solvothermal method. The rich functional groups on the surface of the CDs contribute towards fluorescence emission at 520 nm. The CDs show photo, thermal and ionic stability for use as ink which irradiates bright green fluorescence under UV light at 365 nm, but invisibility in day light. This characteristic will be of interest for applications in optoelectronics, charge storage and electrospinning (Ganesh et al., 2023). The synthesis of graphene, h-BN, and g-C_2N materials using non-biogenic and biogenic materials involving

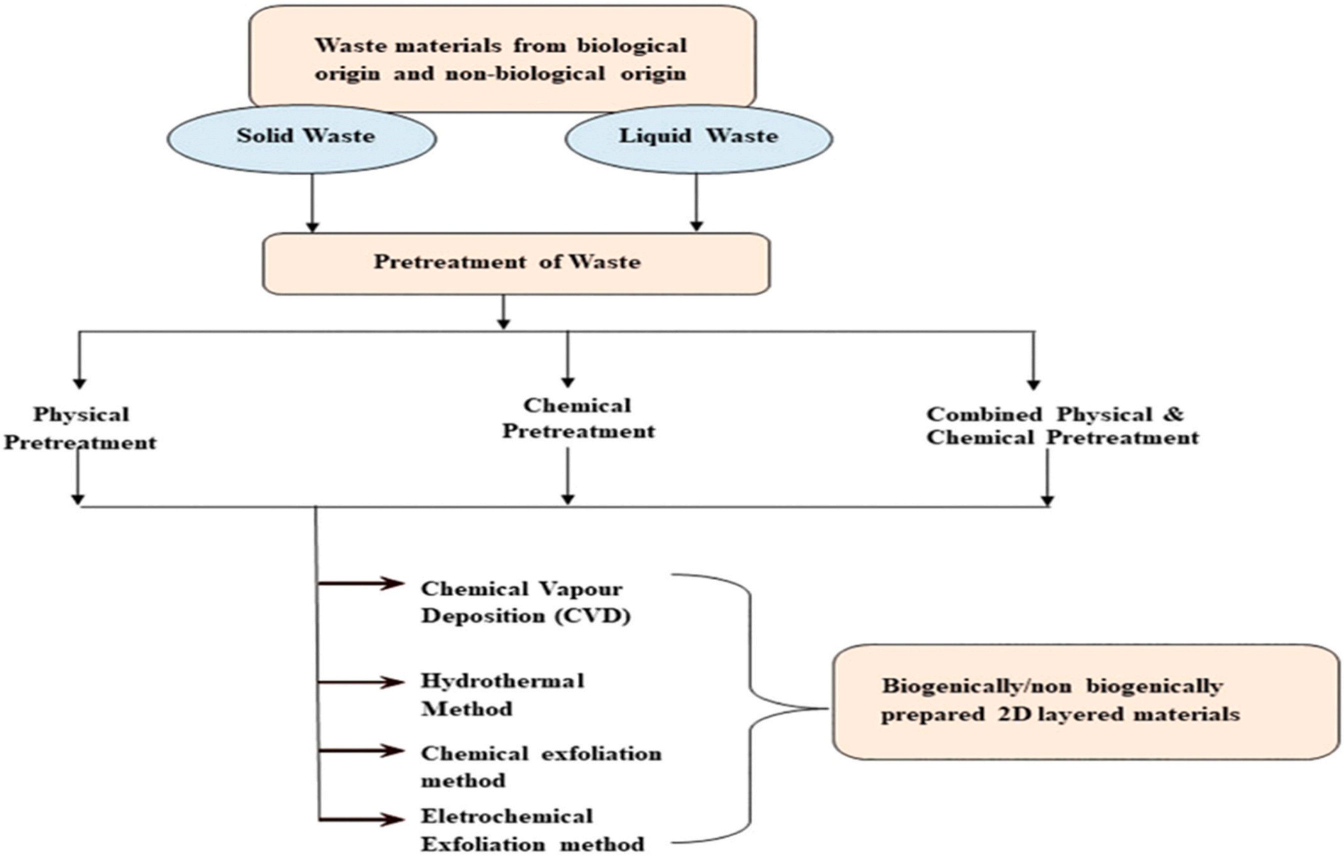

Fig. 4. Framework for synthesis of 2D-layered nano materials using biogenic and non-biogenic waste (Singh et al. 2021) (Under Creative Commons Attribution (CC BY) license).

pre-treatment of the waste materials, followed by conventional and non-conventional techniques are shown in Fig. 4 (Singh et al., 2021). There are good prospects of utilizing natural precursors for industrial-scale production of graphene, graphene oxide (GO), reduced graphene oxide (rGO), graphene quantum dots (GQDs), carbon nanotubes (CNT) and activated carbon (Deng et al., 2016). The ability of electrically charged particles to move frequently through a medium in response to an electrical field makes graphene and graphene-based materials promising for electronic applications (Wang and Shi, 2014) such as transparent electrodes for touch screen devices, rollable e-paper and foldable light emitting diodes (LEDs) (Bae et al., 2010). Industrial palm oil wastes and algal-based carbons can be converted to graphene, and its derivatives (Safian et al., 2020; Hou et al., 2021; Torres et al., 2021). Palm oil wastes are precursors of carbon, where graphene is grown on the nickel substrate via double thermal chemical vapor deposition. Appreciable amount of carbon aggregate and precipitates on the nickel surface produce multilayered graphene. By using palm oil waste, considerable amount of GO and amorphous carbon could be obtained (Mamat et al., 2018). Palm Oil Fuel Ash (POFA)-derived Graphene nanosheets (PDG) have been successfully synthesized by optimizing the temperature, KOH:POFA ratio the reaction time. The yield of more than 25 wt% 1–8-layer PDG nanosheets with less than 0.5 wt% inorganic impurities, are obtained. The highly porous PDG has the surface area enhanced to 1506.6 m^2/g, with smooth edges and defined hexagonal lattices (Ayub et al., 2021).

The GO anode derived from palm oil wastes has shown great potential for industrial applications. Bio-inspired modified graphene anode employed for the fabrication of biochemical fuel cells for energy production from wastewater is superior to the unmodified conventional graphene anodes. (Yaqoob et al., 2021). In the microbial fuel cell utilizing synthetic wastewater containing Cd(II), the energy output of 135.96 mA m^{-2} is almost 8 times more efficient than the unmodified conventional graphene anodes with energy output of 15.65 mA m^{-2}. The fabricated anode can remove Cd(II) with 99% removal efficiency (Table 1) (Yaqoob et al., 2021). There is also huge demand for graphene derivatization to rGO attributable to the versatile properties of graphene. However, the process uses hazardous and corrosive chemicals as reducing agents (Razaq et al., 2022). Oil palm leaves (OPL), PKS and EFBs can be used to produce rGO from GO synthesized from carbonized materials (Nasir et al., 2017). Palm oil leaves extract (POLE) as reducing agent increases carbon to oxygen ratio from 1:1–3:1 in the resulting rGO (Faiz et al., 2020). The degree of graphitization is the highest in the rGO derived from the EFBs, followed by commercial graphite, PKS, and POLE, in decreasing order (Nasir et al., 2017). Another new material increasingly explored for energy storage, water purification, and gas sensor is MXene. Palm oil methyl esters can be combined with MXene to produce high heat transfer efficiency for potential use as heat transfer fluids. Nanofluids have various thermal applications due to their high thermo-physical properties, which add functional properties to the base fluids (Mashtalir et al., 2014; Ren et al., 2015). The thermo-physical characteristics of Palm Oil Methyl Ester (POME)/MXene nanofluids as a new heat transfer fluid, have been improved by adding MXene (Ti_3C_2) nanoflakes to POME at different concentrations (0.01–0.1 wt%). This has enhanced the rapid cooling of MXene-based fluids with thermal conductivity enhanced to 176% at 65 °C and 0.1 wt%, without affecting the viscosity, in comparison to the base fluid (Rahmadiawan et al., 2021). Further advancements in the production of graphene and graphene derivatives from palm oil wastes, and the combination of MXene with oil palm-based bioproducts, can open up and expand the field of bio-based advanced materials.

4.4. Biochemicals, biopharmaceuticals and biomedical applications

Cellulose, hemicellulose, and lignin from oil palm biomass wastes, and biochemicals from algae have diverse applications. Increasing high impact developments have taken place in the field of biomedical and biopharmaceutical applications. Conventionally, biomass conversion into chemicals such as bonding and gum resins have applications for surface covering, plywood, coatings, insulators, and sand moulds and cores in foundry industries (Md. Kawser and Farid Nash, 2000). PKC is rich in crude fibers (6–25%) and crude protein (14–20%) (Abdeltawab and Khattab, 2018). The PKCs and OPTs can be converted into animal feed, fertilizers, or light weight construction materials (Abdeltawab and Khattab, 2018; Mora-Villalobos et al., 2021), while the OPTs can be turned into powder for further processing (Uke et al., 2021). Pyrolyzing the biomass between 300 and 1000 °C, under low or zero oxygen, produces biochar for soil conservation, erosion management, and long-term nutrient recycling (Kahar et al., 2022). Bio-oil as pyrolysis by-product has been developed into flavouring compound, slow-release fertilizer, and balm (Venderbosch et al., 2005). The enzymatic hydrolysis of POME using POME-isolated *Bacillus marisfavi* NA8 releases sugar as a substrate to be transformed into bio-flocculant BM-8. The flocculant BM-8 contains polysaccharides, proteins, and nucleic acids. It is thermally stable and could tolerate a wide range of pH. The flocculant can precipitate out *Chlorella vulgaris* with 90% biomass recovery in 30 mins, suggesting its potential as industrial flocculant (Bukhari et al., 2020).

Algal biomass serves as a sustainable source of biocompounds (Nur and Burma, 2019; Abdullah and Hussein, 2021; Gonzalez-Diaz et al., 2021) for diverse applications as shown in Fig. 5. These biocompounds are lipids, polysaccharides, proteins, and enzymes that exhibit anti-inflammatory, anti-cancer, and antiproliferative, antimicrobial and antioxidative activities. The common algal species are *Dunaliella salina*, *Haematococcus pluvialis*, *Chlorella zofgiensis*, *Chlorella protothecoides Chlorella pyrenoidosa*, *Dunaliella tertiolecta, Chlorella ellipsoidea*, *Chlorella saccharophila*, *Isochrysis sp*., *Odontella aurita*, *Tetraselmis sp*., *Chlorella minutissima*, and *Nannochloropsis oculata* (Singh et al., 2013b; Adarme-Vega et al., 2014; Liu et al., 2014; Hussein et al., 2020; 2022). The algal lipid profile suggests the potential for enhanced absorption of docosahexaenoic acid (DHA) to reduce cholesterol level, and hepatic fibrosis (Lawlor et al., 2017). The primary and secondary metabolites in algae can act as biological factories to produce metal and metal oxide nanoparticles (NPs) (Fawcett et al., 2017). The high-value bioactive compounds such as astaxanthin, β-carotene, lutein, and fatty acids (FAs) can be utilized as food colorants, vitamins, and for cosmetics, and pharmaceutical applications (Begum et al., 2016). Algal compounds used as skin whitening agents, inhibit tyrosinase enzyme, which in turn reduces melanin pigment, the compound responsible for the colour of the skin, hair, and eyes (Wang et al., 2015).

Fig. 6 shows different types of biomedical applications of ulvan, cellulose, and lignin. The sulfated polysaccharides in algal cell wall such as ulvan, alginate, fucoidan, and carrageenan, have pharmaceutical and therapeutic potentials (Muhamad et al., 2019). Fucoidans from brown algae, carrageenans from red algae and ulvans from green algae are used as rheology modifiers, hair conditioners, suspending agents and wound-healing agents (Aditya et al., 2016). Ulvan is a natural sulfated polysaccharide containing 3-sulfated rhamnoglucuronan as the essential component. It has special chemical structure that is rich in L-rhamnosa, D-glucuronic acid, and L-iduronic acid. These are like the structure of glycosaminoglycans found in mammals which renders ulvan to be biocompatible for biomedical applications. Ulvan-based hydrogels are promising for drug delivery, tissue engineering, and wound healing (Sulastri et al., 2021). Cellulose, lignin, lipid NPs and phospholipids from OPF and algae can be developed into Drug Delivery Systems (DDS) (Wang et al., 2021; Toro et al., 2021; Hussein and Abdullah, 2022). DDS deliver drugs to specific targets in human body and enhance the efficacy of chemotherapy drugs. The NP-assisted DDSs use synthetic and nature-derived NPs to store and deliver drugs for the treatment of various diseases (Wijaya et al., 2021).

Cellulose and nano-cellulose are water insoluble, with characteristics such as high strength, optical transparency, and high surface area, with the ability to transfer water-soluble derivatives, biochemicals, and materials. Due to the biocompatibility, biodegradability, and easy removal

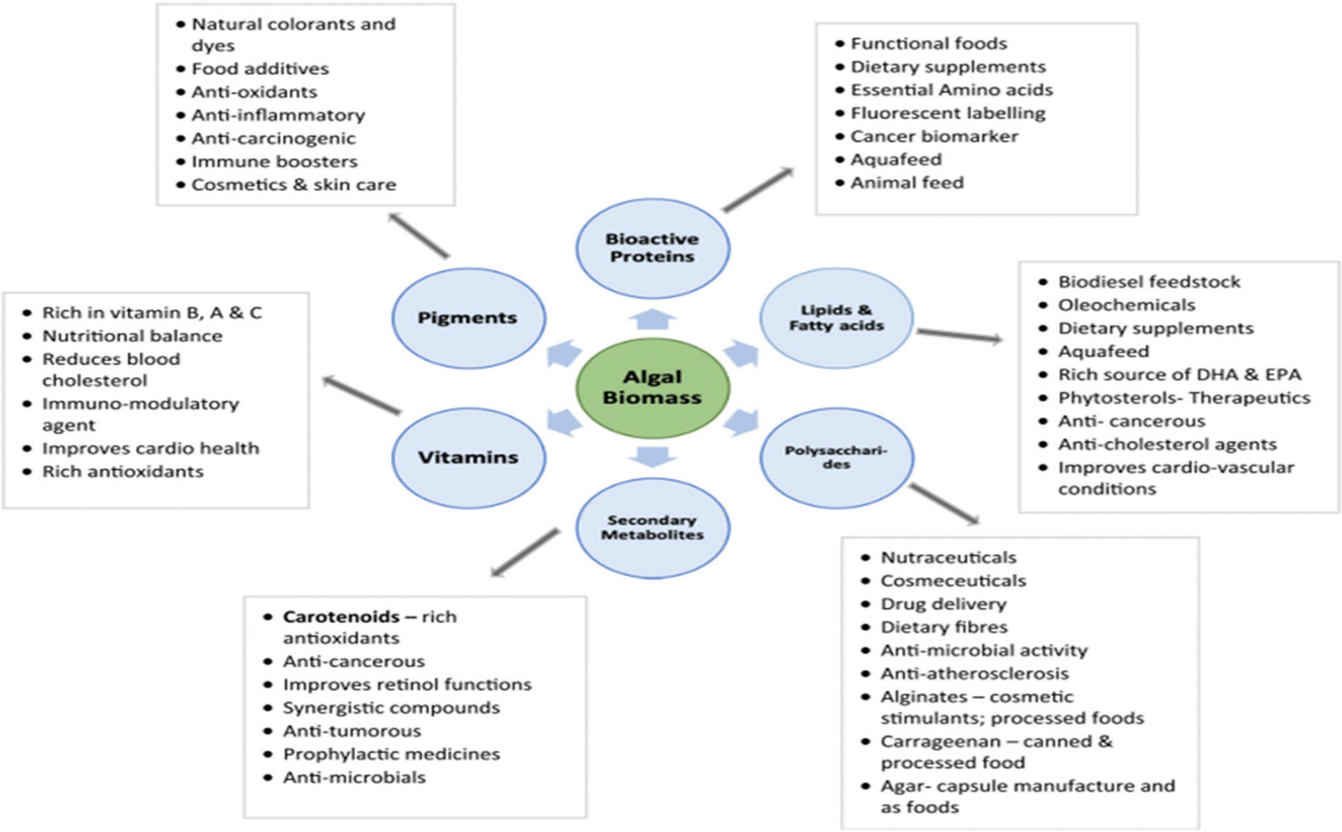

Fig. 5. Biocompounds from Algae and the diverse applications (Uma et al. 2022) (Under Creative Commons Attribution (CC BY) license).

from gastrointestinal tract, cellulose and nanocellulose can be applied in the delivery of anti-cancer drugs, anti-microbial drugs, hemostatic agents, wound-healing agents, and to deliver proteins, nucleic acids, and growth promoting agents for tissue engineering (Wang et al., 2021; Toro et al., 2021). With high drug-loading capacity, attributable to its negative surface charge and large surface area, cellulose can absorb water and has been used as carriers of hydrophilic drugs such as tetracycline hydrochloride (TetHCl), hydroquinone (HQ), procaine hydrochloride (PrHCl), and doxorubicin hydrochloride (DoxHCl), and imipramine hydrochloride (ImHCl). Hydrophilic drugs bind easily due to the abundance of carboxylic and hydroxyl groups on the surface of the cellulose (Wijaya et al., 2021). Cellulose forms interaction with biopolymers, to form multi-species compounds for biological applications, reinforcing agents, water treatment, emulsion Pickering stabilizers, sensors, and energy storage materials (Li et al., 2018). Nanocellulose hydrogel prepared from the EFBs (Padzil et al., 2020) have found applications in drug delivery, wound dressings, food packaging, tissue engineering, additive manufacturing, and biosensing (Wang et al., 2021). Nanofiber scaffolds of cucurmin-loaded EFB-derived CA (90%)/poly(ε-caprolactone) (10%) have been fabricated by electrospinning for potential application in regenerative medicine. The smooth and bead-free electrospun fiber scaffolds, containing cucurmin at 0.5 and 1 wt%, exhibit swelling of 700 and 950%, respectively, in phosphate-buffered saline. Cucurmin is suggested to play a role as natural product, and in improving the hydrophilicity of the scaffold. This in turn results in higher cumulative cucurmin release of 78% with CA/PCL/Cur (1%), as compared to 60% with CA/PCL/Cur (0.5%). The higher concentration of Cur could also have influenced the release kinetics. Both Cur-loaded scaffolds induce higher actin proliferation and expression in fibroblasts than the fiber scaffolds without Cur, suggesting the suitability for wound healing (Suteris et al., 2022).

Lignin also has wide applications in tissue engineering, drug and gene delivery, food science, biofuel, environmental, water purification, pharmaceutical, catalysis, nutraceutical, and energy applications. The advantages are the ease of preparation of the NPs, availability of diverse functional sites, and tunable surfaces, and unique physical properties such as reactivity towards oxygen radicals, renewable nature, metal chelation, biodegradation, and positive interaction with the cells. Lignin-based biomaterials have made significant development in embryo pretreatment technologies (Kumar et al., 2021). Lignin- nanoparticles (LNPs) are used as DDS for curcumin, resveratrol, ovalbumin, benzazoline, irinotecan, sorafenib, and doxorubicin. The loading capacity of LNPs however may not be very high, but the efficiency of encapsulation is very high. The LNPs are functional, possess high absorbability, biodegradability, and non-toxicity to be effective as carriers of drugs and inorganic particles. The challenge is in the synthesis and preparation of targeted LNPs. Hollow LNPs have been prepared by including magnetic Fe_3O_4 NPs functionalised with folic acid (FA) with average size of 314 nm to deliver Doxorubicin hydrochloride (DOX). The construction allows the LNPs and magnetic FA-LNPs to exert no significant cytotoxicity at less than 150 μg/mL, but the magnetic FA-LNPs-DOX results in enhanced cellular uptake by HeLa cells (Zhou et al., 2019). The Integrated Algal-Oil Palm Biorefinery therefore paves new avenue for sustainable production of biocompatible materials together with biochemicals and biopharmaceuticals for novel biomedical applications.

4.5. Green solvents and processes

The materials harvesting, and processing, and product development must strictly embrace the green and sustainable route of production. For altruistic reason, it makes no sense to produce bioenergy whilst utilizing energy intensive processes; or cutting down trees in large tract of land just to build a solar farm. The OPFs and algal biomass require green physical, mechanical, heat and chemical pretreatments to delignify, breakdown the cells, extract out the celluloses or recover lignin and

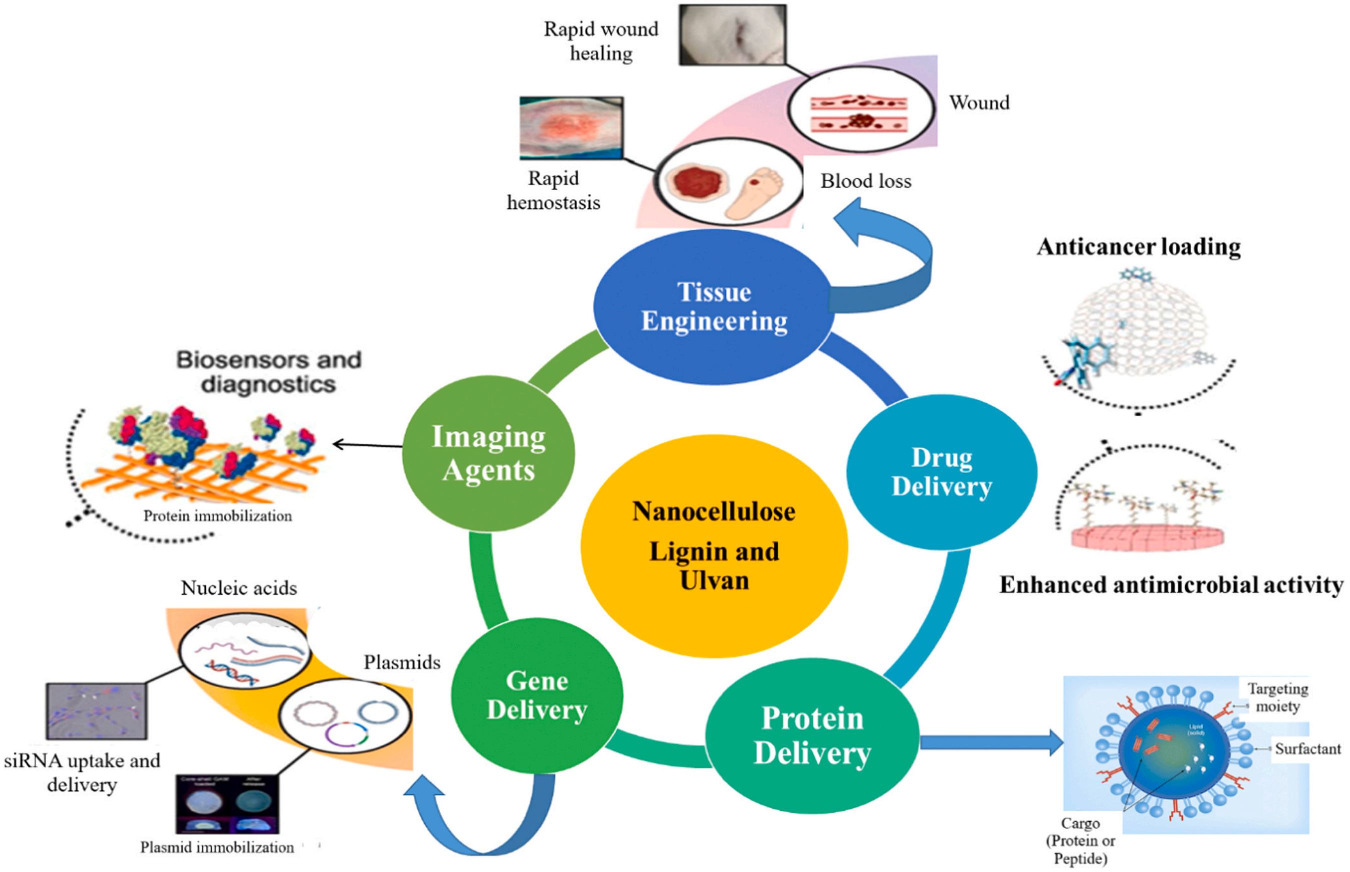

Fig. 6. Different types of biomedical applications of cellulose, lignin and ulvan extracted from bioresources (Modified from Sulastri et al., 2021; Toro et al., 2021; Wang et al., 2021; Wijaya et al., 2021; Patil et al., 2022).

other biochemicals (Nazir et al., 2013; Abdullah et al., 2016a; 2017b; Shah and Abdullah, 2017). The solvent or mixture of solvents should not degrade the compounds and should be specific for compounds of interest such as the lipids (Pragya et al., 2013). Green solvents such as supercritical carbon dioxide, bio-based solvents, ionic liquids, deep eutectic solvents (DES), and switchable solvents are being developed (Imbimbo et al., 2020) for optimal extraction technique that will determine the quantity and quality of bioactive substances at large industrial scale. The use of water for the extraction of polyphenols from agricultural food wastes or cosmetic products is simpler. However, water extractions are more suitable for the separation and purification methods based on the extractive chromatography using polymeric resins or membrane-based clarification and fractionation (Cassano et al., 2019). Supercritical Fluid Extraction (SFE) offers greater extract purity with low environmental impact for valuable components from microalgal biomass such as total lipids, long chain fatty acids and pigments. The supercritical fluid (SF) such as supercritical carbon dioxide (SCO_2) diffuses quickly as a gas but is capable of dissolving materials as a liquid. SCO_2 is ideal for having low viscosity, high diffusion rate, and high volatility. It is easily applicable to thermally labile compounds because of its low critical temperature of 31 °C and critical pressure of 74 bar (Joshi, 2015). CO_2 gas is stored in a storage tank and converted to liquid phase using a condenser. The CO_2 liquid and co-solvent are pumped to a heater unit, where it is heated to supercritical conditions. The SF mixture then enters the extraction vessels, where it rapidly diffuses into the solid matrix and dissolves the material to be extracted. Multiple vessels in parallel can be set up so that the process can be run in semi-continuous mode. The separators are in series to ensure maximum separation, and the "cleaned" CO_2 is passed through a condenser to convert it back to liquid phase for next extraction cycle (Akanda et al., 2012). However, CO_2 is nonpolar and therefore inefficient for the extraction of polar solutes. Volatile polar modifiers or co-solvent such as ethanol, diethyl ether or certain organic acids could compensate for its non-polarity (Manjare and Dhingra, 2019). Bio-based solvents including 2-methyl tetrahydrofuran, terpenes, ethyl lactate, and ethyl acetate are derived from agricultural biomass such as sugarcane lignocellulose and fruit peels (Mahmood et al., 2017; de Jesus et al., 2018). These solvents can selectively extract high-quality neutral lipids from microalgae, not dissimilar to *n*-hexane and chloroform. Both 2-methyl tetrahydrofuran and isoamyl alcohol could extract lipids at higher selectivity and efficiency than the conventional solvent (de Jesus et al., 2018). There is no significant difference in the efficiency and selectivity of terpenes for microalgal oil extraction, as compared to *n*-hexane (Dejoye Tanzi et al., 2012; Mahmood et al., 2017).

Ionic liquids (IL) have been explored to extract biocompounds because of their low viscosity, low vapor pressure, non-volatile nature, large operating temperature range, and extraction efficiency. The ILs are salt solutions containing organic cations and inorganic/organic anions maintained at the temperature of 0–140 °C. The polarity and extraction efficiency of the ILs could be fine-tuned to accommodate different kinds of anions and cations (Yoo et al., 2017). Regenerated cellulose (RC) from EFB cellulose pulp has been synthesized using a mixture of 1-Ethyl-3-methylimidazolium acetate (EMIMAc) and 1-Ethyl-3-methylimidazolium chloride (EMIMCl). The technique transforms Cellulose I into Cellulose II with comparable mechanical strength, but with better Young's Modulus of 83.245 ± 1.183 MPa, and 12.92% elongation (Table 1) (Hassin et al., 2022). Transesterification of glycerol triolate catalysed by basic IL has been achieved for biodiesel preparation (Zhou et al., 2012). Microwave-assisted microalgal lipid extraction using [BMIM][HSO_4] solvent (Pan et al., 2016), and the IL-microwave assisted one-step extraction from wet microalgae, have also been developed (Wahidin et al., 2018). [BMIM][HSO_4] solvent is effective for lipid extraction where microwave irradiation promotes the extraction by more than 15-fold for *C. sorokiniana*, more than 10-fold for *Galdieria sulphuraria* and by manifold for *N. salina* (Pan et al., 2016). Usually, the viscosity of the ILs is high at low temperature, such that the extraction is performed with co-solvent addition at higher temperatures (100–120 °C) (Orr and Rehmann, 2016). Imidazolium-based IL with methanol co-solvent are used for microalgal lipid extraction along with trans-esterification to achieve oil extraction efficiency higher than 70% (Shankar et al., 2017; Wahidin et al., 2018). The fractionation and recovery of various bioproducts including lipids, carbohydrates and carotenoids in a single process is the way forward for IL-based wet extraction of microalgae (Orr and Rehmann, 2016).

Deep eutectic solvents (DESs) are emerging as green alternatives to overcome the limitations of bio-based solvents and ILs. In DES, hydrogen bond donors and acceptors interact with each other via hydrogen bonding resulting in a eutectic mixture. The DESs also have low vapor pressure and volatility which is highly desirable for green solvent (Chen and Mu, 2021), particularly for lipid/oil extraction from microalgae (Tommasi et al., 2017; Cai et al., 2021). Lipid recovery rate from *Chlorella* sp. is higher in DES pretreatment with aqueous choline chloride-oxalic acid at 80.9%, aqueous urea-acetamide at 75.3% and aqueous choline chloride-ethylene glycol at 66.9%, than the untreated biomass at 52%. The profiles of fatty acids especially palmitic, palmitoleic and stearic acids are similar (Lu et al., 2016). The DES with hot water could be used in the washing of biodiesel where the strong ionic interactions from the hydrogen bonds with the impurities, especially with the OH groups, reduce the levels of moisture, free and total glycerol, and mono, di- and triglycerides. The use of triethylene glycol in the DES composition decreases the content of triglyceride, and the increased solubility is attributed to the presence of hydroxyl groups in the glycerol, mono- and diglycerides (dos Santos et al., 2022). The hydrogen-bond donors for DES include oxalic acid, levulinic acid, ethylene glycol, sorbitol, and urea (Tommasi et al., 2017). The application of Choline chloride and oxalic acid at different molar ratio, water addition and reaction temperature for ultrasound-assisted phenolics extraction from *Aegle marmelos* demonstrates the best extraction yield of greater than 60% with DES in combination with Oxalic acid (oxaline11), and 25% water addition at 80 °C. This is due to higher cavitation which reduces viscosity and improves H-bonding between the DES and polyphenols (Saha et al., 2019). One-step treatment of wet *Chlorella* sp. and *Chlorococcum* sp. (GN38) biomass pastes (60–65% water content) with Choline chloride-Acetic acid (Ch-Aa) DES produces 30% higher FAME content than the two-step method. Optimal conditions are achieved after 60 min reaction time, at 110 °C (*Chlorococcum* sp. (GN38)) and 130 °C (*Chlorella* sp.), with composition of DES:Methanol-H_2SO_4 (2%):Microalgae at 60:40:3 ratio (Pan et al., 2017). DES and microwaves (MW) can be viable pretreatment methods to extract fatty acids from diatom *Phaeodactylum tricornutum* with green solvents such as dimethyl carbonate (DMC) and SCO_2 (Tommasi et al., 2017). The combination of Choline chloride and carboxylic acids with DMC extraction enhance the selectivity by 16% and the total fatty acids yield by 80%. The pretreatment with DES-MW and extraction with DMC results in 88% selectivity which is much higher than the 35% selectivity with conventional solvents used during Bligh and Dyer extraction, although the total fatty acid yield and the fatty acid profile are comparable. With DES-MW pretreatment and SCO2 as solvents, the efficiency of extraction is improved significantly with the Total Fatty Acids (TFA) yield increased by 20-fold and the triglyceride extracts are highly purified (Tommasi et al., 2017).

Major challenges in microalgal biomass utilization and conversion to value-added products are the costs incurred and energy consumed for cultivation, algal drying and solvent recovery. A CO_2 switchable solvent extraction of lipid from wet algal biomass is proposed to attain significant positive energy balance based on energy consumption as compared to wet extraction using organic solvents, and SCO_2, and dry extraction (Du et al., 2015). Energy-efficient multiple extraction stages of stressed *Neochloris oleoabundans* result in maximum lipid yield extracted at room temperature after 18 h of extraction at 1:1 (w/w) solvent to feed ratio. For stressed, nonbroken freshwater microalgae, an almost 4.7-fold increase in lipid yield (61.3 dry wt%) is obtained after four cycles of extractions with N-ethylbutylamine, in comparison to the lower yield from non-stressed conditions (Du et al., 2017). Single stage simultaneous extraction-transesterification is a simpler method for conversion of microalgal lipid into biodiesel, while at the same time results in reduced unsaturated fatty acids to improve the quality of biodiesel (Pradana et al., 2020). In single stage biodiesel production, *Spirulina* sp. is processed in a batch stirred-tank reactor at 60 °C with palm oil as co-solvent to methanol and KOH catalyst (1% w/w of palm oil). The highest biodiesel yield is 85.3%, at 10:1 molar ratio of methanol to palm oil, 5:1 wt ratio of palm oil to microalgae. The yield is increased by 34.6% as compared to conventional extraction in the first stage and trans-esterification in the second stage (Pradana et al., 2020). However, this approach also utilized one vegetable oil to process another vegetable oil, and furthermore both are food-based. The application of used cooking oil instead may be more desirable and meets the zero waste and circular economy agenda. The extraction, separation, purification, and recovery of biomolecules such as enzymes, proteins, nucleic acids, or antibodies can be achieved with Aqueous Biphasic System (ABS). The ABS are aqueous solutions of two polymers, or a polymer and a salt above critical concentration. These are highly viscous, resulting in reduced mass transfer and loss of bioactivity. Ideally, the ABS based on branched polymers, with incorporation of special salts, surfactants, nanoparticles, solvents, or magnetic fields should provide low interfacial tension and high content of water for biocompatibility with labile and highly sensitive biological molecules. High product yield and purity is possible with multiple concentrating steps and purification, in a single-step operation. (Kee et al., 2020).

5. Aquaculture applications and Mode of cultivation

The issue of wastewater recycling and utilization can be partially addressed through microalgal cultivation on POME as the growth medium, for conversion into animal and aquaculture feed. These ultimately improve the economics of a biorefinery and bring in community development programme through aquaculture activities. Fishery sector is considered as an important major supplier of animal protein. The Food and Agriculture Organisation (FAO, 2020a), ranks Malaysia as one of the top fish consuming countries in Asia in 2016 (above 59 kg/capita/year), almost double the average in Thailand and China, although still lower than Japan and South Korea. There are two major components - marine capture fisheries and aquaculture. In 2020, the total fishery production amounted to 179 metric tonnes, where 77.3% comes from capture fisheries, while inland fisheries stand at around 0.3%. The production pattern has not changed much but the fish caught are getting smaller and with less diversity (FAO, 2020a), attributable to climate change and overfishing. Aquaculture could provide the answer to this dwindling numbers of fish caught. Nearly 90% of global aquaculture production is currently produced in Asian countries with China dominating the aquaculture products in 2017 (billion metric tonnes) at 46.4, followed by India (6.18) and Indonesia (4.88), while Malaysia is placed 22nd globally (0.194). Aquaculture in Malaysia sub-sector (excluding seaweed) in 2020 produces 218,000 metric tonnes of fish valued at RM 3.1 billion, contributing 22.4% of the country's total fish production. The production of fish food from the aquaculture sector is 224,000 metric tonnes, valued at RM 3.2 billion, a decrease of 2.7% and 3.1% respectively, compared to 2019 (Annual Fisheries Statistics, 2020). The decline can be attributed to inconsistent supply of quality and adequate seeds, changing economic conditions principally the global COVID-19 epidemic (FAO, 2020b), and diseases such as iridovirus (Abdullah et al., 2017a), viral nervous necrosis (VNN) (Ariff et al., 2019), and scale drop disease virus (SDDV) (Nurliyana et al., 2020).

The availability of quality seedstock is critical for commercial success of industrial production of finfish, which stimulates continuous developments of finfish larviculture. Nutritional value and size of food for larvae and fry determine the success of commercial scale larviculture. Food preparation for larviculture involves the use of highly unsaturated fatty acids (HUFAs)-supplemented feeds, the application of suitable live food (phytoplankton and zooplankton) for different larval stages, and the adoption of live food enrichment protocols (Liao, 2001; Rasdi et al., 2020). Microalgae are indispensable in the commercial rearing of marine fish and are used to produce mass quantities of zooplankton (rotifers, copepods, brine shrimp), which in turn serve as food for larval and early juvenile stages of crustaceans and fish. Around 30% of algal biomass produced worldwide is being sold as animal feed (Spolaore et al., 2006). The total crude protein in microalgae can reach as high as 70% which is higher than the fish meal traditionally used as aquaculture feed (Hua et al., 2019). In addition, microalgae play important roles in stabilizing water quality, nutrition of the larvae, and microbial control (Mathew et al., 2021). The commonly used species for animal feed include *Chlorella, Isochrysis, Phaeodactylum, Chaetoceros, Nannochloropsis, Tetraselmis, Dunaliella, Scenedesmus, Thalassiosira and Skeletonema,* and for commercial larviculture operations are *Isochrysis galbana*, *Tetraselmis suecica*, *Monochrysis lutheri*, *Chlorella* and *Nannochloropsis*. Microalgae are used directly in the larval tanks for rearing marine fish larvae. Species with high DHA and eicosapentaenoic acid (EPA) content such as *Nannochloropsis* is introduced during the first feeding of larviculture. Finfish larvae take up microalgae passively with water or indirectly through live food. *Chlorella* is less expensive to cultivate, grows rapidly, and rich in protein content (Lum et al., 2013). *Haematococcus* produces higher amount of astaxanthin as compared to other species and has found wide application in aquaculture as fish feed (Dore and Cysewski, 2019). The carotenoids and astaxanthin from *Haematococcus* are used as coloring agents in salmonid feed (Spolaore et al., 2006).

To meet up with the demands, microalgae are cultured in large scale, in successive manner with culture volume increases at every step of inoculation. The techniques range from less controlled extensive cultivation to monospecific intensive cultures. Microalgae are maintained in batch culture at 18–24 °C, salinity of 20–24 $g.L^{-1}$ and 24 h light, and the culture medium normally used in the laboratory scale cultivation is Walne medium (modified from Laing, 1991) formula. For outdoor culture system, agricultural fertilizers are used starting from 500 L volume. The success of commercial production of microalgae depends on cost-effective large-scale culture systems (Borowitzka, 1999), either open air (batch) or closed (continuous) cultivation system. In batch culture, microalgae are normally cultured outdoor in ponds, tanks or raceway. The productivity of microalgal species grown in open air is normally less than that theoretically possible, due to exposure to the elements and unpredictable weather. The biomass sampling and harvesting are also more challenging. The biomass and lipid content in a photobioreactor (PBR) are normally higher than the open tank due to the more controlled and well-defined environment (Shah et al., 2018). Mass culture in closed system can be photoautotrophic, mixotrophic or heterotrophic, allowing for optimal environment for enhanced productivity, and free from contaminants such as heavy metals and micro-organisms. These however can be expensive, difficult to scale up, and may require artificial lighting.

In Malaysia, large commercial finfish hatcheries mostly use open-air systems with sunlight. There are a few commercial hatcheries using imported heterotrophic microalgae, grown in PBR. It is very costly at RM 450/L but it is far easier than the laborious culturing of microalgae in big open tanks and ponds. The fundamental principle of a new PBR design is to reduce the light path, to increase light availability and to ensure the reactors are well mixed for optimal light and gas exchange. Such system could produce high density microalgae in a relatively smaller volume of culture media and yet almost axenic. Most design is either tubular form (Briassoulis et al., 2010; Quinn et al., 2012); or rectangular flat panel system (Hsieh and Wu, 2009; Acién et al., 2017). The Fisheries Research Institute, Pulau Sayak, Kedah (FRIPS), Malaysia has used rectangular PBR to provide more surface for light illumination of high density *Nannochloropsis* sp. cultivation (Teoh et al., 2021). In the conventional culture method, a total of 150 L of green water (at 1.0×10^7 cell/mL) has to be pumped into the larvae tank (Teoh et al., 2021). The newly designed PBR not only attains high density culture, but also with less water consumption (Table 1). POME as a low-cost carbon source is rich in protein, nitrogenous substances, lipids, and minerals for microbial and algal growth. Although phosphorous in POME are considered as pollutants, these are nutrients that promote microalgal productivity for carbohydrates, lipids, and proteins. POME can be processed to separate out oil, water and sludge. The water part which is rich in nutrient is suitable as a medium for microalgal propagation. The oil part is kept as ingredient of oil source for aquaculture feed formulation while the sludge part for fertilizer The produced microalgae will be harvested and undergo drying process and later used directly as protein source for aquaculture feed formulation. It is possible to reduce the cost of aquaculture feed formulation by using microalgae by at least 50% as compared to the insect-based feed (Nagappan et al., 2021). Outdoor large-scale cultivation of *Arthrospira platensis* in 1% v/v fresh POME has resulted in higher maximum specific growth rate (0.25/d) and biomass productivity (0.211 g/L.d) than the Control culture grown in modified Kosaric medium. However, the contents (% Cell DW) of chlorophyll (1.05), carotenoid (0.57) and phycocyanin (12) are comparable to Control (Sukumaran et al., 2014). High palmitic acids in *N. oculata* and *T. suecica* are obtained when cultures are grown at 10% POME in sea water (Shah et al., 2016). High level of long chain polyunsaturated fatty acids (PUFA) in microalgae is necessary to make it suitable as a replacement to fish fatty acids (Lenihan-Geels et al., 2013).

6. The way forward

Oil palm industry, even with the implementation of RSPO, MSPO and ISPO to make things right, is already one of the most scrutinized and regulated industry in the world today. The controversies with regards to the issues of land clearing, deforestation and destruction of wildlife habitat are now being addressed by the Government and industries. Even with the industrial standards met, there are still abundant of solid, liquid and gas wastes generated that can be harnessed to make the industry becoming more sustainable and environmentally friendly by addressing the economics of biomass conversion and waste valorization into value-added products. The different strategies and approaches when implemented within the Integrated Algal-Oil Biorefinery framework can make the process more sustainable and realize the Circular Economy and 17 agendas of the SDGs. The "Zero Waste Concept" ensures that the generated wastes are re-used or converted, and not just dispose of at the landfill, or sent to the incinerator and burnt. There has been great interest towards eco-friendly technologies and materials to reduce over-dependence on fossil fuels which leads to GHG emissions. The future lies in hybrid approach, integrating conventional technique with latest reactor design, and economically feasible technologies as a sustainable strategy for holistic environmental remediation and bioproducts co-generation.

The reality of industrial requirements, market demand and the cost factor dictate whether the different types of advanced technologies will be adopted. These necessitate heavy financial commitment which normally can only be met by big plantation and conglomerates. In addressing waste and wastewater treatment, Advanced Oxidation Process (AOP) can break down a wide range of fine organic pollutants, by making use of strong reactive hydroxyl radicals ($E_0 = 2.8$ eV), utilizing photon energy and without further chemical treatment. The technology using UV-A with long wavelengths from 315 to 400 nm, and UV-C with short-wavelength radiation of 100–280 nm, could degrade most environmental pollutants. Although there is no production of sludge, low cost, fast reaction rate, and good operation under pressure and room temperature conditions (Tetteh et al., 2019), the application of UV/O_3 and UV/H_2O_2 processes in general necessitates large amount of oxidizer, making it uneconomical. The application of TiO_2 and ZnO photocatalysis (Ng et al., 2019), while sophisticated in technological advancement, may not be practical for POME treatment, as it incurs cost, in comparison to the straight-forward biological treatment.

The remediation of organic contaminants in POME using algae, fungus and bacteria is sustainable and efficient (Abdulsalam et al., 2018), though may need optimization on a case-by-case basis, to attain environmental remediation with sustainable energy co-generation. Membranes are commonly integrated with biological and chemical treatment, or as stand-alone systems in the secondary treatment of wastewater. The coupled cultivation and pre-harvesting of microalgae in a membrane photobioreactor (Bilad et al., 2014); and the integrated ultrasonic membrane anaerobic system (IUMAS) technology for POME treatment are attractive solutions as compared to using either ultrasonic or membrane technology individually (Abdurahman et al., 2017). The rate of movement of components by partial permeation and rejection through pores of different sizes are attractive for applications in microbial fuel cells, removal of organic and inorganic components, disinfection, pathogen removal, and desalination (Tetteh et al., 2019). The major concern is the re-usability of membrane material over a prolonged period. The ultimate aim is not just for the wastewater treatment, or produce pure water from POME, but also the recovery of protein, carbohydrate, and the pharmaceutical and biotechnological by-products (Ahmad et al., 2006, Wu et al., 2009). Reuse of treated water needs thorough evaluation for safety aspects especially due to the development of antibiotic-resistant bacteria and resistance genes (Hong et al., 2018).

To become viable alternatives to fossil-based energy, polymers and chemicals, the scale of production of bioenergy, biopolymers and bioproducts must be significantly increased using economical route of technological adoption and materials development. Of increasing interest is the use of furfural (2-furaldehyde) and levulinic acid and their derivatives from the conversion of lignocellulosic biomass as versatile platforms for the synthesis of bio-based chemicals, fuel precursors, bioplastics, and solvents (Mariscal et al., 2016; Barcala et al., 2021; Sajid et al., 2021). The safe storage and delivery of biogas and biofuels for commercial vehicles (Nirmala et al., 2022), and household, must be addressed, together with solving and optimizing the energy and fuel production. The use of agro-biomass-derived electrodes for energy storage and supercapacitors is largely at research and development stage, and more investment is required to realize its potential and applicability. For biopolymers, the end-of-life infrastructure for biodegradability and recyclability of bio-based materials must be put in place (Dalton et al., 2022). Microalgal cultivation on wastewater must address the challenges at large-scale implementation which include the systems used for cultivation or mode of operation, the selection of superior algal species, and the strategies for growth such as heterotrophic, autotrophic or mixotrophic, the types and characteristics of wastewater and industrial effluents, and the stepwise strategies such as single or two-stage cultivation for maximal growth and maximal production of high-value compounds (Nur and Burma, 2019). The high value compounds such as carotenoids and antioxidant compounds, with palmitic, stearic, and oleic acids as the major fatty acids for biodiesel, can be promoted by two-stage cultivation of high-density microalgal biomass and simultaneous biocompounds production. The strategies of varying light intensity, and combination of salt stressors with medium replacement (Ali et al., 2021; El-fayoumy et al., 2023) should address whether greater level of energy is being generated to compensate for the use of high light intensity and complex media for cultivation and for biomass harvesting, drying, extraction and product isolation. Otherwise, the result will be a net negative energy production instead.

The efforts in decarbonizing the energy sector by making use of oil palm biomass have already made tremendous progress (Zamri et al., 2022), and will only move at faster pace with stronger commitment from Government and stakeholders for a greener present and future endeavour. The existing power plants or palm oil mills can be converted into biorefineries with some re-purposing, re-addition of new equipments, or with completely new facilities (Rathore et al., 2016; Laosiripojana et al., 2018). Techno-economic analysis is pertinent to determine the most economically viable option of a biorefinery such as whether the route should involve the production of biodiesel, pigment, and animal feed; or biogas and pigments using two-stage fermentation; or biohydrogen and pigment (Banu et al., 2020). To improve the economics, different methods of algal cultivation, harvesting, oil extraction and biofuel production technologies must be developed (Pragya et al., 2013; 2018; Ali et al., 2024). The adoption of microalgal cultivation in high-rate algal pond (HRAP) to treat aquaculture effluent improves the quality of effluents to be released to the environment and enhances the economics of Recirculatory Aquaculture System (RAS) fish farming. The highly nutritious effluents elevate the protein and amino acid components of microalgae, making it suitable as fattening feed for partial replacement of the fish meal. At 10.19 ha scale, the cost of water treatment ranges from €1.37–1.66/m^3. The cost of the equipment covers 76–84% of capital expenditure, while labour covers 28–36% of operational cost. The techno-economic analysis suggests that the economic feasibility can be much improved from microalgal biomass production for fish feed, and with reduction in labour and HRAP costs (Vazquez-Romero et al., 2024). The main issue with Life Cycle Assessment (LCA) is when the data is extrapolated either from lab scale data or from literature. This has limitations in interpretation with uncertain predictability. Life-cycle Inventory (LCI) conducted using primary data from industrial plant will provide a more robust base for analysis. An LCI on industrial-scale plant that cultivates 1200 kg DW/yr. of *Chlorella vulgaris* in 40.3 m^3 of vertically stacked horizontal PBRs has been developed. After centrifugation, a total of 200 g DW/L of microalgal biomass is produced. The LCI suggests that same amounts of water and chemicals are consumed between cleaning and cultivation phases, but much energy is used for temperature control, aeration and pumping during cultivation. To improve plant performance and productivity, the utilization of water recycling strategies, and energy optimization will be the key factors. Plant location, construction materials and transportation of materials will also have to be factored in to improve the economic and environmental analyses (Gurreri et al., 2023).

For many pretreatments and extraction, organic solvents are still the main solvents such as hexane–methanol to pre-treat the EFB to remove oil/wax (Suteris et al., 2022), acetone to produce EFB-cellulose acetate (Wan Daud and Djuneid, 2015), and dimethylformamide (DMF) in producing PKS-based carbon dot (Ganesh et al., 2023) and PKS-lignin/PAN blend (Thongsai et al., 2021). DMF is actually more toxic than dimethylsulfoxide (DMSO) (Kleiner, 2018; Stancu et al., 2023). The use of toxic solvents such as chloroform, methanol, and hexane to extract lipids from microalgal biomass defeats the main purpose of producing green energy via a green route. DES and bio-based solvents from agricultural biomass look promising as future solvent systems but concerted efforts should be made to maximize their scalability and applicability. DES has high dissolution capacity of biocompounds, low toxicity and more environmentally friendly. It has tremendous potential as a replacement to conventional solvents for applications in food, cosmetic and biopharmaceutical industries. The problem with DES is its high viscosity which necessitates modification to improve its extraction efficiency. The DES supramolecular structure is also sensitive to any abrupt changes that could reduce the yield (Saha et al., 2019). To address some of the challenges facing the industrial-scale application of biofuel such as biodiesel production, the application of simultaneous oil extraction and transesterification should be considered (Makareviciene et al., 2020). The application of ABS for bioproduct purification at industrial scale must tackle the issue of the time taken for product harvesting and separation. In bioreactor operations extractive fermentation, crystallization, precipitation, microfluidic and analytical devices, and micropatterning, the operational costs of the ABS, the reuse of phase-forming components and the additives, and reduction in upstream and downstream processing steps, must be optimized (Kee et al., 2020).

Fresh perspectives on Palm Oil industries, not just from economic point of view, but more importantly in addressing renewable energy production, climate change and poverty, should place the implementation of Integrated Algal-Oil Palm Biorefinery into an action-orientated mode. Apart from plantation biomass and agricultural residues, there are other potential biomass resources such as forestry biomass and forest residues, wastes from livestock and fisheries industries and municipal wastes (Hamzeh et al., 2011; Ministry of Plantation and Commodities, 2023), that should be harnessed. Aquaculture as an integral component of a biorefinery will not only enhance the domestic fish supply to lower income consumers (Amankwah et al., 2018), but also create employment opportunities, support local economic multipliers, and generate revenue (Belton et al., 2012; Toufique and Belton, 2014). The philosophical aspect such as that based on "**HEESBA**", which comes from Arabic word "Hisbah" for "Accountability" (for **H**ealth-consciousness, **E**nvironmental and Safety awareness, **E**nergy sufficiency, **S**ocial--inclusiveness, **B**usiness acumen, and **A**daptability and Agility) (Abdullah and Hussein, 2021; Abdullah, 2021), must be included in the systems development and engineering of a biorefinery that strives for social, profit and wisdom-oriented enterprise. HEESBA Concept which promotes the 4 diamonds to be polished, namely - Bioenergy, Biomaterial, Biochemical and Education, must be addressed by those involved in promoting the agendas of Global SDGs. The lower income group should be trained in harnessing the value of circular economy involving waste collection, reutilization, conversion or composting as a part of community activities. Promotion of sustainable agriculture and aquaculture practices through training and education will improve the environment and eco-system, elevate household revenue, increase food supply, and reduce the price, making it more affordable and accessible to the poor and lower income group, and larger segment of the society. The collaboration of small-scale and large-scale enterprises will allow smallholder support to coexist with the larger market to enhance its role in macroeconomic growth (Wiggins et al., 2010). The Integrated Algal-Oil Palm Biorefinery framework addresses global issues by making use of locally available strength and geographical context to operate. The Oil palm industries could serve as a model system especially to other crop industries and large-scale plantation in the developing and developed world, to illustrate what can be done to harness the strength and explore the potentials on renewable energy production and green products co-generation.

7. Conclusion

There is a great need to address the 5 pillars of global security - Climate-Energy-Food-Water-Socio/Economy Nexus, in a more action-orientated mode. Palm oil industry has now largely focused to address the issues of better resource and waste management, and environmental sustainability, instead of just producing palm oil singularly, throughout the life cycle of plantation, or mill operation. The Algal-Oil Palm Biorefinery framework provides avenues for green alternatives for environmental remediation, and waste valorization into biofuels, biomaterials and biochemicals for wide variety of industrial applications. The bioenergy production must meet the energy demand whilst reducing GHG emission via biodiesel, bioethanol, and biogas route. These are the far more promising candidates considering the large agricultural communities especially in the developing world, and the existing infrastructures and ready to use petroleum-based facilities. The compressed biogas must meet the safety standards for transportation and distribution. Of increasing interest is to explore biohydrogen production from dark fermentation based on POME treatment and to develop sustainable aviation fuel based on palm oil residues and microalgal oil. Biochar from biomass wastes can be applied for its high heating value and in agricultural sector as soil conditioner. The biopolymers and its derivatives from oil palm biomass wastes and POME could solve the global plastic pollution problem. The diverse properties of biomaterials can be developed into green construction materials, biosorbents, materials in energy storage and supercapacitors, cellulose or lignin-based composites and nanoparticles, graphene-based and optoelectronic products, and MXene-based applications. The co-generation of biomolecules from agro-biomass and biocompounds from microalgae tackle the issue of effectiveness and efficiency of medical treatment, drug delivery and affordability of modern healthcare through manufacturing of economical biomedical devices, biopharmaceuticals, and nutraceuticals. The hybrid approach, integrating conventional technique with economically feasible green technologies and processes will be the way forward. Microalgae, being indispensable in aquaculture, can be developed into animal feed and as functional food. In the long run, the adoption of HEESBA philosophy with the inclusion of community-based programs in waste collection and composting centres, agro-business, and aquaculture activities, address the challenges of climate, energy and food security, forest clearing and over-fishing at sea from social and economic dimension. The main agenda should be to fight poverty globally and for a more inclusive global community-development within the boundary and defined biorefinery set-up.

CRediT authorship contribution statement

Muhammad Shahid Nazir: Writing – original draft, Investigation. **Hanaa Ali Hussein:** Writing – original draft, Investigation. **Syed Muhammad Usman Shah:** Writing – original draft, Investigation. **Nizakat Azra:** Writing – original draft, Investigation. **Ramsha Iftikhar:** Writing – original draft, Investigation. **Muhammad Saqlain Iqbal:** Writing – original draft, Investigation. **Zeenat Qamar:** Writing – original draft, Investigation. **Zulfiqar Ahmad:** Writing – original draft, Investigation. **Muhammad Afzaal:** Writing – original draft, Investigation. **Ahmad Daud Om:** Writing – original draft, Investigation. **Shaharah Mohd Idris:** Writing – original draft, Investigation. **Aweng Eh Rak:** Writing – original draft, Investigation. **Yung-Tse Hung:** Writing – review & editing. **Mohd Azmuddin Abdullah:** Writing – review & editing, Investigation, Visualization, Supervision, Resources, Project administration, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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