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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

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Highlights

- Need to address the Climate-Energy-Food-Water-Socio/Economy Nexus for global security
- Waste valourization within an Integrated Algal-Oil Palm Biorefinery framework
- Circular economy with environmental remediation and bioproduct co-generation
- Green solvents and processes for feedstock pretreatment and product development
- HEESBA philosophy for inclusive community development and poverty eradication

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-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/bio-energy 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.

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.

Section snippets

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 …

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 …

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, …

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 …

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 …

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 …

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:** …

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. …

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Recommended articles

References (327)

The presence of Vibrionaceae, *Betanodavirus* and *Iridovirus* in marine cage-cultured fish: role of fish size, water physicochemical parameters and relationships among the pathogens

Aquacult. Rep.. (2017)

M. Abdullah *et al.*

Autoclave and ultra-sonication treatments of oil palm empty fruit bunch fibers for cellulose extraction and its polypropylene composite properties

J. Clean. Prod. (2016)

M.A. Abdullah *et al.*

Physicochemical and sorption characteristics of Malaysian *Ceiba pentandra* (L.) Gaertn. as a natural oil sorbent

J. Hazard. Mater. (2010)

M.A. Abdullah *et al.*

Comparative study on structural modification of *Ceiba pentandra* for oil sorption and Palm Oil Mill Effluent treatment

Desalin. Water Treat. (2015)

N.H. Abdurahman *et al.*

An integrated ultrasonic membrane anaerobic system (IUMAS) for palm oil mill effluent (POME) treatment

Energy Proc. (2017)

F. Abnisa *et al.*

Utilization possibilities of palm shell as a source of biomass energy in Malaysia by producing bio-oil in pyrolysis process

Biomass Bioenerg. (2011)

F.G. Acién *et al.*

Photobioreactors for the production of microalgae

In Microalgae-based biofuels and bioproducts(2017)

A.T. Adeleye *et al.*

Sustainable synthesis and applications of polyhydroxyalkanoates (PHAs) from biomass

Proc. Biochem. (2020)

A. Ahmad *et al.*

Adsorption of residue oil from palm oil mill effluent using powder and flake chitosan: equilibrium and kinetic studies

Water Res (2005)

A. Ahmad *et al.*

Membrane treatment for palm oil mill effluent: effect of transmembrane pressure and crossflow velocity

Desalinat (2005)

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Cited by (9)

Innovative circular bioeconomy and decarbonization approaches in palm oil waste management: A review

2025, Process Safety and Environmental Protection

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2025, Process Safety and Environmental Protection

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Recent advances in harnessing biolubricants to enhance tribological performance and environmental responsibility – Bibliometric review (2015–2024)

2024, Cleaner Engineering and Technology

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2024, Chemical Engineering Journal

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> …Biomass is a widely available renewable energy source [9], over 40 million tonnes of inedible plant material are produced globally each year [10], with the majority discarded. Biorefineries offer a promising solution by recycling and converting the energy and renewable carbon in waste biomass into sustainable biofuels [11] and biochemicals [12], promoting the circular economy [13]. Second–generation biofuel derived from agricultural and forest residues are promising technologies as they do not compete with the food supply [6,14]….

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2024, Microbe (Netherlands)

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Thermodynamic Analysis of the Relationship Between Energy Conversion Efficiency in Industrial Enterprises and Economic Growth ↗

2024, International Journal of Heat and Technology

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