Integrated Biomaterials Engineering of Oil Palm Fibres and Microalgae for Bioenergy, Environmental Remediation, and Conversion into Value-Added-Products

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Abstract. The 2030's core agenda for 17 Sustainable Development Goals aims to bring systems thinking and holistic solution to ensure that progress for People and Profit do not side-line planet as the major stakeholder. Discussion on the Economics issues should bring in the Environment and Socio-cultural diversity dimension as equal components. This may necessitate a complete revamp of human activities such that efforts to tackle famine and poverty and the emerging infectious diseases are not divorced from addressing the problems brought about by climate change and the destruction of eco-systems and habitat for wildlife. The focus of this review article is to highlight research and development in integrated biomaterials engineering of oil palm fibres and microalgae for sustainable bioenergy production, environmental remediation and conversion into value added-products via integrated palm oil milling processes and algal biorefinery. Eco-friendly extraction of cellulose and the development of composite materials for different applications will be highlighted. The use of microalgae for bioenergy, effluent remediation and the utilization of microalgal extracts in anticancer agent formulation will be discussed. This hopefully could bring forth insights towards collaboration among the policymakers, government agencies, industries and academics to tackle the immediate and pressing problems facing the world today.

1. Introduction

The increasing world population and the disastrous outcomes of global climate change necessitate a complete revamp of human activities to mitigate any potential calamity on the planet and its inhabitants. Global warming has been caused by greenhouse gas emissions, of which nearly 80% is from carbon dioxide, mainly from the energy sector, industries, transport, and wastes [1]. The impact on the environment from forest clearing, particulate matters in the air, heavy metal or plastic pollution have become a major concern especially on human health and on wildlife, and marine and aquatic eco-system.
Indonesia (56.5%) and Malaysia (27.9%) are the two world’s largest producer of palm oil [2-3], with the combined production of 64.2 million metric tonnes (MT) of crude palm oil as compared to about 11.8 million MT by other producing countries [2]. These have also produced agro-wastes in large quantities. The biomass can be converted into biofuels production such as bioethanol, bio-oil or biodiesel, turned into pellets or briquettes for electricity or heat generation; or further processed and refined to obtain cellulose, hemicellulose or lignin.

Clean Development Mechanism (CDM) has led to more sustainable energy management in palm oil mill with the possibility of algal co-cultivation for bioenergy production and reuse of biomass agro-wastes. The palm oil mill effluent (POME) can be anaerobically-treated for biogas production in co-application with microalgal cultivation in photobioreactor or large-scale open-tanks [4-6]. The microalgal products are suitable for biochemical or pharmaceutical applications [7-8], and the oil palm cellululosic materials can be converted into composites [9-11], or for biosensor applications [12-13].

The objectives of this review article were to highlight the integrated biomaterials engineering based on palm oil milling and microalgal biorefinery which could provide the answers towards sustainable bioenergy production, environmental remediation and conversion into value-added products.

2. Oil-palm fibres utilization and conversion

The oil palm empty fruit bunches (EFB) and fibres such as the mesocarp or shells have been utilized as soil conditioners, fertilizers or toxic gas absorbents [9, 14-15], and the moulded oil palm fibre products are used in the manufacturing of furniture, packaging, electronics, or construction and automobile industries [16]. The carbon molecular sieve (CMS) from oil palm shells, having precise and uniform micro or mesopores, have potential applications as gas or liquid sorbents [17-18]. Different pretreatment techniques are required to enhance the digestibility of EFB for conversion into value-added products as it contains about 25% lignin [19-20]. Eco-friendly extraction of purely extracted cellulose (PEC) from EFB, based on autoclave and ultrasonication methods, have yielded 64 and 49% cellulose, respectively (table 1). The α-cellulose content of 93.7% and crystallinity of 70% from the autoclave method are higher than the α-cellulose content of 91.3%, and crystallinity of 68.7% from the sonication method [10, 19].

| Properties          | Ultra-sonication | Autoclave |
|---------------------|------------------|-----------|
| Moisture (%)        | 9.9              | 9.89      |
| α-Cellulose (%)     | 91.3             | 93.7      |
| Particle size (μm)  | 15               | 14.5      |
| Density (g/cm³)     | 1.58             | 1.59      |
| Molecular Weight (g/mol) | $1.49 \times 10^5$ | $1.87 \times 10^5$ |
| Degree of polymerization | 919            | 1154      |

2.1 Composite materials

The polypropylene (PP) composites using injection moulding, with 25% PEC loading, achieve a high tensile strength of 26.7-27.3 MPa without any coupling agent addition (figure 1). This has great potential to be developed into household items and utensils [10]. The surface-engineered PECs with carboxylic acid and EDTA have successfully removed Pb(II) ions at 232.9-236.7 mg/g. The sorbents can also be utilized for diesel desulphurization, achieving high sulphur removal (300-350 ppm) from the Pb-Oxalate and Pb-EDTA-modified sorbents, as compared to the non-metal loaded sorbents (80-110) [21]. The agro-based magnetic biosorbents (AMBs) have also been synthesized from the fibres of Ceiba pentandra, EFB and PECs with 97.7-99.4% Pb(II) removal efficiency, and at least capable of 5 cycles of adsorption/desorption process without losing significant performance [11].
2.2 Biosensor development

Fabrication of a novel PEC-hydroxyapatite (HAp)-carbon-modified electrode (CME) composite for qualitative and quantitative analysis of trace Pb(II) ions in the aqueous medium, blood serum and POME, employing cyclic voltammetry and square wave anodic stripping voltammetry, have been developed [12-13]. The newly developed PEC-HAp-CME exhibits favourable characteristics, with high sensitivity and capable of detecting multiple ions at the same time (figure 2). It has successfully achieved the limit of detection of 0.095 ppb for trace Pb(II) ions in the aqueous system, and 0.11 ppb in blood serum and POME [12-13, 22].

3. Microalgal biorefinery

3.1 POME remediation and Bioenergy co-generation

Utilization of microalgal species such as *Nannochloropsis oculata* and *Chlorella* sp. could improve the POME remediation. The co-cultivation of *N. oculata* with EFB, POME and the sludge inoculum in an
anaerobic reactor, not only achieves high removal efficiency of BOD (84-98%) and COD (90-97%) but also attains the highest biomethane (4606-5018 mL CH₄/L POME.day). With *Chlorella* co-cultivation, the highest biomethane was 5276 mL CH₄/L POME.day, and without microalgae, the biomethane level is just 3462 mL CH₄/L POME.day [23-25].

![Figure 3](image.png)

**Figure 3.** Morphological changes of breast cancer, MCF-7 cells, after 72 h treatment for (a) Control; (b) *T. suecica*-CHL; (c) AgNPs–*T. suecica*-CHL; (d) AgNPs; (e) Anti-cancer drug, Tamoxifen (TMX) [8]

Filtered POME in seawater can be used as an alternative medium to cultivate microalgae, thus removing the need for expensive synthetic/chemical media. At 10% POME in seawater for *N. oculata* and *T. suecica* cultivation, high cell growth ($\mu_{\text{max}}$ of 0.21 and 0.20 day⁻¹, respectively) and high lipid content (39 and 27%, respectively), with high content of palmitic acid (C16:0) (28.2 and 36.5%, respectively) have been reported, suggesting their suitability for biodiesel production. The lipid content of *N. oculata* is also higher in 5L photobioreactor (40%) as compared to 300 L open tank (30.7%), with palmitic acid (22%) and oleic acid (7%) produced [26-27].
3.2 Microalgal pharmaceutical products

Microalgae are the main sources of antioxidants and pharmacologically important anticancer, anti-inflammatory, and antiviral compounds [4, 7]. The flavonoids and the phenolics are the major phytoconstituents in microalgae, responsible for these diverse bioactivities which can pave the way for the production of antioxidants, therapeutic drugs or cosmetics [28-30]. In cancer treatment, as chemotherapy normally kills both cancer and normal healthy cells, the use of nanotechnology and targeted drug delivery can open up a new avenue for cancer therapeutics with minimal or no side-effects [8, 31-32]. Silver nanoparticles (AgNPs) is one of the medically-related and metallic NPs with different reported levels of cytotoxicity in vitro with the selective possibility to target specific diseases and cancer cells and tissue [33]. The microalgal extracts and compounds with metal NPs could be harnessed together in cancer therapy, especially for theranostics application. The AgNPs-T. suecica chloroform (CHL) extract co-application at the 2:1 ratio has achieved the IC₅₀ of 6.60 and 53.7 µg/mL on breast cancer cells, MCF-7 and 4T1 cells, respectively, while exhibiting no cytotoxic effects against the normal Vero cells (figure 3) [8]. This suggests great potential in the use of microalgal products from Integrated Biorefinery system, not just for bioenergy and environmental remediation, but also for high-value pharmaceutical applications.

4. Conclusion

Integrated biomaterials engineering of microalgae and oil palm fibres could address the issues of achieving global sustainable development goals and combating climate change and greenhouse gas emission. The processes further emphasize eco-friendly and cleaner production route based on Palm Oil Milling and Microalgal co-cultivation integrated biorefinery model. The lignocellulosic oil palm fibres can be converted into composite materials for diverse applications, while the palm oil mill effluent can be remediated via microalgal co-cultivation with bioenergy co-generation. The microalgal products can be further developed for pharmaceutical applications which should add value to the integrated biorefinery concept.

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