Integrated algal biorefinery and palm oil milling for bioenergy, biomaterials and biopharmaceuticals

M A Abdullah1 and H A Hussein1,2
1 Institute of Marine Biotechnology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
2 College of Dentistry, University of Basrah, 00964, Basrah, Iraq

E-mail: azmuddin@umt.edu.my; joule1602@gmail.com

Abstract. The call for greener processes and eco-friendly products has been the essence of the 2030’s core agenda on 17 Sustainable Development Goals. The major challenge is in bringing systems thinking and holistic worldview to the planning and strategies to develop the Economics whilst incorporating the Environment, and Socio-cultural diversity dimension as equal components. This means a total revamp of human activities such that the discussion on climate change, famine and poverty, destruction of eco-systems and habitat for wildlife, and the emerging infectious diseases, is as relevant as, if not more important than, discussing about artificial intelligence, robotics, flying and driver-less vehicles, and exploration to Mars. There is an urgent need for resource optimization, better biodiversity management and improved agro-practices for food production and distribution, affordable health care, and cleaner energy, air and water, with strict monitoring, regulation and enforcement to minimize emission, pollution and wastage. The focus of this presentation is to highlight research and development efforts towards the realization of sustainable bioenergy production, environmental remediation and conversion into biomaterials via integrated algal biorefinery and palm oil milling processes. Recent development in microalgal research with nanotechnology for biopharmaceuticals and anti-cancer products will be discussed. The image problem and the negative perception surrounding oil palm industries especially with regards to the impact on the environment, and the efforts towards a more sustainable production route will be highlighted. This hopefully could bring forth insights towards partnerships and collaboration among the industrialists, investors, economists, scientists, engineers, and social scientists to tackle the immediate and pressing problems facing the Planet and the People, whilst reaping the Profit, yesterday, today and tomorrow.

1. Introduction
Integrated algal biorefinery and palm oil milling has great potential to achieve the Global Sustainable Development Goals (SDGs) agenda especially with regards to addressing the issues of clean and affordable energy, the development of sustainable cities and the communities within, with responsible consumption and production, and lesser or zero wastage. As the global CO2 emissions from fossil fuels have also increased 15-fold [1], more effort should be made into the development of green technology and environmentally-
friendly materials for cleaner production based on algal cultivation and palm oil milling [2]-[7]. Of great importance is to strive for optimal use of locally available resources, whilst reducing the costs and the environmental impact [8]. With the combined production of 64.2 million metric tonnes of crude palm oil, Indonesia (56.5%) and Malaysia (27.9%) are globally the two biggest palm oil producers [9]. The residues such as the oil palm empty fruit bunches (EFB), mesocarp fibres (MF), palm kernel shells (PKS), palm kernel cake (PKC), and palm oil mill effluent (POME) have great potentials to be turned into value-added products through technologies for composting, pelletizing, briquetting, pressing, pre-treatments, co-generation and pyrolysis [4]-[5], [10]-[14]. The microalgal biomass co-cultivation within the palm oil mill setting is attractive for renewable generation of biofuels [15]-[17], waste remediation [3], [15] and conversion into value-added biomaterials [4]-[5], and high-value biocompounds [2]-[3]. The objectives of this review article was to explore the implementation of the biorefinery concept for bioenergy production and value-added products based on palm oil milling and microalgal co-cultivation, making use of the bio/nanotechnology platform.

2. Integrated Biorefinery

2.1 Bioenergy Production and POME remediation

The palm oil methyl ester posses low engine emissions with high oxidation stability and nitrogen oxide emission [18]. EFB can be changed into bioethanol by hydrolysis, distillation and fermentation or into bio-oil by fast pyrolysis and gasification [19]-[20]. The EFB and palm kernel addition can be utilized in the anaerobic digestion process with POME and sludge inoculum [21]. Algal co-cultivation can be implemented in the palm oil mill for sustainable energy management, environmental remediation and high value biochemical and biomaterials [17], [22] (Figure 1). Co-digestion of Chlorella sp. (2 mL/mL POME) with the EFB (0.12 g/mL POME) has produced 5295.8 mL CH₄/L POME/day with equally high removal efficiency of BOD (95%), COD (98%), TOC (78%) and TN (78%) after 7 days [23]. The co-cultivation of Nannochloropsis oculata (2 mL/mL POME) and EFB (0.12 g/mL POME) also attains high biomethane (4606-5018 mL CH₄/L POME/day) and removal efficiency of BOD (84-98%), COD (90-97%) and TOC (65-80%) [24]. For co-cultivation of N. oculata and Chlorella sp. (1 mL/mL POME) with EFB (0.12 g/mL POME), the biomethane production (4651.9 mL CH₄/L POME/day) remains high [25]. The filtered POME at 10% composition in sea water used as an alternative medium for algal cultivation could enhance cell performance [26]-[27]. The cultivation of Pavlova lutheri at 5-300 L is successfully achieved, but the cell growth (0.35 g/L) in 300 L open-tank is far lower than that achieved in 250 mL reaction vessel (0.43-0.45 g/L) [28]. The 5 L photobioreactor (PBR) cultivation of N. oculata, Tetraselmis suecica, Isochrysis galbana and P. lutheri has attained considerably high biomass (0.62-0.96 g/L) and lipid content (31.6-42.2%) [29]. The fatty acids such as pentadecanoic, C15:0 (8.16%), palmitic, C16:0 (18.4%) and oleic, C18:1 (11.3%) in N. oculata; and palmitic, C16:0 (35.2%), palmitoleic, C16:1 (23.3%) and oleic, C18:1 (13.8%) in P. lutheri, are all highest in 5 L PBR [29].
2.2 Biomaterials

Eco-friendly technique based on autoclave has been developed with formic acid and hydrogen peroxide to yield 64% purely-extracted cellulose (PEC) of 93.7% α-cellulose content and 70% crystallinity [4], [30]. The polypropylene with 25% PEC composites attain 26.7-27.3 MPa tensile strength, without any addition of coupling agents [4]. The surface engineering of PECs with EDTA treatment and loaded with Pb achieves high desulphurization of diesel with 300-350 ppm sulphur removal as compared to 80-110 ppm without Pb-loaded modified sorbents [31]. EFB and the fibers can be manufactured into furnitures, electronics, packaging or building and automobile materials [32]-[33]. An agro-based magnetic biosorbents based on EFB, celluloses from EFB and Ceiba pentandra have been developed to achieve 97.7-99.4% Pb(II) removal efficiency from aqueous system which can be reused for 5 adsorption/desorption cycles [34]. Fabrication of a novel Cellulose-Hydroxyapatite (HAp)-Carbon Electrode has achieved successful detection of Pb(II) ions at trace level with the Limit of Detection (LOD) at 0.11 µg/L, and the Limit of Quantification (LOQ) at 0.36-0.37 µg/L, in blood serum and POME [35]-[36].

3. Biopharmaceuticals

Marine algal bioactive compounds can be developed as anti-cancer or other therapeutic drugs [22], [37]-[38]. The microalgal extracts and compounds such as silver nanoparticles (AgNPs) have great potentials in cancer therapy and for theranostics application. High cytotoxicity at the IC_{50} of 6.60 and 53.7 on MCF-7 and 4T1 breast cancer cells, respectively, has been achieved with the AgNPs-T. suecica chloroform extract at the 2:1 ratio co-application, but with no cytotoxicity exhibited on the normal Vero cells [39].
phospholipids (PL) from microalgae, are suitable for the production of liposomes, providing the combination of the hydrophobic compounds of interest and omega-3 (ω-3) fatty acids and could enhance the adsorption of docosahexaenoic acid (DHA), and decrease the cholesterol and the hepatic fibrosis [40]. This could open up new avenue on the use of microalgal natural products with nanoparticles [39] and for liposomes as drug delivery systems [41], for high-value pharmaceutical applications.

4. Global Sustainable Development Goals and Life-cycle Analysis (LCA)

The integrated biorefinery concept based on palm oil mill [16] and microalgae co-cultivation (Figure 2) should meet the sustainable development goals on low cost and clean energy (goal 7), economic development and decent work (goal 8), and innovation, industry and infrastructure (goal 9). The spill-over impacts include in reducing inequalities (goal 10), creating sustainable cities and communities (goal 11), and responsible consumption and manufacture (goal 12) [42]. The optimal options should not only be based on economic performance indicators, but also on environmental and social indicators. Based on Life-cycle analysis (LCA), palm biodiesel can reduce greenhouse gases (GHG) by 46-73%, as compared to diesel, but the production of nitrogen-fertilizer and its application in the plantation, and the emissions from the ponds treating the POME could lead to major environmental impacts [43]. The palm oil mill-microalgal biorefinery should include options such as the oil recovery, biogas, sugar feedstock, thermo-chemical processes [44], with considerations for commodity chemicals, the aquaculture and animal feeds production, biofertilizers and biocomposites [45], and the high-value biopharmaceuticals, EPA-rich oil and protein extracts [44], [46] to make it a more socially-environmentally-economically viable venture.

![Figure 2](image_url)

Figure 2. Integrated biorefinery based on Palm Oil Mill and Microalgae co-cultivation (Modified from [16]).
5. Conclusion
Integrated Microalgal Biorefinery and Palm Oil Milling could meet the global sustainable development goals in combating climate change and greenhouse gas emission by achieving clean and more affordable energy, promoting decent work and economic growth through the promotion of green industry, innovation and infrastructure. At the same time, reduction of inequalities, creation of sustainable cities with civic conscious communities, practising responsible consumption and production, thus generating reduced, recycled or zero wastes, could be attained. These are achieved by the re-utilization of oil palm residues, bioenergy production, waste remediation and micro-algal co-cultivation with conversion into value-added products. Co-digestion of microalgae with POME and EFB could attain higher biomethane rate with high removal efficiencies of COD and BOD. The POME can also be utilized as an alternative medium for algal cultivation and at the correct cultivation conditions and reactor configuration, specific metabolites or fatty acids composition can be engineered for its final intended applications. Eco-friendly techniques can be adopted for cellulose extraction from oil palm fibres for use in the polymer composites development or for surface engineered for environmental remediation application. Microagal cultivation in a biorefinery concept can be further developed for biopharmaceuticals production or as feed for aquaculture.

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