Opportunity of Smart Aquaculture and Eco-Farming Integration in POME Bioremediation and Phycoremediation System for Environmental Sustainability

Titin Handayani
Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency

Arif Dwi Santoso
Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency

Netty Widyastuti
Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency

Ira Nurhayati Djarot
Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency

他

https://doi.org/10.5109/7363484

出版情報：Evergreen. 12 (2), pp.903-931, 2025-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Opportunity of Smart Aquaculture and Eco-Farming Integration in POME Bioremediation and Phycoremediation System for Environmental Sustainability

Titin Handayani[1,*], Arif Dwi Santoso[1], Netty Widyastuti[1], Ira Nurhayati Djarot[1], Amita I Sitomurni[1], Akhmad Rifai[1], Abdul Aziz[1], Heri Apriyanto[1], Nadirah Nadirah[1], Kusrestuwardhani Kusrestuwardhani[1], Taslim Rochmadi[1], Anggara Lomak P[1], Adim Hadi[1], Heru Mulyono[1], Dadi Soedjati[1], Djatmiko Pinardi[1], Feddy Suryanto[2]

[1]Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia, South Tangerang 15314, Banten, Indonesia
[2]Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia, South Tangerang 15314, Banten, Indonesia

*Author to whom correspondence should be addressed:
E-mail: titi001@brin.go.id

(Received October 11, 2024; Revised March 19, 2025; Accepted May 26, 2025)

Abstract: The increasing production of palm oil mill effluent (POME), which contains pollutants, causes serious environmental problems. The POME treatment can be carried out biologically process by using microalgae, it's called phycoremediation. Biorefineries produced from microalgae biomass cultivated on POME have been widely observed by researchers and found to be very promising. Another alternative to utilizing biomass from treated POME is smart aquaculture and eco-farming. There is no published literature on the integration of these two systems. Therefore, the objectives of this study are to provide the available literature on bioremediation and phycoremediation of POME, to assess the potential reuse of POME treated for integrated smart aquaculture and eco-farming to highlight scientific and regulatory gaps and implementation obstacles. Based on the data and information gathered regarding the large amount of POME in Indonesia and other countries, the adoption of large-scale smart aquaculture and eco-farming is particularly helpful, as monitoring can be done promptly and efficiently. The implementation of new model smart farming systems in developing nations requires greater support from the government at the low farm level and the business sector. This review can be utilized to advance the state of the art in environmental sustainability of POME remediation systems.

Keywords: biorefinery; bioremediation; microalgae; Palm Oil Mill Effluent; phycoremediation; smart aquaculture; eco-farming

1. Introduction

Eukaryotic algae, including microalgae and cyanobacteria, that provide an alternative to currently employed traditional biological treatments that are energy-intensive and ecologically favorable for the treatment of wastewater[1]. Bioremediation is an activity system that uses biological processes to reduce, degrade, modify, eliminate, immobilize, detoxify, mineralize, or transform pollutant concentrations to non-harmful or non-toxic levels[2]. In addition to being a sustainable source of biomass, CO_2 fixation using microalgae in wastewater treatment is efficient and practical[3]. Microalgae can consume carbon, organic, and inorganic components in wastewater treatment, such as N and P, for growth, reducing the concentration of these elements in the wastewater. Phycoremediation is defined as the use of microalgae to treat wastes or wastewater[3].

Microalgae cultivation media containing nutrients is a significant economic component with an impact on the long-term viability of microalgae cells in culture. The cost of widely used synthetic media is high, hence alternate

Cite: T. Handayani et al., "Opportunity of Smart Aquaculture and Eco-Farming Integration in POME Bioremediation and Phycoremediation System for Environmental Sustainability". Evergreen, 12 (02) 903-931 (2025). https://doi.org/10.5109/7363484.

media alternatives must be sought. This alternative media can come from industrial or household wastewater. Palm oil, also known as Palm Oil Mill Effluent (POME), is one source of organic waste from industry that can become pollutants to the environment. The key benefit of wastewater treatment utilizing microalgae is the production of O_2, which is required for heterotrophic bacteria to biodegrade carbon compounds. Although it is difficult to compare the effects of microalgae culture in wastewater treatment, numerous studies have shown that microalgae formation can help with nutrient removal in wastewater [4].

Indonesia has become the world's largest producer of Crude Palm Oil (CPO), with a total production of 32 million tons, accounting for approximately 46.6% of worldwide CPO production as the palm oil sector expands. The demand for CPOs in the global market is escalating. According to Figures from worldwide, the anticipated global demand for CPO in 2020 is 95.7 million tons. Waste production is rising in tandem with the demand for CPO[5]. According to the study's findings, processing 1 (one) tonne of oil palm Fresh Fruit Bunches (FFB) will result in waste that includes empty oil palm fruit bunches weighing up to 23% or about 230 kg, shell waste weighing up to 6.5% or about 65 kg, and palm sludge (wet decanter solid) that weighs up to 4% (or 40 kg), fiber that weighs up to 13% or about 130 kg, and liquid waste that weighs up Studying the biological treatment provided by microalgae is crucial due to the rise in POME.

Palm oil or CPO is the mainstay of foreign exchange earning commodity for Indonesia from the agro-industry sector, which produces around 85-90% of the total world palm oil production. Riau Province has a palm oil plantation area of 2.8 million hectares with total CPO production, which has increased from the previous year, namely 9.1 million tons in 2017 and 9.8 million tons in 2018[5]. The expanding Indonesian palm oil industry will generate an increasing amount of liquid waste. POME contains carbon and nitrogen that can be used as nutrients for microalgae growth as well as for pollutant removal in wastewater[6].

According to recent reports, oil palm production is wreaking havoc on the environment, particularly in Southeast Asia. It has been reported that the POME wastewater treatment system produces pollutants that can damage the environment. [5] POME bioremediation and phycoremediation have been widely observed by researchers. These procedures produce important biorefineries such as biodiesel and other bioenergy. Many have researched microalgae cultivation using POME wastewater media, but most of them are still on a laboratory scale.[4] For this reason, it is necessary to evaluate the research results on the potential of microalgae in POME processing and sustainability.

The possible issue is that it is uneconomical because further processes are required before it can be used, which demands a large cost, so the price of biorefinery becomes expensive. As a solution to the challenge, this study proposes another method for employing collected microalgae biomass for fish feed in an integrated system. Furthermore, aquaculture's liquid waste can be used as agricultural fertilizer. This smart aquaculture and eco-farming concept is quite profitable. This integration system of POME remediation has no literature that publishes such study results, therefore the concept design that will be developed is the originality of the role of microalgae with POME medium in environmental sustainability. Reuse of POME treated for integrated smart aquaculture and eco-farming to highlight scientific and regulatory gaps and implementation obstacles.

The objectives of this study are to provide the available literature on bioremediation and phycoremediated POME, to assess the potential reuse of POME treated for integrated smart aquaculture and eco-farming to highlight scientific and regulatory gaps and implementation obstacles. The studies carried out covered the diversity of microalgae found in POME, selected microalgae capable of growing in POME to produce useful ingredients for biorefinery, and methods of pollutant removal processes in POME. In addition, the study then discussed the potential for sustainable aquaculture, and eco-farming as an environmental sustainability contribution.

2. Characteristics of POME

Coconut industry liquid waste Palm oil mill effluent (POME) includes a high concentration of organic compounds that can damage groundwater and bodies of water. When organic contaminants are large enough to enter streams, they can degrade water quality and diminish the carrying capacity of plants and the surrounding aquatic ecosystem. Reduced environmental carrying capacity causes the death of aquatic organisms, which slows the growth of other aquatic plants and increases odor, making it an ideal breeding ground for bacteria, both pathogenic bacteria (bacteria that cause disease) until it grows and grows and apathogenic bacteria (non-producing bacteria that can cause disease). Concentrate BOD (Biological Oxygen Demand) and TSS (Total Suspended Solids) waste from the palm oil mill that was released directly into the environment and does not fulfill quality standards, is what you get [4].

Characteristic chemicals and pollutants of POME are listed in Table 1 which summarizes the organic chemical properties. Additionally, non-organic chemical properties and heavy metal concentrations are given Iron (Fe), Manganese (Mn), and Zinc (Zn) which exceed the requirement threshold and cause toxic pollution to the environment. The role of microalgae in eliminating heavy metals, which are harmful contaminants, is critical in combating environmental pollution[7,8].

Heavy metal content was determined using silver nanoparticles [9]. This approach is suitable for POME that contains heavy metals. Polysulfone/chitosan/polyvinyl alcohol integrated composite membranes can also be used to extract heavy metals like mercury. Polyvinyl alcohol integral composite membranes [10].

Table 1: POME chemical and pollutants characteristic

Parameter		Range	Standard discharge limits (mg/L)
Protein*	g/L	4.2 – 6.0	-
Carbohydrate*	g/L	28.10 – 30.30	-
Total sugar*	g/L	1.5-3.	-
Fiber*	g/L	0.7-2.3	-
Fat*	g/L	6.00-7.20	-
Ash*	g/L	6.50–9.70	-
Nitrogen**	mg/L	180-1400	10
Phosphate**	mg/L	37.175	-
Phenol**	mg/L	≤0.0001	-
Potassium**	g/L	1.459	-
Sulphate**	g/L	1.032	-
Ammonia**	mg/L	125	10
Iron (Fe)**	mg/L	1757	1.0
Manganese (Mn)**	mg/L	62	1.0
Zinc (Zn)**	mg/L	1075	1.0
COD ***	mg/L	40000 – 90000	50
BOD ***	mg/L	15000 – 30000	20
Suspended solid ***	mg/L	50000– 54000	50
Oil and grease	mg/L	130-18000	10
pH***		3-5	6-9

Ref. *[11]; **[12]; *** [13]

3. Bioremediation and Phycoremediation in Removing POME Pollutants

In the removal of POME contaminants, bioremediation and phytoremediation are used. The bioremediation process begins with the removal of contaminants by microorganisms, specifically bacteria. Microalgae will use the byproducts of bacteria's breakdown of organic material to thrive. Meanwhile, microalgae remove hazardous heavy metal contaminants that bacteria are unable to ingest and break down. Microalgae cells store heavy metals. The process of microalgae absorbing hazardous heavy metal contaminants is known as phycoremediation[14,15]. Figure 1 depicts the variety of indigenous microalgae kinds found in POME. Figure 2 depicts the interaction process of bacteria and microalgae in cleanup.

Aside from bioremediation, the biomass and value products obtained during WW treatment make phycoremediation more suited and superior to all others[16]. Microalgae might be used to remove all toxins from wastewater, and high-value metabolites and chemicals generated from algal biomass could be used in industrial applications, increasing the value of waste streams[7].

4. Diversity of Indigenous Microalgae in POME

The microalgae consortium is a mixture of various microalgae species that naturally live together with various other microorganisms, such as bacteria[17,18]. A report from the research bacteria, namely *Bacillus* sp. POME microalgae consortium species have been isolated and identified[19,20]. The species diversity of the microalgae consortium is presented in Figure 1.

Microalgae consortium culture has faster growth and higher biomass than monoculture [21], with high biomass growth, will produce high lipid content as well[22,23]. Not only does the microalgae consortium have bioenergy potential, but it can also remove nutrients from wastewater[24,25]. The consortium of indigenous microalgae showed better growth and stability than microalgae monocultures, and could remove more than 98% COD in milk wastewater[26,27]. The COD levels in wastewater decrease along with the activity of microalgae that produce oxygen from the photosynthesis process[28,29]. In this study, a semi-continuous culture technique was carried out by changing the culture with new nutrients within a certain period. Time biomass productivity will increase along with the ratio of nutrients added to the microalgae culture[30]. Semi-continuous culture techniques increased biomass production by 38.5% with a biomass yield of 7.51±0.22 gr, while batch culture was 6.53±0.16 g[31].

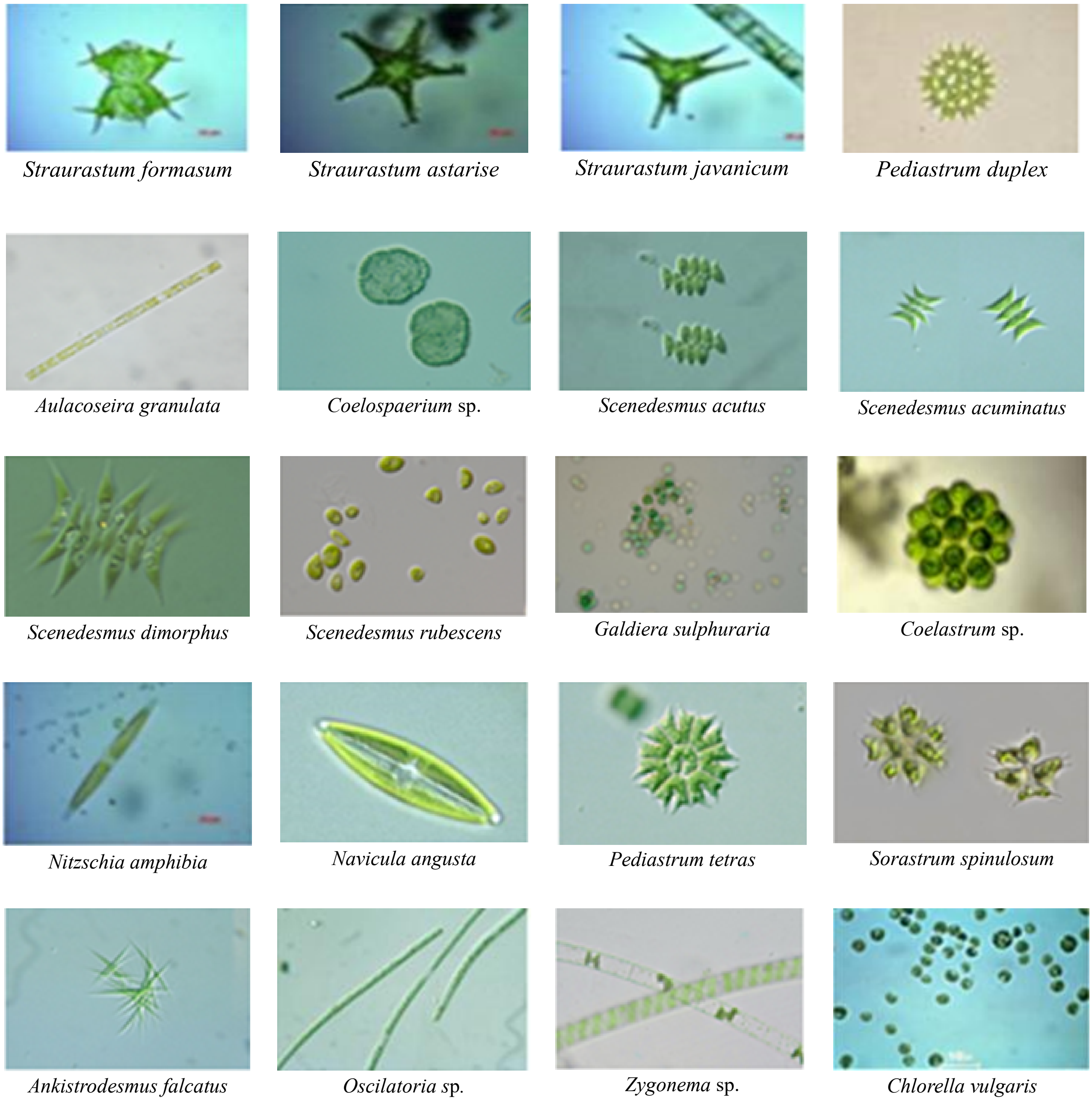


Fig 1: Morphology of the diversity of microalgae and cyanobacteria species isolated from POME wastewater [17)]

The adaptation phase was not seen in every treatment, because the microalgae cells that were inserted into each flat-photobioreactor came from cultures that were in the exponential phase, so the microalgae cells were fast in growing and dividing, states that the adaptation phase usually occurs when the inoculum is inoculated into a new medium with different chemical components. Indigenous microalgae consortia do not require a long adaptation. Time in their growth, so the microalgae cells will quickly enter the exponential phase [32)].

5. Interaction of Microalgae and Bacteria in Wastewater Treatment

Wastewater treatment with microalgae is a green process that can eliminate pollution[33,34)]. Several species of microalgae have the potential to process POME as *Scenedesmus acutus, Scenedesmus acuminatus, Scenedesmus dimorphus, Scenedesmus rubescens, and Chlorella vulgaris*; because through photosynthesis, microalgae process POME to produce biomass by utilizing nitrogen and phosphorus compounds present in POME [17)]. Figure 1 provides an illustration of the wastewater treatment process by microalgae and bacteria to produce biomass, both microalgae and bacteria. The two microorganisms interact where microalgae produce oxygen from photosynthesis with wastewater nutrients [35,36)]. Furthermore, bacteria utilize oxygen for their metabolic activities. These activities generate carbon dioxide, nitrogen, phosphorus, vitamins, and other substances that are used in the growth of microalgae

(Figure 2).
Because the microalgae biomass produced has the potential to become a major source of biofuel, using microalgae for POME processing is very cost-effective [37,38]. Microalgae with lipid content of more than 40% are very potential for biofuel. The results of the research above (Table 1) show that the species of *Tetraselmis suecica* and *Chlorella pyrenoidosa,* with lipid content of 68% and 68% have the most potential for biofuel raw materials.

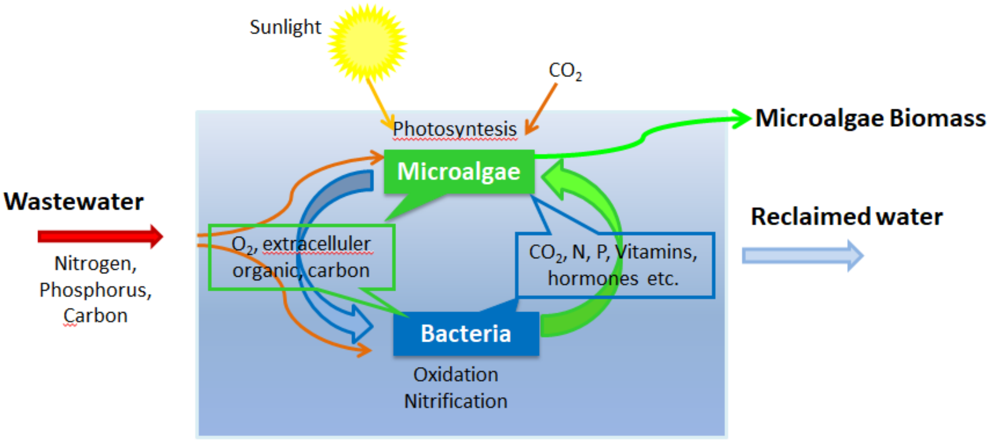


Fig. 2: Schematic of interaction and molecular exchange between microalgae and bacteria in wastewater treatment.

Another benefit of microalgae is that they can be grown on ground that is not suitable for agriculture [39,40]. Microalgae also can reduce BOD and COD from POME, thereby reducing pollution[41,42]. POME has a wide and profitable application in microalgae cultivation. This is because using microalgae can reduce not only the nutrient content of POME; but also the resulting biomass, which can be used as a biorefinery source with added value. POME-grown microalgae are high in lipids, proteins, and carbohydrates, and can be used as feed and fuel. Another advantage, microalgae produce material that has potential value if used for compounds of biofuels and bioactive that benefit the energy and pharmaceutical industries.

6. Factors of Microalgae Limiting Growth in POME

The growth of microalgae is supplied by media containing nutrients according to their life needs. POME ponds contain nitrogen, phosphorus, and carbon, which is a nutrient essential for microalgae growth[43,44]. In addition to nutrients from POME, light intensity, glucose concentration, and carbon dioxide concentration can boost microalgae growth and lipid content [4]. Much research on POME is used for microalgae media and the conclusion is that POME contains the nutrients needed by microalgae growth which are cultivated in open ponds with sufficient sunlight for photosynthesis.
Several variables, particularly photosynthesis, play an important role in microalgae growth requirements. Thus, carbon dioxide concentration and light intensity will be the primary factors that can influence microalgae growth. The effect of the two limiting factors for the microalgae growth was studied, as illustrated in Figure 1[45]. According to the findings of this investigation, microalgae growth is directly related to light intensity[46]. High carbon dioxide concentrations cause the medium to become acidic, reducing photosynthetic activity and slowing growth rate. The ideal CO_2 concentration was discovered 12.5% [47]. The maximum lipid production of *Ettlia* sp. YC001, on the other hand, was discovered to be below 0.05% CO_2 concentration and 400 E/m2/s light intensity[48]. Furthermore, at different microalgae loads, green light produced the most photosynthetic activity and the highest rate of oxygen production [49].
Microalgae have a quick cell multiplication time and a flexible metabolism. Most are photoautotrophs, but due to changes in conditions and environment, many species undergo metabolic changes and become heterotrophs. The energy source for microalgae to carry out photosynthesis is carbon dioxide and carbon in organic molecules [50].
POME ponds that are in a flooded condition, because wastewater is discharged into the pond with no flow, will promote the growth of microalgae. On the other hand, if there is water movement, it will interfere with the expansion of microalgae. Only in a calm stream can microalgae grow. Table 2 shows the range of optimum conditions for the growth of microalgae using POME.

Table 2: Environmental factors microalgae cultivation using POME [34]

Parameters	Range	Optimum
Temperature (ºC)	17-28	20-25
Salinity (mg/L)	13,000-30,000	22,000-25,000
Photoperiod light and dark)	-	16:8 (Minimum) 24 h (Maximum)
pH	7.0-9.0	8.2-8.7
Rate of CO_2	1-4%	1% of volume di air
Nutrient	-	N:P (16:1)and Silicon

7. Case Study of POME Bioremediation

In the last few decades, numerous approaches for treating POME have been documented. Anaerobic systems commonly utilized in POME degradation include
tank digestion and facultative ponds, tank digestion and mechanical aeration, physicochemical and biological treatment, and decanter and facultative ponds. However, these systems have some downsides, including greenhouse gas emissions, long retention times, inconsistency in nutrient removal, and enormous land area needs[51)]. This study only presents an update on the results of POME bioremediation research for the last 4 years which can be seen in Table 3.

Table 3: Case study of POME bioremediation

Microorganism	Infrastructure	Pollutants reduction	Ref.
Meyerozyma guilliermondii	Flask experiments under aerobic condition	As a result, this strain is appropriate to be used in the remediation of POME.	51)
The chicken droppings and cow dung	clean plastic containers	The bacteria, mold, and yeast are useful in rehabilitation of POME-polluted soil and possibly	52,53)
Microorganisms found in cow dung included Proteus, Bacillus, Escherichia coli, Pseudomonas, Micrococus, and Corynebacterium, as well as Fusarium, Aspergillus, Pernicillium, Geothricum, and Mucor fungus species. Candida sp. yeast.	There are two different plastic containers. Set A included the POME-contaminated soil (PCS), whereas set B was augmented (amended) with 100g of dried and marshed cow dung.	Cowdung microorganisms have the potential to break down organic contaminants in the POME-contaminated soil.	54)
Aspergillus niger	Lab scale	*A. niger* has been shown to be 70% effective at removing COD.	55)
Anaerobic microorganism	Ponding system	success implementation of bioremediation and its challenges.	56)

8. Pre-Treatment of POME for Microalgae Cultivation

Before using POME for microalgae cultivation, it must be pre-treated. POME pre-treatment processes include thermal, chemical, mechanical, and biological processes. POME pre-treatment, such as coagulation and absorption processes, can increase sunlight penetration during the microalgae culture process in the POME system[57)]. Rice flour and tapioca flour can be used in the coagulation process. In contrast, the absorption process can be carried out by utilizing activated carbon derived from palm shell biomass. This is an excellent way to repurpose the biomass generated by the palm oil industry.

POME pre-treatment with chemicals or activated carbon before microalgae are cultivated for thickening and absorption of color. Turbidity of wastewater can be reduced by adding activated carbon; so that microalgae can carry out photosynthesis more effectively. Activated carbon was reported to microalgae growth[58)].

Activated carbon generated from palm kernel shells has been shown to reduce turbidity by up to 83.33%, COD by up to 83.91%, and suspended solids by up to 92.30%. This decrease was higher than the coagulation procedure with rice and tapioca flour. However, the absorption process with activated carbon is longer than the coagulant process[40)]. The dark color of POME is caused by lignocellulosic plant components which contain lignin, cellulose, and hemicellulose as well as carbohydrate components, namely hexoses, and pentoses. Heat-acid treatment is another way of POME pre-treatment to reduce dark color[41)]. The carbohydrate content in POME was broken down into glucose, the acid-heat pre-treatment method hydrogen. POME lignin dissolves easily in acid during the pre-treatment process[59)].

POME pre-treatment will help improve the microalgae growth process to produce sugars to be used as a medium. The pre-treatment process by removing the lignin that causes the dark color, provides an opportunity for more light to enter the media for the photosynthesis process to increase the microalgae growth. As a result, the use of POME for microalgae culture is feasible, and must be processed first to reduce BOD, COD, turbidity, and suspended solids to maximize POME utilization of microalgae. A new method called autoclaving was used, which resulted in increased yield and productivity of microalgae biomass to treat wastewater[41)]. At the same time treating wastewater with pre-treatment similar to autoclaving, centrifugation, and filtration, but this method requires energy for the process[60)]. Several studies reported that microalgae cultivation in POME media was found to accumulate high levels of lipids. Pretreatment was evaluated using several parameters, including pH, particle size, stirring speed, and POME dose.

9. Case Study of POME Phycoremediation by Tolerant Microalgae

Microalgae using POME media in this study were grown in reactors with the necessary infrastructure to monitor their growth optimally. Microalgae cultivation can be done in two types of reactors: horizontal and vertical photobioreactors and open raceway ponds. Table 4 below summarizes the results of microalgae research with various growth process methods.

Table 4: Case study of POME pollutants removal by tolerant microalgae and produce biomass

Source of POME/consentration	Microalgae	Infrastructure cultivation	Pollutants reduction and Product/output	Ref.
POME from Waste Water Treatment Process pond with COD concentration 250 mg/L	*Chlorella sorokiniana, Botryococcus seditious, Tetraselmis* sp, *Chlorella vulgaris, Chlorella pyrenoidosa*.	Room temperature Light intensity illumination continuous ± 15 µmol m^{-2} x^{-1}	*Chlorella sorokiniana* is the predominant species. It has the highest biomass and lipid productivity. Reduce COD and BOD	61)
POME diluted 50% + 1 g/L urea	*Chlorella* sp.	Laboratory scale. Temperature 28 ^{o}C	*Chlorella* sp showed a higher specific growth rate (0.066/day), at 50% POME 1gr/L urea,	62)
POME extracted from an anaerobic pond and diluted by 40%	*Spirulina platensis*	Laboratory scale Light intensity 4000 – 6000 Lx	POME has the potential to be used as an microalgae medium due to the reduction of external nutrients such as NaHCO3, urea, and micronutrients. The benefits of clean treated POME after algae biomass harvesting. Saved 50% on synthetic nutrients while producing 5.93gr/l wet biomass for 9 days.	63)
POME from Waste Water Treatment Process	*Spirulina platensis*	1000 ml Erlenmeyer. Lighting for 24 hours using TL lamp.	The addition of 200 mg/l NaHCO3 results in the best nutrient composition. C,N,P levels in the media fell from 20.60% to 84.69%, 87.52% to 93.74%, and 29.44% to 76.66% at the end of cultivation.	64)
POME from the Waste Water Treatment Process Pond, undiluted	*Chlorella pyrenoidosa*	3 L PBR (Photobioreactor) Temperature: 24-26 ^{o}C, mixing speed: 60 rpm 8:16 light jam (T:G) pH 6,5 – 7,5 150 µmol $m^{-2}x^{-1}$ light intensity	POME was diluted ten times to lessen the shadowing effects on the growth of microalgae. Under continuous illumination, the highest amount of biomass (39.41 g/L) and lipid productivity (42 mg/L.d) were obtained.	65)
POME was 1% diluted	*Arthrospira platensis*	Outdoor tank with 10 L culture media in a 20 L tank	*A. platensis* can be cultured in 1% v/v fresh POME without compromising its growth or pigment production.	66)
POME with a COD concentration of 250 mg/L from the Waste Water	*Chlorella pyrenoidosa*	Photobioreactor HPBR 5 L with impeller turbine	A high microalgae growth rate (1.80 d1) was seen at 250 mg COD/L of substrate	67)

Treatment Process Pond.		Temperature: 30 ºC Light intensity: 4 lamp @ 32 W continuous white fluorescent light cahaya fluoresense (24 jam) Germany, Philip C:N = 100:6		
POME from the Waste Water Treatment Process Pond with a COD concentration of 250 mg/L	*Chlamydomonas incerta*	Laboratory scale Temperayure 30 ºC Light intensity 15 mol m-2 x -1	The cells developed slightly rough and corrugated textures, and some particles were discovered on the cell wall's surface. POME is a promising approach for either natural environmental treatment or as a high-lipid-content raw material for biofuel production.	68)
500 mL POME was diluted in 400 mL deionization water.	*Chlorella* sp	Laboratory scale	The mass transfer of CO_2 from the gas phase into the liquid phase is the main area for improvement in order to increase the percentage of CO_2 recovered.	69)
POME with a COD concentration of 130 mg/L from the Waste Water Treatment Process Pond	*Botryococcus braunii*	Laboratory scale	The biomass contained lipid (39.9%) and carbohydrate (41.03%), which could be used as a biofuel source.	28)
POME with a COD concentration of 250 mg/L from the Waste Water Treatment Process Pond	*Chlamydomonas incerta*	Laboratory scale	The maximum biomass productivity and specific growth rate for the 16/8 cycle were 0.122 for the 24/0 L/D cycle. COD removal was 88%, TN removal was 97.3, and TP removal was 99.8%.	70)
POME has been pre-treated.	*Coelastrella* sp. *Chlamydomonas* sp. and *Scenedesmus* sp.	Laboratory scale	These native microalgal species have a high potential for cultivated in POME, phycoremediation and CO_2 biofixation.	71)
Following the aerobic treatment method, higher POME concentrations were obtained and kept at 20°C.	*Haematococcus pluvialis* and *Chromochloris zofingiensis*	Laboratory scale	POME has the potential to be used microalgae cultivation to produce astaxanthin.	72)
5% anaerobic digested POME + 0.075% NPK + sea water	*Isochrysis* sp.	Photobioreactor, outdoor	Produce higher biomass, lipid, fatty acid content than microalgae cultivated indoor laboratory.	73)
10% POME + sea water	*Nannochloropsis . oculate* and *Tetraselmis suecica*	Culture in the laboratory	39% lipid; 29.24% SFA, 9.07% PUFA, and 93.6% COD removal	74)
POME 150 mg/L COD	*C. vulgaris*	Batch culture in laboratory	Produce lipid, carbohydrate, and reduce COD..	29)
POME at a concentration of 250 mg/L COD	*B.braunii*	Laboratory culture flask.	Produce carbohydrate and lipid.	29)
1% raw fresh POME +	*S. platensis*	Green house	Produce phycocyanin,	66)

commercial nutrient		cultivation;	carotenoid, and chlorophyl in biomass.	
10% POME digested + water	*C. vulgaris*	Culture in the laboratory flask batch cultivation; 10 k lux light for 24 hours.	Produce lipid, protein, carbohydrate; and linolenic acid.	75)

The concept of integrating smart aquaculture and eco-farming in a post-POME phytoremediation system is presented in Figure 3. The POME is collected in a basin for bioremediation. The addition of appropriate microorganisms is required for the process. Microalgae consume the organic materials and oxygen created when the organic components in the POME are destroyed to perform phycoremediation. Microalgae's performance in phycoremediation leads to harvested biomass being used as a biorefinery feedstock. While the obtained liquid microalgae biomass contains nutrients and residual biomass. The material is then pumped into a pond for use as aquaculture media. Aquaculture pond fluids containing fish excrement can be used as agricultural fertilizer in addition to producing fish. As a result, including smart eco-farming has a positive impact.

Microalgae cultivation with POME is typically done in raceway open ponds. Another option is to cultivate microalgae in photobioreactors. The microalgae *Synechococcus (*Cyanobacteria) was successfully grown in a photobioreactor with extra NPK fertilizer [76]. The photobioreactors used comprise polydispersed flow on rectangular airlift with mixing performance [77].

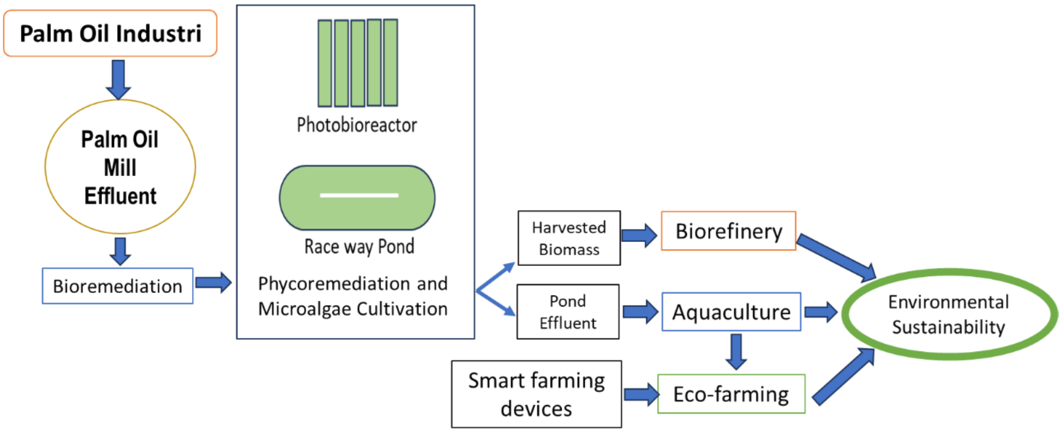


Fig. 3: Concept of circular economy integrating system smart aquaculture, eco-farming in post POME phycoremediation

10. POME Based Biorefinery Production

The majority of studies on the environmental impact of biorefinery derived from microalgae cultivated in wastewater which is widely published have focused on biofuel. Reviews of available publications from 1999 to 2021 that LCA was used to assess the environmental impact of biofuel production. Some research has concentrated on certain bioproduct categories other than biofuels (Table 5). They concluded that, except for biopolymers, all bioproducts use less nonrenewable energy and emit fewer greenhouse gases than their fossil-based counterparts. However, they stated that it cannot be concluded that one bioproduct outperforms others in terms of environmental performance.

However, because they used different frameworks (a border and allocation approach) and have varying levels of accuracy, transparency, and consistency, is impossible to compare their outcomes rationally[78]. Furthermore, the environmental evaluation of the biorefinery context is still in its early stages for two key reasons: (1) not all likely environmental issues, such as Indirect Land Use Change (ILUC) are addressed, and (2) different types of uncertainty are not considered [79]. As a result, environmental evaluation based on LCA is crucial in making strategic decisions about future biorefinery deployments.

Table 5: Comparison LCA of biorefinery production from microalgae

Types of biorefinery	Topic research	Boundary	Results	Ref.
Briquette	Producing energy recovery using briquette by microalgae cultivated in wastewater	Cradle to grave	Microalgae cultivated in wastewater using briquette feasible to environmentally friendly technology	80)

			and potential to produce alternative energy.	
Biochar	Biochar from microalgae	Cradle to grave	Potential to applicate in other fields.	81)
Biofuel	Biofuel production from microalgae cultivated in anaerobic digested wastewater	Cradle to grave	A promising approach could be biofuel production from microalgae combined with wastewater treatment.	82)
Bio-oil	Bio-oil production from microalgae biomass through pyrolysis processing regime	Cradle to grave	Utilization waste for microalgae nutrients were reducing the proposition's environmental impact.	83)
Biodiesel	Biodiesel from estuarine microalgae	Cradle to grave	The wastewater-biocatalyst scenario to produce biodiesel have benefit to reduce cost wastewater remediation.	84)
Biomethane	Biomethane is produced by cultured microalgae coupled to the biogas process.	Cradle to grave	Progress can be made by lowering mixing costs and increasing circulation between different production steps, or by improving the anaerobic process efficiency under controlled conditions. This new bioenergy generation process is fiercely competitive with other biofuel production processes.	85)
Biohythane	Biohytane is produced by biomass microalgae cultivated in food waste through anaerobic fermentation in the two-stage reactor.	Cradle to grave	This new bioenergy generation process is fiercely competitive with other biofuel production processes.	86)
Bioethanol	Microalgae production in a tropical country	Cradle to grave	As a result, this study predicted that microalgae-to-bioethanol conversion would have a positive impact on both energy and the environment.	87)
Biobutanol	Biobutanol is produced from genetic engineering of Cyanobacteria	Cradle to grave	A high cumulative energy demand in all scenarios indicates that this process is required to displace fossil fuels or even first and second-generation bioethanol.	88)
Bioplastic	There haven't been many LCA studies published specifically for microalgae-derived bioplastics.			89)

The problem is land availability and requirements. Large-scale biofuel production can necessitate vast tracts of land. Many countries cannot afford to divert land from agricultural production. The debate over "food vs. fuel" is complicated. Land, water, and agricultural chemicals are all required to produce food and biomass [90]. Food and fuel do not have to compete, especially if environmental protection and sustainable manufacturing methods are carefully planned. However, the reality is more complicated. [91].

Microalgae for biorefinery integration into the palm oil industry can help to achieve by addressing the problems and consequences of climate change and greenhouse gas emissions, to achieve global sustainable development goals[92,93]. Clean energy and affordable economic growth can be achieved simultaneously through, innovation, green industry, and infrastructure. The program creates sustainability by promoting responsible production and consumption[94].

There are few studies available, which describe the Life Cycle Assessment (LCA) of bioplastic from microalgae. [95] Microalgae biomass is one of the long-term stages toward a greener world since biorefinery made from algal biomass is more environmentally friendly.[96] There are classes and species of microalgae that have yet to be recognized. As a result, the species chosen for the experiment is complicated, and more research is needed to investigate the qualities and efficiency of each species. Furthermore, algal genetic engineering experiments are restricted to the laboratory. The utilization of microalgae in biorefinery leads to the release of harmful greenhouse gases, such as carbon dioxide, methane, and nitrous oxide. This issue can be mitigated by employing techniques such as incineration.[97,98].

Despite its high nutrient content, using POME as a growing medium for microalgae on an industrial scale remains difficult. To begin with, the presence of a high concentration of organic components such as tannins, lignin, and phenolic compounds may be detrimental to growth [21]. High suspended solids concentrations may provide a dark coloration that could prevent light from penetrating, which is essential for developing photosynthetic organisms.[99,100].

Microalgae cultivation as an alternative to molecular farming techniques could aid in the development of pharmaceuticals based on natural microalgae chemicals, either directly as drugs or as essential molecules in biochemical drug production[101,102]. Microalgae bioactive compounds can add value and boost biorefinery economic competitiveness in various applications, including the food industry, and the discovery of new enzymes and drugs. On the other hand, the utilization of microalgae cultivation products contributes to biotechnology, toxicology, and biological systems[103,104].

The sustainable use of microalgal biomass to produce fuel is still under investigation, with much research to be done and evaluated, even just for the cultivation stage. The results show the importance of choosing restrictions in the cultivation process to become biofuels, especially regarding energy use, fertilizer choice, water use, and microalgae composition. Improvements in various fields simultaneously can lead to rapid progress in the development of environmentally friendly microalgal biofuels. There are various advantages of treating POME with microalgae. This POME treatment approach not only decreases contaminants in wastewater; but also offers new opportunities for various applications[105.106].

LCA which combines economic performance, and the impact of environmental and social indicators, is the best option for making more informed and knowledge-based decisions[107,108]. Nonetheless, before implementing large-scale POME-integrated biorefinery production facilities and pilot-scale tests, product toxicological and techno-economic feasibility studies are required. The phrase "techno-economic analysis" (TEA) is frequently used to describe the economic benefits and technical challenges of using this biomass in a biorefinery setup[109,110]. There are various advantages to using microalgae as a feedstock in the manufacturing of renewable fuels and products. Given the importance of cultivation productivity in the cost of producing algal biomass, more TEA analysis is needed to fully comprehend the economic potential of employing high-protein, low-cost microalgae for biorefinery conversion.

An economic analysis of the biorefinery based on the parameters listed in Table 6 was conducted. Table 6 contains the data used to conduct the economic assessment of the design chain. A discounted cash flow analysis is performed for capital cost, assuming a facility lifetime of 20 years and a 10% discount rate. Capital costs are assessed based on manufacturing capacity and equipment material, whereas operating costs comprise utilities, administrative, labor, and maintenance expenses.

Based on the amount of CO_2 and biogas effluent created by the palm oil mill and biogas plant, 112.3 t/y of dry algae are produced when grown in an open pond, whereas 2,176 t/y of dry algae are produced in a tubular photobioreactor. Open ponds have a low investment cost but limited productivity. In contrast, tubular photobioreactors have a high production cost but are efficient and produce a lot of biomass[111].

Table 6: Economic parameter of bioavailability process and product [112]

Parameters	Classification	Value	Unit	Ref.
Biogas	Selling price	0.46	USD/m^3	113)
Electricity	Selling price	93.75	USD/MWh	114)
Biodiesel	Selling price	729.12	USD/m3	115)
Glycerol	Selling price	1.05	USD/kg	116)
Alum	Raw material price	2.07	USD/kg	117)
Chitosan	Raw material price	2	USD/kg	116)
Hexane	Raw material price	0.47	USD/kg	116)
Isopropanol	Raw material price	1.35	USD/kg	118)
Biogas facility	Operating cost	27.65	USD/t	119)
Algae biorefinery:				
Open pond	Capital cost	34,100	USD/ha	120)
	Operating cost	14.96	USD/t	121)
Tubular photobioreactor	Capital cost	2,619	USD/m^3	122)
	Operating cost	580	USD/t	123)
Flocculation	Capital cost	2,550	USD/ha	124)
	Operating cost	15.66	USD/t	125)
Centrifugation	Capital cost	42.25	USD/t	126)
	Operating cost	2.34	USD/m^3	127)
Drying	Capital cost	112.30	USD/t	114)
	Operating cost	134.20	USD/t	128)

Solvent extraction	Capital cost	24,300	USD/ha	121)
	Operating cost	4,780	USD/ha/y	120)
Base catalysed transesterification and biodiesel refining	Capital cost	9,188	USD/m^3	126)
	Operating cost	110.95	USD/m^3	129)
Combustion	Capital cost	0.91	USD/MWh	114)

The best-performing biorefinery in terms of economic performance integrated glycerol valorization process research and development enables economically viable biorefinery schemes using *Scenedesmus dimorphus* microalgae biomass as a feedstock[130], and *Desmodesmus* sp.[79) 131]. Economic sensitivity analyses were carried out r to find additional major cost drivers; and a resource assessment comparison was carried out to analyze aspects such as water and CO_2 requirements 80 [132]. Algae cultivation near point sources such as power plants as a biosequestration approach for CO_2 reduction, as well as the use of algae in nutrient recycling and environmental remediation, are increasingly developing as key study fields 81 [133]. The overall results of this study showed that growing microalgae in POME to manufacture biorefinery will make it more practical by lowering the cost of production overall per unit of bioproduct.

The LCA and TEA analysis shows that using flue gas as microalgae nutrition via bio-fixation and wastewater is very profitable. As a result, these two contaminants can create microalgae, which is beneficial in a densely populated industrial setting. The investment's profitability is boosted in certain circumstances, which is critical considering the location of the microalgae biomass production plant. This is a system that will benefit not just the environment and public health (by reducing trash and GHG emissions), but also the economy (by lowering operational costs). This is the establishment of a long-term industry. The study's findings pave the way for future research, particularly modeling a full and integrated system encompassing all stakeholders 82 [134].

The exploration of the POME processing sustainability index with microalgae is currently in its early stages. As a result, combining a microalgal system with conventional POME treatment appears practical and encouraging. Because of its potential as a source of bioenergy, including microalgal culture in current POME treatment methods has become far more feasible. To optimize the socioeconomic advantage of algae-derived biodiesel growth, places with a high socioeconomic effect multiplier should be chosen, taking regional climate, marginal land, and socioeconomic aspects into account.

Microalgal biomass has been demonstrated to be one of the most efficient and ecologically friendly alternative energy sources, serving as a realistic and sustainable source of biofuel that can help reduce atmospheric greenhouse gas emissions. The use of a biorefinery technique to extract many products from a single operating process provides the path for the development of microalgal biomass-based technologies. According to the biorefinery complexity index, one of the most promising approaches for attaining this goal is a biorefinery platform that transforms microalgal biomass into fuels, food, nutritional and feed additives, fertilizers, and pharmaceuticals[131].

11. Case Study Technology of Smart Agriculture

A complete overview of the various technologies that are transforming the field of smart agriculture presented in Table 7. It shows how each technology, from drones and big data analytics to blockchain and GIS, contributes differently to improving agricultural operations. These improvements provide numerous benefits, including increased efficiency, precision in resource management, improved crop monitoring, and greater decision-making capabilities. However, they present their own set of obstacles, such as high implementation costs, the need for specialized expertise, and worries about data security and privacy. Understanding these technologies in the context of their benefits and drawbacks is critical for fully realizing their promise in smart agriculture. This nuanced approach assists stakeholders in navigating the intricacies of technological integration in farming, ensuring that the transition to more intelligent agricultural systems is both sustainable and beneficial to all concerned.

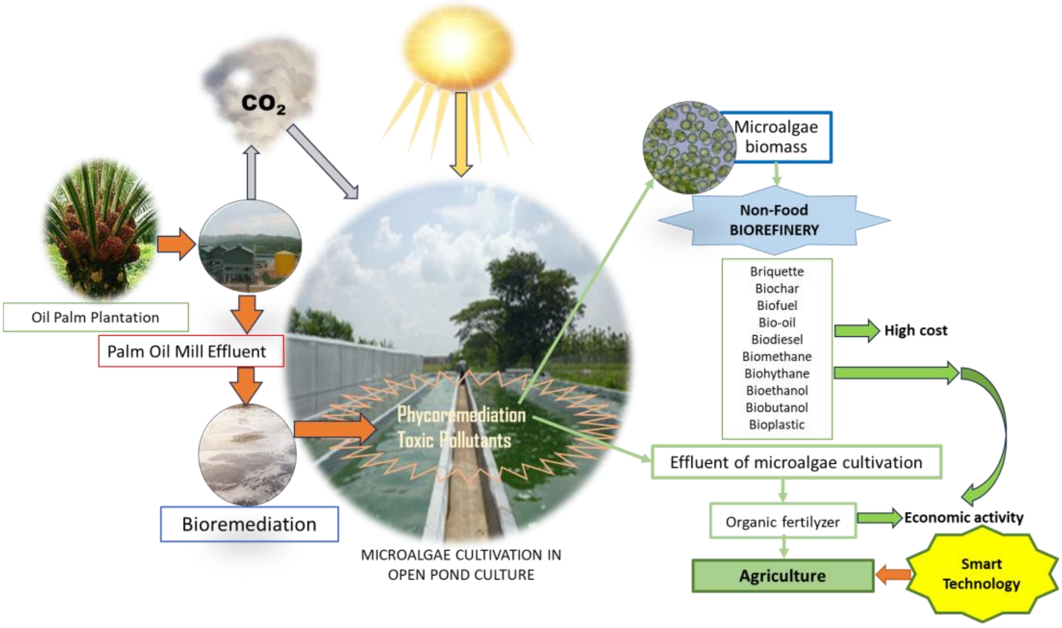
Table 7: Technological Innovations in Smart Agriculture: Advantages and Challenges [135]

Technology	Advantages	Challenges	Ref.
Drones	Provide aerial surveillance for crop monitoring, pest detection, and soilhealth assessment.	Require skilled operation, affected by weather conditions, and involve regulatory and privacy concerns.	136)
Big DataAnalytics	Enable processing and analysis of vast datasets for predictive insights,enhancing decision-making.	Require sophisticated infrastructure, expertise in data analysis, and pose data privacy concerns.	137)

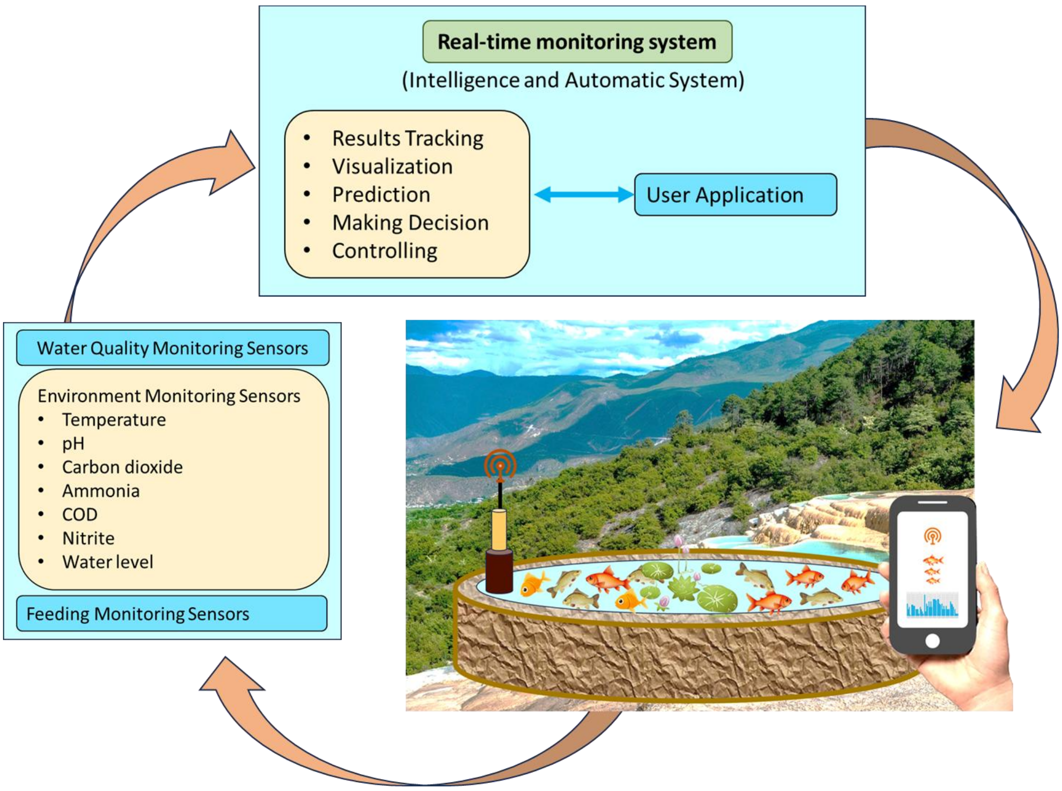
Cloud Computing	Offers scalable storage and processing power for agriculturaldata, accessible from anywhere.	Depend on reliable internet connectivityand raise concerns about data security and sovereignty.	138,139,140)
Internet of Things (IoT)	Facilitate real-time monitoring and management of farm conditions, improving efficiency.	Need continuous internet connectivity,can be costly to implement, and have security vulnerabilities.	141,142)
AI Algorithms	Automate processes, provide data- driven insights for farming operations, and enhance precision inagriculture.	Require large, quality datasets for training, potential bias in algorithms, andcan be complex to integrate.	143,144,145,146)
Machine Learning	Offers predictive capabilities foryield forecasting and disease detection, improving resource management.	Challenges in data acquisition and processing, accuracy of predictions, and understanding complex agricultural ecosystems.	147,148,149)
Renewable Energy Solutions	Provide sustainable energy sourcesfor powering agricultural technology, reducing carbon footprint.	Initial setup costs can be high, andefficiency can be dependent on environmental conditions.	150)
Precision Agriculture	Enables targeted application of resources like water and fertilizers,leading to cost savings and sustainability.	High initial investment in technology and requires training for farmers to adapt to new systems.	141,150)
Satellite Imagery	Offers large-scale monitoring of crophealth, soil conditions, and environmental changes.	Requires access to advanced satellite data and expertise in remote sensing analysis.	151)
Robotics and Automation	Enhance efficiency in tasks like planting, harvesting, and weeding,reducing manual labor.	High cost of robotics technology, maintenance requirements, and need for technical expertise.	152,153,154)
Soil and Crop Sensors	Provide precise data on soil moisture, pH levels, and crop healthfor informed decision-making.	Need for regular calibration, durability in different weather conditions, and initial cost.	155)
Natural Language Processing (NLP)	Facilitates user-friendly interfacesfor technology and enables local language support for farmers.	Complexity in developing accurate NLP models for different languages and dialects.	156,154)
GIS and Mapping Technologies	Enable detailed spatial analysis forfarm planning, resource management, and yield estimation.	Requires geospatial data expertise and integration with other farm management systems.	157, 154)
Blockchain for Supply Chain	Enhances transparency and traceability in the agricultural supplychain, ensuring product authenticity.	Complexity in implementation, scalability issues, and requirement ofindustry-wide adoption.	154)

12. Opportunity of Smart Aquaculture and Eco-farming Integration System Concept in POME Phycoremediation

The use of the circular economy by reusing palm oil waste, co-generating bioenergy, treating waste through microalgae cultivation, and then converting it into produce that has added value. Economic factors can be improved by extracting high-value biochemicals and developing biomaterial-based goods even further [132]. Concept of smart aquaculture and eco-farming integration system in POME phycoremediation illustrated in Figure 4a. Aquaculture is an essential trend aimed at minimizing labor costs, enhancing operational efficiency, and increasing production. Additionally, future IoT-driven systems might aim to detect fish diseases and prevent losses in productivity. Illustrates that the Internet of Things (IoT) is an innovative and promising technology offering novel solutions across various sectors, including smart aquaculture (Figure 4b) and smart eco-farming (Figure 4c). IoT has greatly enhanced agricultural management practices, enabling connectivity among agricultural devices and equipment to optimize decisions regarding fertilizer usage and irrigation

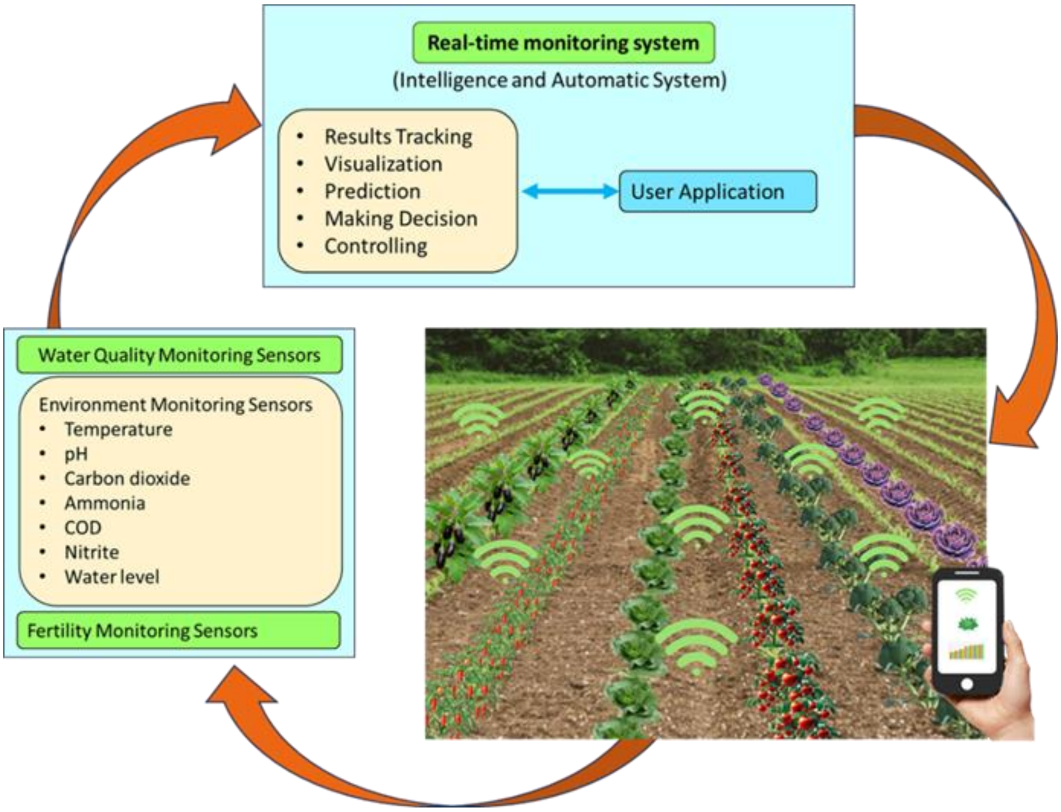


(a)



(b)

Cite: T. Handayani et al., "Opportunity of Smart Aquaculture and Eco-Farming Integration in POME Bioremediation and Phycoremediation System for Environmental Sustainability". Evergreen, 12 (02) 903-931 (2025). https://doi.org/10.5109/7363484.



(c)

Fig. 4: (a) Illustration of smart aquaculture and eco-farming integration system concept in POME phycoremediation**, (b)** Overview of smart aquaculture control and monitoring system, and **(c)** Overview of smart eco-farming control and monitoring system

12.1. Waste components from aquaculture systems

Many researchers have described the components of waste produced by aquaculture systems. The focus of this literature review will be drawn to the principal aquaculture wastes derived from feed. Aquaculture wastes can be divided into two types: solid wastes and dissolved wastes [133)].

12.2. Solid wastes

Unused feed and fecal droppings from farmed fish are the main sources of solid waste. They contain fish that do not survive the culturing procedure on occasion. Solid waste is further subdivided into suspended solids and settled solids. The suspended solids are small particles that remain suspended in water unless coagulation or sedimentation methods are used, and they are the most difficult type of solids to remove from culture systems. The settled solids are bigger particles that settle quickly and are easily removed from the culture column[82)].

Solid wastes are considered extremely hazardous since they can clog fish gills and cause mortality, particularly in the event of big settled particles. These wastes increase total suspended and total dissolved solids when left for an extended period and allowed to degrade. They may also enhance nitrogenous substances in the farmed fish and stress them. Solid waste in aquaculture contains around 30% of feed waste that is easier to remove through recirculating aquaculture systems than in flow-through systems [158)].

12.3. Dissolved wastes

Dissolved waste is the result of fish metabolism or uneaten feed. The two most important components of concern in dissolved wastes are nitrogen (N) and phosphorus (P) products. These two elements are necessary for the production of protein, which is the fundamental component of fish diet. Fish, regardless of species, require a high crude protein level in their diet, ranging from 25 to 50%. heavy-protein fish diets are heavy in nitrogen and phosphorus, and the fish retains less than half of these potential water contaminants (nitrogen and phosphorus[159)].

Nitrogen is primarily evacuated as dissolved ammonia, while phosphorus is excreted as particulates. Aquaculture has a high potential for environmental pollution since fish are unable to utilize a large amount of N and P, the key nutrients (components) of the diet. As a result, it is classified as industrial waste. These nutrients enter the body and are then eliminated as waste. When these nutrients enter the water, they can harm fish and other aquatic life81). These chemical components have the potential to serve as fertilizer in agricultural systems [84)].

Combining coagulation-flocculation and membrane techniques can reduce POME effluent pollution[160)].

12.4. Smart Eco-farming Using Waste of Aquaculture

Economic prosperity in recent times has been concentrated in the fields of information technology and farm software development[161)]. To achieve meaningful progress, particularly in a given area, the strategy should prioritize the following goals: protecting natural resources, maximizing resource efficiency, boosting productivity and profitability, and enhancing quality and competitiveness by lowering production costs. The idea behind integrated fish farming is to gradually combine two or more typically independent farming systems to create a larger farming system that primarily focuses on fish. An integrated, or triple-A, system consists of farming, aquaculture, and agriculture and is cost-effective and self-sufficient. This kind of farming provides very good resource efficiency when it comes to transferring waste or byproducts from one system to another. To maximize output, it also makes it possible to use available farming space effectivel[162)].

Result of incorporating smart eco-farming, there is a sustainable environmental system, often known as a circular economy. This technology is more cost-effective than biorefinery production because microalgae biomass is used directly, eliminating the requirement for costs associated with the biomass utilization process. Smart aquaculture and eco-farming can be employed as an alternative method in the usage of POME and microalgae that are more practical and economical to create opportunities to make sustainable production operations [161)].

In recent decades, aquaculture has emerged as the fastest-growing food production industry. The supply-demand gap for fish is constantly growing, and dwindling freshwater availability is becoming a key constraint on productivity. Investigating alternative water sources, such as treated wastewater (TWW), is becoming a popular technique for meeting agriculture's increasing water demand. People have been reusing wastewater (TWW) for agriculture and aquaculture for centuries[162)]. According to research, fish are safe for human food in terms of microbiological contamination and heavy metal and organic micropollutant bioaccumulation, with levels found to be within international human consumption guidelines. Furthermore, employing TWW as an alternate water source for aquaculture has both economic and ecological benefits[(50)]. Recirculating Aquaculture Systems (RAS) are water-efficient, eco-friendly, and highly productive intensive farming systems[163)].

The aquaculture technique is critical for eco farmers who struggle to obtain fertilizer due to high costs. It is crucial since this form of farming is organic, eco-friendly, and long-term[164)]. Aquaculture waste is put into the soil directly and will be generated in the integrated farming system (IFS) as a result of integration that is called an eco-farming system centered on attempts to protect and preserve nature by utilizing organic waste products as agricultural media[165)].

Animal and plant waste is put into the soil directly or by composting, as a substantial amount of agricultural waste will be generated in the IFS as a result of integration, and it aids in the improvement of the soil's physical, chemical, and biological health. The implementation of IFS technology on a large scale throughout India will improve and sustain small and marginal farmers' livelihoods, allowing them to double their revenue on the same plot of land while improving employment and meeting the nutritional needs of the farm family[166,167,168)].

The research study proved the usefulness of smart farming in improving and increasing agricultural productivity to help close the food demand gap. The Internet of Things (IoT) is widely regarded as the foundation of smart agriculture technology since it connects all components of smart systems, not only in agriculture but also in other applications[169)]. In agriculture, IoT can be used in a range of disciplines such as farm monitoring, irrigation[170)] pest management[171,172)], harvesting, and so on[173,174)]. Based on the literature that has been studied, it can compare social, economic, and environmental aspects of smart farming and conventional farming, the results of which are shown in Table 8.

Table 8: Comparison of Smart Farming and Conventional Farming in social, economic, and environmental aspects

Aspects	Smart Farming	Conventional Farming	Ref.
Social	The agricultural tools used are already in the form of machines. Such as tractors, planting machines, fertilizer machines, drones, irrigation machines, and harvesting machines. Machine tools are run automatically so they do not require much labour. On the downside, smart farming reduces employment because it is operated by experts.	The agricultural tools used are still very simple and are operated by many laborers, providing employment opportunities for the community.	175)
Economy	Modern equipment is costly, but efficient and increases agricultural production.	The processing and operation of the tools do not cost much, but it is inefficient, and agricultural production is low.	176, 177) 178) 179)

Cite: T. Handayani et al., "Opportunity of Smart Aquaculture and Eco-Farming Integration in POME Bioremediation and Phycoremediation System for Environmental Sustainability". Evergreen, 12 (02) 903-931 (2025). https://doi.org/10.5109/7363484.

Environment	The concept of using organic materials so as not to damage the soil and environmentally friendly agriculture that can be sustainable.	The concept of using inorganic materials that in the long run damage the soil resulting in agriculture that is not environmentally friendly and consequently unsustainable.	180,181,182)

An integrated multi-trophic aquaculture business that combined fed aquaculture with organic extractive aquaculture saw a 20% rise in shellfish production and a profit increase of more than 230%, according to the study's findings. and 68%, in comparison to separate monocultures of shellfish and finfish. Using a variety of trophic level organisms, it has been noted that these creative integrated technological practices in aquaculture are a sustainable development in the aquaculture industry because they maximize nutrient uptake, enhance water quality, and possibly generate more revenue. The primary obstacles to this sustainable system are the need for a large amount of land for farming and the difficulties in coordinating many species, both of which call for additional technical innovations that can overcome the constraints [183,184)].

POME-based bioenergy with microalgae has received a lot of attention.[55)] Smart aquaculture and eco-farming have yet to be researched. As a result, these problems are being studied to find novel methods for POME use. Smart farming is also known as smart agriculture in Indonesia. This is a farming method that makes use of technology. For example, the use of a platform linked to a tablet or smartphone device. Furthermore, smart farming makes farming activities more environmentally friendly. The idea is to make agricultural data collection easier. Easily obtain field data such as soil nutrient status, air humidity, meteorological conditions, and so on. Food security should become easier to attain as technology advances in the 4.0 era. Smart farming in developing nations enables real-time analysis and mapping of soil features, as well as proper decision management. Finally, smart farming in developing nations needs increasing support from governments, small farms, and the business sector.

13. Implementation of Smart Aquaculture and Eco-farming

The implementation discussed in this study is an example of implementation outcomes from handling trash other than POME because there is no literature on POME handling for smart agriculture. India has conducted machine learning to sort rice grains using machine learning (ML) algorithms. The simulation results show that the suggested ML method outperforms the conventional machine, developing predictive models. This technique outperforms current machine learning-based classifiers in terms of computational efficiency and accuracy while sorting rice grains. The main gain is increased productivity, but the drawback is a lack of contemporary solutions to address climate change[185,186).]

The implementation of smart farming has been done in Thailand using the Solar Water Pumping Irrigation System (SWPS) in plantation and agricultural irrigation systems to enhance food security. The use of SWPS to supply water for irrigation has shown to be successful and efficient. This technology is affordable to maintain and simple to use. In agricultural and plantation settings, where diesel pump usage is necessary due to relatively high demand, the implementation of SWPS is also significantly less expensive. Farmers profit from applying SWPS irrigation systems in several ways, including higher agricultural product productivity, increased revenue, improved product quality, and increased process efficiency[187)].

The advancements in technology have had a variety of impacts on the agricultural sector. The foundation of artificial intelligence is the idea that it can characterize human intelligence in a way that a computer can replicate it for a variety of tasks, both basic and complicated. Artificial intelligence seeks to accomplish the following: learning, thinking, and perception. The adoption of several complex models (deep learning methodology and machine learning) has transformed farming into digital farming. Farm management systems are evolving into full artificial intelligence systems through the integration of ML with sensor data. These systems provide sophisticated recommendations and insights for future decisions and actions, ultimately aimed at optimizing productivity[188,189)].

Agriculture, whether traditional or modern, has the opportunity to become an agritourism area today. The growth of agritourism, which promotes higher income, is at last able to retain young people employed in the agricultural industry. The communities' ultimate choice would protect their property and inspire youth to pursue careers in tourism and agriculture[190,191)]

Make a significant contribution to the agricultural industry by offering a hydroponics system that is sustainable and requires little or no electricity. By doing this, we can utilize this technology not only in metropolitan but also in rural places to develop an agricultural system that uses hydroponics to harness the potential of solar power for heat maintenance[192)]. Crop drying is typically done with sunshine, however with smart farming, rice drying may be done using an electrohydrodynamic drying system[193,194)]. Drying with coal fuel heating and identification of coal pulverizer anomalies using a long short-term memory (LSTM) and autoencoder (AE)[195)]. Smart farming system monitoring can make use of power monitoring for on-grid photovoltaic systems via a low-cost, open-source IoT platform[196)]. Sustainable smart farming, in addition to

having a plan for feeding animals[197]. The microalgae *Chlorella vulgaris* and *Spirulina platensis* culture consortium is a possible cathode compartment, whereas the anode compartment is filled with artificial tempe (fermented soybean cake) effluent containing indigenous bacteria capable of decomposing organic molecules[198,199].
Smart farming is a sustainable agriculture system that supports the Industry 4.0 program. Several forms of study have been conducted to map the interlinkages between Industry 4.0 and Sustainability, although disciplinary prisms frequently neglect the social dimension of sustainability. Nonetheless, the technologically driven character of Industry 4.0 technologies, along with the relatively early stage of their lifecycle, brings to the forefront several challenges that are highlighted in triple-bottom-line categorization. Economic consequences include the high cost and complexities of assessing financial benefits and economic effectiveness. Environmental consequences may include concerns such as increased e-waste, increased energy consumption, deforestation, and environmental deterioration caused by industrialization and unsustainable economic decisions[200]. Social consequences may include subtle effects on communities as a result of the intentional or unintentional use of technology). Human-robot interface challenges, unemployment risks, and privacy concerns are only a few of the social implications [201].

14. Conclusions

The conclusions that can be obtained from this literature study are several strains of microalgae species can be cultivated in POME to remove pollutants, namely *Chlamydomonas sp, Tetraselmis suecica*, *Nannochloropsis oculata*, *Chlorella pyrenoidosa*, *Chlorella* sp, *Spirulina platensis*, *Chlorella sorokiniana* and *Arthrospira platensis*. However, the success of POME wastewater treatment by microalgae depends on its cultivation technique, selection of suitable species and environmental conditions that promote growth.
Generally, research on microalgae cultivation in POME is still at the laboratory scale level. So there is still no one who has carried out a sustainability analysis through LCA. More research is needed to use an appropriate, sustainable, and cost-effective cultivation system to transform microalgae biomass into value-added products.
The majority of studies on the environmental impact of biorefinery derived from microalgae cultivated in wastewater which is widely published have focused on bioenergy. However, bioenergy-based biorefineries are difficult to sustain due to high production costs.
Based on the data and information gathered regarding the large amounts of POME in Indonesia and other countries, the adoption of large-scale smart aquaculture and eco-farming is particularly helpful, as monitoring can be done promptly and efficiently. The implementation of new model smart farming systems in developing nations requires greater support from the government at the low farm level and the business sector.

15. Recommendation

Microalgae-based POME processing research is still in its early stages. As a result, combining a microalgal system with traditional POME treatment appears to be both promising and practicable. Given its potential for bioenergy production, incorporating microalgal culture into existing POME treatment systems has become much more viable. To optimize the socioeconomic advantage of microalgae-based biorefinery development, places with a high socioeconomic effect multiplier should be selected, taking into account regional climate, marginal land, and socioeconomic characteristics. Microalgal biomass is one of the most efficient and environmentally friendly alternative energy sources, as well as a promising and sustainable source of biofuel capable of reducing atmospheric greenhouse gas emissions, microalgal biomass is a highly efficient and ecologically friendly alternative bioavailable source. The use of a biorefinery technique that recovers many products from a single operating process allows for the development of microalgal biomass-based technologies. According to the biorefinery complexity index, converting microalgal biomass into fuels, food, nutritional and feed supplements, fertilizers, and pharmaceuticals is one of the most promising approaches for attaining this aim.
Smart farming is a sustainable agricultural system that complements the Industry 4.0 initiative. Several types of research have been performed to map the interconnections between Industry 4.0 and Sustainability. However, disciplinary prisms usually overlook the social dimension of sustainability. Nonetheless, the technologically driven nature of Industry 4.0 technologies, together with their relatively early stage of development, brings to the forefront certain issues identified in triple-bottom-line categorization. Economic repercussions include the high expense and complexity of determining financial benefits and economic effectiveness. Environmental consequences may include concerns such as increasing e-waste, higher energy consumption, deforestation, and environmental degradation induced by industrialization and unsustainable economic decisions.

Acknowledgment

The authors would like to thank Head of the Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency Indonesia for granting permission for the research.
Conflicts of Interest
The authors declare no conflict of interest.

Nomenclature

AE	Autoencoder
BOD	Biological Oxygen Demand
C	Carbon
^{o}C	Celsius degree
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CPO	Crude Palm Oil
FFB	Fresh Fruit Bunches
g/L	gram per liter
HPBR	Hybrid Photobioreactor
HRAPs	High-Rate Algal Ponds
ILUC	Indirect Land Use Change
IFS	Integrated Farming System
IoT	Internet of Things
K lux	K = First Initial of Mr. Keshra Bhudia Lux = Nickname of Mrs. Laxmi Bhudia
L	Liter
LSTM	Long Short-Term Memory
L/D cycle	liter per day
LCA	Life Cycle Assessment
mg/L	milligram per liter
ml	milliliter
mol	a common scientific unit for measuring huge numbers of very small substances, such as atoms, molecules, or other specific particles.
MJ	megajoule
N	Nitrogen
$NaHCO_3$	Natrium bicarbonate
O	Oxygen
P	Phosphate
PHB	Photobioreactor
POME	Palm Oil Mill Effluent
ppm	Part per million
PUFA	Polyunsaturated Fatty Acid
RAS	Recirculating Aquaculture Systems
SFA	Sales Force Automation
SWPS	Solar Water Pumping Irrigation System
TEA	Techno-economic Analysis
TN	Total Nitrogen
TP	Total Phosphate
TWW	Treated Wastewater
Coelastrella sp. UKM4	The name of *Coelastrella* sp. strain
W	Watt

References

1) J. D. Sheehan, J. Jiang, J., and P. E. Savage, "Algae and environmental sustainability," Johnson Matthey Technology Review, (2017). https://doi.org/10.1595/205651317X695109
2) E. Abatenh, B. Gizaw, Z. Tsegaye, and M. Wassie, "The role of microorganisms in bioremediation-A review," Open Journal of Environmental Biology, 2(1) 030-046 (2017). https://www.peertechz.com/
3) T. Handayani, A. Mulyanto, F. E. Priyanto, and R. Nugroho, "Utilization of Dairy Industry Wastewater for Nutrition of Microalgae *Chlorella vulgaris*," URICSE, Journal of Physics: Conference Series 1655 (2020) 012123. IOP Publishing (2020) https://doi.org/10.1088/1742-6596/1655/1/01212.
4) P. Chawla, A. Malik, T. R. Sreekrishnan, V. Dalvi, and D. Gola, "Selection of optimum combination via comprehensive comparison of multiple algal cultures for treatment of diverse wastewaters," Environmental Technology and Innovation, 18, 100758, (2020) https://doi.org/10.1016/j.eti.2020.100758
5) Directorate General of Plantation, "Statistik Perkebunan Indonesia," (2018). https://repository.pertanian.go.id/handle/123456789/18665
6) E. M. A Haroun, T. Khalid, A. M. Altawil, G. A. M. Osman, and E. E. Diab, "Potentiality of municipal sludge for biological gas production at Soba Station South of Khartoum (Sudan)," World Journal of Biology and Biotechnology. 5(2), 1-11, (2020). https://doi.org/10.33865/wjb.005.02.0300
7) F. Xia, Q. Yao, J. Zhang, and D. Wang, "Effects of seasonal variation and resuspension on microplastics in river sediments," Environmental Pollution 286, 117403 (2021). https://doi.org/10.1016/j.envpol.2021.117403
8) J. Reichert, V. Tirpitz, R. Anand, K. Bach, J. Knopp, P. Schubert, T. Wilke, and M. Ziegler, "Interactive effects of microplastic pollution and heat stress on reef-building corals, " Environmental Pollution, 290, 118010, (2021). https://doi.org/10.1016/j.envpol.2021.118010
9) M.A. Serunting, O.F.T. Maryana, E. Syafitri, S. Balqis, and E. Windiastuti, "Green synthesis silver nanoparticles (agents) using lamtoro pods extract (*Leucaena leucocephala*) and their potential for mercury ion detection," Evergreen, 8 (1) 63–68 (2021). https://doi.org/10.5109/4372261.
10) N.Z.K. Shaari, L.H. Rozlee, and M.F. Basri, "Synthesis and evaluation of polysulfone/chitosan/ polyvinyl alcohol integral composite membranes for the removal of mercury ion," Evergreen, 8 (2) 484491 (2021). https://doi.org/10.5109/ 4480733.
11) S. Sinnaraprasat, and P. Fongsatitkul, "Optimal condition of Fenton's reagent to enhance the alcohol production from palm oil mill effluent (POME)," Environment Asia, 4(2), (2021). http://dx.doi.org/10.14456/ea.2011.12
12) M. Mellyanawaty, F. M. A. Chusna, H. Sudibyo, N. Nurjanah, and W. Budhijanto, "Influence of Nutrient Impregnated into Zeolite Addition on Anaerobic Digestion of Palm Oil Mill Effluent (POME)," IOP Conference Series: Materials Science and Engineering, 316 (1), (2018). https://doi.org/10.1088/1757-899X/316/1/012069.
13) N. A. Sasongko, and R. A. T. Noguchi," Introduction

of Integrated Energy Plantation Model for Microalgae-Using Palm Oil Mill Effluent (POME)," Journal of the Japan Institute of Energy, 94, 561–570, (2014). http://dx.doi.org/10.3775/jie.94.561

14) R. Saeed, and F. X. Malcata, "Is genetic engineering a route to enhance microalgae-mediated bioremediation of heavy metal-containing effluents?," Molecules 27(5), 1473, (2022). https://doi.org/10.3390/molecules27051473

15) M. Nanda, K. K. Jaiswal, V. Kumar, M. Verma, M. S. Vlaskin, P. Gururani, H. Kim, M. F. Alajmi, and A. Hussain, "Bio-remediation capacity for Cd(II) and Pb(II) from the aqueous medium by two novel strains of microalgae and their effect on lipidomics and metabolomics," Journal of Water Process Engineering, 44, 102404, (2021). https://doi.org/10.1016/j.jwpe.2021.102404

16) J. A. Bryant, T. M. Clemente, D. A. Viviani, A.A. Fong, K. A. Thomas, P. Kemp, D. M. Karl, A. E. White, and E. F. De Long, " Diversity and activity of communities inhabiting plastic debris in the North Pacific Gyre," mSystems 1, e00024-16, (2016). https://doi.org/10.1128/msystems.00024-16

17) S. R. Subashchandrabose, B. Ramakrishnan, M. Megharaj, K. Venkateswarlu, and R. Naidu, "Consortia of cyanobacteria/microalgae and bacteria: biotechnological potential," Biotechnology advances 29(6), 896-907 (2011). https://doi.org/10.1016/j.biotechadv.2011.07.009.

18) L. Aditya, T.M. Indra Mahlia, L. N. Nguyen, H. P. Vu, and L. D. Nghiem, "Microalgae-bacteria consortium for wastewater treatment and biomass production," Science of The Total Environment, 838(1), 155871, (2022), https://doi.org/10.1016/j.scitotenv.2022.155871

19) J. H. Purba, L. D. Amalia, F. S. Othman, A. Yuzir, S. E. Mohamad, K. Iwamoto, N. Abdullah, K. Shimizu, and J. Hermana, "Enhanced cultivation and lipid production of isolated microalgae strains using municipal wastewater." Environmental Technology & Innovation 27,102444(2022). https://doi.org/10.1016/j.eti.2022.102444.

20) J. C. Lee, J. H. Joo, B. H. Chun, K. Moon, S. H. Song, Y. J. Kim, S. M. Lee, and A. H. Lee, "Isolation and screening of indigenous microalgae species for domestic and livestock wastewater treatment, biodiesel production, and carbon sequestration," Journal of Environmental Management, 318, 115648, (2022). . https://doi.org/10.1016/j.jenvman.2022.115648

21) A. I. Aigbodion, O. N. Ogbebor, E. U. Ikhuoria, S. O. Omorogbe, M. Maliki, "Microbial population of palm oil mill effluent (POME) and efficiency of selected isolates in biogas production," Journal of Plantation Crops. (2014). https://doi.org/10.1128/msystems.00024-16

22) M. K. Ji, R. A. I. Abou-Shanab, S. H. Kim, E. S. Salama, S. H. Lee, A. N. Kabra, Y. S. Lee, S. Hong, B. H. Jeon, "Cultivation of microalgae species in tertiary municipal wastewater supplemented with CO_2 for nutrient removal and biomass production," Ecological Engineering 58,142-148 (2013). https://doi.org/10.1016/j.ecoleng.2013.06.020

23) A. Vadiveloo, L. Foster, C. Kwambai, P. A. Bahri, and N. R. Moheimani, "Microalgae cultivation for the treatment of anaerobically digested municipal centrate (ADMC) and anaerobically digested abattoir effluent (ADAE)," Science of The Total Environment, 775, 145853, (2021), https://doi.org/10.1016/j.scitotenv.2021.145853

24) D. H. Cho, R. Ramanan, J. Heoc, Z. Kang, B. H. Kim, C. Y. Ahn, H. M. Oh, H. S. Kim, "Organic carbon, influent microbial diversity, and temperature strongly influence algal diversity and biomass in raceway ponds treating raw municipal wastewater." Bioresource Technology, 191,481-487(2015). https://doi.org/10.1016/j.biortech.2015.02.013.

25) M. A. Ibrahim, A. Al-Thukair, A. R. Shaikh, W. Farooq, and I. Ahmad, "Isolation of indigenous microalgae: nitrogen/phosphorous removal and biofuel production," Biofuels, 11(3), 269-276 (2020). https://doi.org/10.1080/17597269.2017.1358947

26) R. Kothari, R. Prasad, V. Kumar, D. P. Singh, "Production of biodiesel from microalgae Chlamydomonas polypyrenoideum grown on dairy industry wastewater," Bioresource Technology 144, 499-503(2013). https://doi.org/10.1016/j.biortech.2013.06.116

27) N. Talapatra, R. Gautam, V. Mittal, and U.K. Ghosh, "A comparative study of the growth of microalgae-bacteria symbiotic consortium with the axenic culture of microalgae in dairy wastewater through extraction and quantification of chlorophyll," Materials Today: Proc. 80(3), 2268-2273 (2023). https://doi.org/10.1016/j.matpr.2021.06.227

28) R. V. Kapoore, T. O. Butler, J. Pandhal, and S. Vaidyanathan, "Microwave-assisted extraction for microalgae: From biofuels to biorefinery." Biology 7(1),1-18 (2018). https://doi.org/10.3390/biology7010018.

29) B. Malakar, D. Das, and K. Mohanty, "Utilization of Chlorella biomass grown in waste peels-based substrate for simultaneous production of biofuel and value-added products under microalgal biorefnery approach," Waste and Biomass Valorization 14, 3589–3601, (2023). https://doi.org/10.1007/s12649-023-02058-y

30) J. S. Yang, E. Rasa, P. Tantayotai, K. M. Scow, H. I. Yuan, and K. R. Hristova, " Mathematical model of Chlorella minutissima UTEX2341 growth and lipid

production under photoheterotrophic fermentation conditions," Bioresource Technology (2011). https://doi.org/10.1016/j.biortech.2010.10.049.

31) M. D. Bresaola, A. I. Morocho-Jácome, M. C. Matsudo, and J. C. M. de Carvalho," Semi-continuous process as a promising technique in Ankistrodesmus braunii cultivation in photobioreactor," Journal of Applied Phycology. (2019). https://doi.org/10.1007/s10811-019-01774-0.
32) C. Nurhayati, H. Basuni, and R. P.,"Optimasi Pengolahan Limbah Cair Karet Remah Menggunakan Mikroalga Indigen dalam Menurunkan Kadar BOD, COD, TSS.," Jurnal Dinamika Penelitian Industri., 24(1), 16–26 (2013). https://doi.org/10.28959/jdpi.v24i1.652
33) T. Biswas, S. Bhushan, S. K. Prajapati, and S. R. Chaudhuri, "An eco-friendly strategy for dairy wastewater remediation with high lipid microalgae-bacterial biomass production," Journal of Environmental Management, 286, 112196 (2021). https://doi.org/10.1016/j.jenvman.2021.112196
34) C. C. A. Loures, G. R. L. Samanamud, A. P. B. R. de Freitas, I. S. Oliveira, L. V. de Freitas, and C. R. de Oliveira Almeida, "The use of advanced oxidation processes (AOPs) in dairy effluent treatment," American Journal of Theoretical and Applied Statistics, 3(6-1),42-46, (2015). https://doi.org/10.11648/j.ajtas.s.2014030601.15
35) G. González, L. Maria, and L. E. De-Bashan. "Toward the enhancement of microalgal metabolite production through microalgae–bacteria consortia," Biology, 10(4), 282, (2021). https://doi.org/10.3390/biology10040282
36) M. S. Islam, I. Maamoun, O. Falyouna, O. Eljamal, and B.B. Saha, "Arsenic removal from contaminated water utilizing novel green composite chlorella vulgaris and nano zero-valent iron," Journal of Molecular Liquids, 370, 121005 (2023). https://doi.org/10.1016/ j.molliq.2022.121005.
37) R. A. Efroymson, H. Jager, S. Mandal, E. S. Parish, and T. Mathews, "Better management practices for environmentally sustainable production of microalgae and algal biofuels," Journal of cleaner production, 289, 125150 (2021). https://doi.org/10.1016/j.jclepro.2020.125150.
38) Y. Li, Z. Qiu, H. Cui, L. Wang, and L. Zhang, "Simultaneous promotion of microalgal CO_2 assimilation, biomass accumulation, lipid production, and wastewater nutrient removal by adding 5-aminolevulinic acid". ACS Sustainable Chem. Eng. 10(45), 14715–14723 (2022). https://doi.org/10.1021/acssuschemeng.2c03089
39) D. F. Correa, H. L. Beyer, H. P. Possingham, J. E. Fargione, J. D. Hill, and P. M. Schenk, "Microalgal biofuel production at national scales: Reducing conflicts with agricultural lands and biodiversity within countrie,." Energy, 215 (2021): 119033. https://doi.org/10.1016/j.energy.2020.119033
40) C. Onumaegbu, J. Mooney, A. Alaswad, and A.G. Olabi, "Pre-treatment methods for production of biofuel from microalgae biomass," Renewable and Sustainable Energy Reviews, 93, 16-26 (2018). https://doi.org/10.1016/j.rser.2018.04.015.
41) S. S. Low, K. X. Bong, M. Mubashir, C. K. Cheng, M. K. Lam, J. W. Lim, Y. C. Ho, K. T. Lee, H. S. H. Munawaroh, and P. L. Show. "Microalgae cultivation in palm oil mill effluent (POME) treatment and biofuel production." Sustainability, 13(6),3247. (2021). https://doi.org/10.3390/su13063247
42) W. Y. Cheah, P. L. Show, J. C. Juan, J. S. Chang, and T. C. Ling, "Microalgae cultivation in palm oil mill effluent (POME) for lipid production and pollutant removal," Energy Conversion and Management. 174(2018), 430-438. https://doi.org/10.1016/j.enconman.2018.08.057
43) J. Asomaning, P. Mussone, D. C. Bressler, "Two-stage thermal conversion of inedible lipid feedstocks to renewable chemicals and fuels." Bioresource Technology, 158,55-62 (2014). https://doi.org/10.1016/j.biortech.2014.01.136
44) M. Tale, S. Ghosh, B. Kapadnis, and S. Kale, "Isolation and characterization of microalgae for biodiesel production from Nisargruna biogas plant effluent," Bioresource Technology. 169(2014), 328-335. https://doi.org/10.1016/j.biortech.2014.06.017
45) P. Bhuyar, S. Sundararaju, M. H. A. Rahim, R. Ramaraj, G. P. G. N. Maniam, "Microalgae cultivation using palm oil mill effluent as a growth medium for lipid production with the effect of CO_2 supply and light intensity. Biomass Convers. Biorefinery (2019). https://doi.org/10.1007/s13399-019-00548-5
46) M. N. Metsoviti, G. Papapolymerou, and I. T. K. N. Karapanagiotidis, "Effect of light intensity and quality on growth rate and composition of *Chlorella vulgaris*," Plants, 9, 31 (2020). http://dx.doi.org/10.3390/plants9010031
47) M. Li, M. Zhou, C. Tan, and Tian, X.," Enhancement of CO2 bio fixation and bioenergy generation using a novel airlift type photosynthetic microbial fuel cell," Bioresource Technology. (2019). https://doi.org/10.1016/j.biortech.2018.10.078.
48) S. Kim, M. Moon, M. Kwak, and B. C. Y. Lee, "Statistical optimization of light intensity, and concentration for lipid production derived from attached cultivation of green microalga *Ettlia* sp," Sci. Rep., 8, 15390. (2018). https://www.nature.com/articles/s41598-018-33793-1
49) D. Kang, K. T. Kim, T. Y. Heo, G. Kwon, and C. P.

Lim, ”Inhibition of photosynthetic activity in wastewater-borne microalgal–bacterial consortia under various light conditions,” Sustainability, 11, 2951 (2019). https://doi.org/10.3390/su11102951
50) T. Perumal, M. N. Sulaiman, and C. Y. Leong,” Internet of Things (IoT) enabled water monitoring system. 2015 IEEE 4th Global Conference on Consumer Electronics, GCCE 2015,” (2016). https://doi.org/10.1109/GCCE.2015.7398710.
51) B. Ganapathy, A. Yahya, and N. Ibrahim, ”Bioremediation of Palm Oil mill Effluent (POME) using indigenous Meyerozyma guilliermondii,” Environmental Science and Pollution Research 26:11113-11125 (2019). https://link.springer.com/article/10.1007/s11356-019-04334-8
52) A. Akhbari, P. K. Kutty, O. C. Chuen, S. Ibrahim, "A study of palm oil mill processing and environmental assessment of palm oil mill effluent treatment." Environmental Engineering Research 25(2),212-221(2020). https://doi.org/10.4491/eer.2018.452
53) U. Hasanudin, R. Sugiharto, A. Haryanto, T. Setiadi, and Fujie, “Palm oil mill effluent treatment and utilization to ensure the sustainability of palm oil industries,” Water Sci Technol 72(7), 1089–1095 (2015). https://doi.org/10.2166/wst.2015.311
54) C. Vincent, Wokem, and I. A. Yamisigh,” Bioremediation of Palm Oil Mill Effluent (POME) contaminated soil using cow dung,” Greener Journal of Microbiology and Antimicrobials 6(1),1-7 (2021). https://gjournals.org/GJMA.
55) A. Z. Athoillah, and F. B. Ahmad, ”Biodiesel production from bioremediation of Palm Oil Mill Effluent via Oleaginous fungi,” Clean Soil Air Water. (2022). https://doi.org/10.1002/clen.202200025.
56) I. B. A. Razak, N. H. Bohari, E. M. M. Fishal, N. I. Mohamad, M. N. Azmi, and M. F. F. M. Razali, H. Ibrahim, “Aerobic degradation process in Palm Oil Mill issues, challenges and upsurging its efficiency through bioremediation,” Journal of Water Resource and Protection 14(7) (2022). https://doi.org/10.4236/jwarp.2022.147027
57) M. S. Takriff, M. Z. Zakaria, and M. S. T. Y. H. Sajab,” Pre-treatments anaerobic Palm Oil Mill Effluent (POME) for microalgae treatment,” Indian J. Sci. Technol, 9, 1–8 (2016). https://doi.org/10.1088/1757-899X/1051/1/012062
58) G. Markou, and I. G. D. Chatzipavlidis,” Cultivation of *Arthrospira (Spirulina) platensis* in olive-oil mill wastewater treated with sodium hypochlorite,” Bioresour. Technol., 112, 234–241 (2012). https://doi.org/10.1016/j.biortech.2012.02.098
59) M. Saha, and C. M. J. Eskicioglu,” Microwave, ultrasonic and chemo-mechanical pretreatments for enhancing methane potential of pulp mill wastewater treatment sludge,” Bioresour. Technol., 102, 7815–7826 (2011). https://doi.org/10.1016/j.biortech.2011.06.053
60) S. M. U. Shah, A. Ahmad, M. F. Othman, M. A. Abdullah,” Effects of palm oil mill effluent media on cell growth and lipid content of *Nannochloropsis oculata* and *Tetraselmis suecica*,” International Journal of Green Energy, 13(2) (2016). https://doi.org/10.1080/15435075.2014.938340.
61) E. V. Putri, M. F. M. Din, and Z. J. Ahmed, “Investigation of microalgae for high lipid content using palm oil mill effluent (POME) as carbon source,” International Conference on Environment and Industrial Innovation, IPCluddin H, Chelliapan S. 2011. BEE.(2011). https://eprints.utm.my/45965/
62) T. Handayani, I. N. Djarot, N. Widyastuti, F. D. Arianti, A. Rifai, et al. “Biogas quality and nutrient remediation in palm oil mill effluent through *Chlorella vulgaris* cultivation using a photobioreactor,” Global J. Environ. Sci. Manage. (GJESM) 10(4): 1-24 (2024), https://doi.org/10.22034/gjesm.2024.04.03
63) M. A. Nur, and G. Dwi Hartanto, “ Enhancement of Biomass Production from *Spirulina* sp Cultivated in POME Medium,” Proceeding of International Conference on Chemical and Material Engineering 2012. https://eprints.undip.ac.id/36886/
64) F. Yuli Anggita Sari, and M. A. I. Suryajaya, “Kultivasi mikroalga *Spirulina platensis* dalam media POME dengan variasi konsentrasi POME dan komposisi jumlah nutrien. Jurnal Teknologi Kimia Dan Industri, 1(1), (2012). https://ejournal3.undip.ac.id/index.php/jtki/article/view/1102/1125
65) J. O. Jimoh, S. Rahmah, S. Mazelan, M. Jalilah, J. B. Olasunkanmi, L. S. Lim, M. A. Ghaffar, Y. M. Chang, K. Bhubalan, and H. J. Liew, “Impact of face mask microplastics pollution on the aquatic environment and aquaculture organisms,” Environmental Pollution, 317, 120769, (2023), https://doi.org/10.1016/j.envpol.2022.120769
66) P. Sukumaran, R. Nulit, S. Zulkifly, N. Halimoon, and H. I. A. Omar, ”Potential of fresh POME as a growth medium in mass production of *Arthrospira platensis*,” Int J Curr Microbiol AppSci, 3, 235–250, (2014). https://www.researchgate.net/deref/
67) H. Kamyab, M. F. Din, C. T. Lee, A. Keyvanfar, and A. M. M. Shafaghat,”Lipid production by microalgae Chlorella pyrenoidosa cultivated in palm oil effluent (POME) using hybrid photobioreactor (HPBR),”Desalination and Water Treatment, 1, 1–13, (2014). https://doi.org/10.1080/19443994.2014.957943
68) H. Kamyab, S. Chelliapan, M. F. Md Din, C. T. Lee, S. Rezania, T. Khademi, and C. P. C. Bong,”Isolate

new microalgal strain for biodiesel production and using FTIR spectroscopy for assessment of pollutant removal from Palm Oil Mill Effluent (POME)," Chemical Engineering Transactions, 63, (2018). https://doi.org/10.3303/CET1863016.

69) A. D. Ahmad, and J. T. D. G Salihon," Evaluation of CO_2 Seques-tration by microalgae culture in Palm Oil Mill Effluent (POME) medium Advanced materials research," Trans Tech, 1113, 311–316, (2015). https://doi.org/10.4028/www.scientific.net/AMR.1113.311

70) S. Rezania, and M. Alqadi, "Cultivation of Chlamydomonas incerta in Palm Oil Mill Effluent : Effect of Photoperiod and Carbon Dioxide Concentration in the Growth and Bioma," The 5th International Conference on Environmental Engineering 2017At: Surabaya, Indonesia. https://www.researchgate.net/publication/327664354

71) G. T. Ding, Z. Yaakob, M. S. Takriff, J. Salihon, and M. S. Abd Rahaman," Biomass production and nutrients removal by a newly-isolated microalgal strain *Chlamydomonas* sp in palm oil mill effluent (POME). International Journal of Hydrogen Energy, 41(8), (2016). https://doi.org/10.1016/j.ijhydene.2015.12.010.

72) M. M. R. Shah, "Astaxanthin Production by Microalgae *Haematococcus pluvialis* Through Wastewater Treatment: Waste to Resource," Book of Application of Microalgae in Wastewater Treatment, 17-39, (2019). https://doi.org/10.1007/978-3-030-13909-4_2.

73) C. S. Vairappan, and A. M. Yen, "Palm oil mill effluent (POME) cultured marine microalgae as supplementary diet for rotifer culture," Journal of Applied Phycology, 20(5), (2008). https://doi.org/10.1007/s10811-007-9305-1

74) S. Shah, A. Ahmad, M. Othman, and M. Abdullah,"Enhancement of lipid content in *Isochrysis galbana* and *Pavlova lutheri* using palm oil mill effluent as an alternative medium," Chem. Eng. Trans., 37, 733–738 (2016). https://doi.org/10.3303/CET1437123

75) M. A. B. Habib, F. M. Yusoff, S. M. Phang, and S. Mohamed, " Growth and nutritional values of Moina micrura fed on *Chlorella vulgaris* grown in digested Palm Oil Mill Effluent," Asian Fisheries Science, 16(2), 107–119, (2003). https://doi.org/10.33997/j.afs.2003.16.2.002.

76) S.R. Ardiansyah, A.M. Orlando, A. Rahman, and N.B. Prihantini, "Tubular photobioreactor: a preliminary experiment using Synechococcus sp. (Cyanobacteria) cultivated in NPK media for biomass production as a biofuel feedstock," Evergreen, 6 (2), 157–161, (2019). https://doi.org/10.5109/2321011

77) H.I. Muhammad, A. Rahman, N.B. Prihantini, and N. Deendarlianto, "The application of poly-dispersed flow on rectangular airlift photobioreactor mixing performance," Evergreen, 7(4), 571–579, (2020). http://dx.doi.org/10.5109/4150508

78) E. Gnansounou, A. Dauriat, J. Villegas, and L. Panichelli," Life cycle assessment of biofuels: Energy and greenhouse gas balances. In Bioresource Technology, 100(21), (2009). https://doi.org/10.1016/j.biortech.2009.05.067.

79) D. Chittora, M. Meena, T. Barupal, P. Swapnil, and K. Sharma, "Cyanobacteria as a source of biofertilizers for sustainable agriculture," Biochemistry and Biophysics Reports, 22 (January) 100737 (2020). https://doi.org/10.1016/j.bbrep.2020.100737.

80) B. B. Marangon, M. L. Calijuri, J. de S. Castro, and P. P. Assemany, "A life cycle assessment of energy recovery using briquette from wastewater grown microalgae biomass," J. Environ. Manage., 285, (2021). https://doi.org/10.1016/j.jenvman.2021.112171.

81) R. Morya, T. Raj, Y. Lee, A. K. Pandey, D. Kumar, R. R. Singhania, S. Singh, J. P. Verma, S. H. Kim, "Recent updates in biohydrogen production strategies and life–cycle assessment for sustainable future," Bioresource Technology, 366, 128159, (2022). https://doi.org/10.1016/j.biortech.2022.128159

82) G. Li, Z. Lu, J. Zhang, H. Li, Y. Zhou, A. M. I. Zayan, Z. Huang, "Life cycle assessment of biofuel production from microalgae cultivated in anaerobic digested wastewater," Int. J. Agric. Biol. Eng., 13(1), (2020). https://doi.org/10.25165/j.ijabe.20201301.4178.

83) S. Grierson, V. Strezov, J. Bengtsson," Life cycle assessment of a microalgae biomass cultivation, bio-oil extraction, and pyrolysis processing regime," Algal Research 2(3), 299-311, (2013).. https://doi.org/10.1016/j.algal.2013.04.004.

84) G. Saranya, T. V. Ramachandra, "Life cycle assessment of biodiesel from estuarine microalgae," Energy Convers. Manag. X 8, 100065, (2020). https://doi.org/10.1016/j.ecmx.2020.100065.

85) P. Collet, A. H. Arnaud, L. Lardon, M. Ras, R. A., Goy, J. P. Steyer, " (2015). Life-cycle assessment of microalgae culture coupled to biogas production. Bioresour. Technol., 102(1), 207-214, (2015). https://doi.org/10.1016/j.biortech.2010.06.154.

86) C. Sun, A. Xia, Q. Liao, Q. Fu, Y. Huang, X. Zhu, " (2019). Life-cycle assessment of biohythane production via two-stage anaerobic fermentation from microalgae and food waste," Renew. Sustain. Energy Rev. 112, 395-410, (2019).

https://doi.org/10.1016/j.rser.2019.05.061.

87) N. Hossain, J. Zaini, and T. M. Indra Mahlia, "Life cycle assessment, energy balance and sensitivity analysis of bioethanol production from microalgae in a tropical country," Renew. Sustain. Energy Rev., 115, 109371, (2019). https://doi.org/10.1016/j.rser.2019.109371.

88) A. Nilsson, K. Shabestary, M. Brandão, and E. P. Hudson, "Environmental impacts and limitations of third-generation biobutanol: Life cycle assessment of n-butanol produced by genetically engineered cyanobacteria," J. Ind. Ecol., 24(1), (2020). https://doi.org/10.1111/jiec.12843.

89) M. Bussa, A. Eisen, C. Zollfrank, and H. Röder, "Life cycle assessment of microalgae products: State of the art and their potential for the production of polylactid acid," Journal of Cleaner Production, vol. 213. 2019, doi: 10.1016/j.jclepro.2018.12.048.

90) M. A. Delucchi," Impacts of biofuels on climate change, water use, and land use," Annals of the New York Academy of Sciences 1195, (2010). https://doi.org/10.1111/j.1749-6632.2010.05457.x.

91) M. Havukainen, S. Väisänen, V. Uusitalo, M. Luoranen, J. Havukainen, and R. Soukka, "Recognizing socioeconomic risks and benefits related to biofuel production in developing countries: Framework for analysis. WIT," Transactions on Ecology and the Environment, 173, (2013). https://doi.org/10.2495/SDP130411.

92) T. Y. Wu, A. W. Mohammad, J. M. Jahim, and N. Anuar, "A holistic approach to managing palm oil mill effluent (POME): Biotechnological advances in the sustainable reuse of POME." Biotechnology Advances, 27(1),40-52,(2009). https://doi.org/10.1016/j.biotechadv.2008.08.005

93) N. N. A. Hamid, and J. S. Lim, "Techno-economic assessment of an Integrated Algae-based biorefinery with Palm Oil Mill," Chemical Engineering Transactions, 63, 169-174, (2018). https://doi.org/10.3303/CET1863029

94) W. Ali, H. Ali, S. Souissi, and P. Zinck, "Are bioplastics an ecofriendly alternative to fossil fuel plastics?." Environmental Chemistry Letters, 21(4), 1991-2002, (2023). https://doi.org/10.1007/s10311-023-01601-6.

95) M.Ghasemlou, F. Daver, B. J. Murdoch, A. S. Ball, E. P. Ivanova, and B. Adhikar, "Biodegradation of novel bioplastics made of starch, polyhydroxyurethanes and cellulose nanocrystals in soil environment," Science of The Total Environment, 815, 152684, (2022). https://doi.org/10.1016/j.scitotenv.2021.152684

96) R. León-Bañares, D. González-Ballester, A. Galván, E. Fernández, "Transgenic microalgae as green cell-factories." Trends in Biotechnology, 22(1),45-52, (2004). https://doi.org/10.1016/j.tibtech.2003.11.003

97) S. Leu, and S. Boussiba, "Advances in the production of high-value products by microalgae," Industrial Biotechnology, 10(3),169-183, (2014). https://doi.org/10.1089/ind.2013.0039

98) S. R. Ardiansyah, A. M. Orlando, A. Rahman, N. B. Prihantini, and Nasruddin, "Effect of aeration in simple photobioreactor system for biomass production of *Synechococcus* sp. (Cyanobacteria) HS-7 and HS-9 as Biofuel Feedstock," E3S Web of Conferences 67, 1-6, (2018). https://doi.org/10.1051/e3sconf/20186702006

99) D. de Freitas Coêlho, L. L. Tundisi, K. S. Cerqueira, J. R. da Silva Rodrigues, P. G. Mazzola, E. B. Tambourgi, and R. R. de Souza, "Microalgae: Cultivation aspects and bioactive compounds," Brazilian Archives of Biology and Technology, 62, (2019). https://doi.org/10.1590/1678-4324-2019180343.

100) M. Benedetti, V. Vecchi, S. Barera, and L. Dall'Osto," Biomass from microalgae: The potential of domestication towards sustainable biofactories," Microbial Cell Factories, 17(1),(2018). https://doi.org/10.1186/s12934-018-1019-3

101) M. A. Abduli, A. Naghib, M. Yonesi, and A. Akbari," (2011). Life cycle assessment (LCA) of solid waste management strategies in Tehran: Landfill and composting plus landfill. Environmental Monitoring and Assessment, 178, (1–4), (2011). https://doi.org/10.1007/s10661-010-1707-x.

102) M. I. Silva, A. L. Gonçalves, V. J. P. Vilar, J. C. M. Pires," Article experimental and techno-economic study on the use of microalgae for paper industry effluents remediation," Sustainability (Switzerland), 13(3), 1–29 (2021). https://doi.org/10.3390/su13031314.

103) E. M. Tejada Carbajal, E. Martínez Hernández, L. Fernández Linares, E. Novelo Maldonado, and R. Limas Ballesteros,"Techno-economic analysis of Scenedesmus dimorphus microalgae biorefinery scenarios for biodiesel production and glycerol valorization," Bioresource Technology Reports, 12(2020). https://doi.org/10.1016/j.biteb.2020.100605

104) P. Wang, Y. Shao, Y. Geng, R. Mushtaq, W. Yang, M. Li, X. Sun, H. Wang, and G. Chen," Advanced treatment of secondary effluent from wastewater treatment plant by a newly isolated microalga *Desmodesmus* sp. SNN1," Frontiers in Microbiology, 14 (2023). https://doi.org/10.3389/fmicb.2023.1111468

105) R. Davis, A. Aden, and P. T. Pienkos,"Techno-economic analysis of autotrophic microalgae for fuel production," Applied Energy, 88(10)(2011). https://doi.org/10.1016/j.apenergy.2011.04.018

106) G. G. Zaimes, and V. Khanna, " (2013). Microalgal biomass production pathways: Evaluation of life cycle environmental impacts. Biotechnology for Biofuels, 6(1)(2013). https://doi.org/10.1186/1754-6834-6-88.

107) T. Handayani, F. E. Priyanto, S. Sulistia, A. N. Oktaviani, N. Sopiah, and A. Dwi," Integrated Microalgae Cultivation for Sustainable Wastewater Treatment and Carbon Dioxide Bio-Fixation in Milk Factories," International Journal of Sustainable Development and Planning 18(9), 2941–2952(2023). https://doi.org/10.18280/ijsdp.180932

108) A. D. Santoso, J. Hariyanti, D. Pinardi, K. Kusretuwardani, N. Widyastuti, I. N. Djarot, T. Handayani, A. I. Sitomurni, H. Apriyanto," Sustainability index analysis of microalgae cultivation from biorefinery palm oil mill effluent," Global Journal of Environmental Science and Management, 9(3), 559–576, (2023) https://doi.org/10.22035/gjesm.2023.03.13

109) W. J. Martinez-Burgos, E. Bittencourt Sydney, A. Bianchi Pedroni Medeiros, A. I. Magalhães, J. C. de Carvalho, S. G. Karp, L. Porto de Souza Vandenberghe, et al., "Agro-industrial wastewater in a circular economy: Characteristics, impacts, and applications for bioenergy and biochemicals," Bioresource Technology, 341, 125795, (2021). https://doi.org/10.1016/j.biortech.2021.125795

110) A. B. Daudaa, A. Ajadib, A. S. Tola-Fabunmic, and A. P. Ayoola Olusegun Akinwole," Waste production in aquaculture: Sources, components, and management in different culture systems," Aquaculture and Fisheries, 4(3), 81-88, (2019). https://doi.org/10.1016/j.aaf.2018.10.002

111) A. Goli, A. Shamiri, A. Talaiekhozani, N. Eshtiaghi, N. Aghamohammadi, and M. K. Aroua, "An overview of biological processes and their potential for CO_2 capture, Journal of Environmental Management, 183, 41-58, (2016). https://doi.org/10.1016/j.jenvman.2016.08.054

112) N. N.A. Hamid, and J. S. Lim, "Techno-economic assessment of an integrated algae-based biorefinery with palm oil mill," Chemical Engineering Transactions, 63, 169-174, (2018). doi: 10.3303/CET1863029.

113) Socalgas, "Biogas and biomethane, socalgas.com/for-your-business/power-generation/biogas- biomethane>, accessed 9.13.16. 2016, https://www.europeanbiogas.eu/about-biogas-and-biomethane/

114) M.N.M. Idris., H. Hashim, J. S. Lim, and C. S. Ho., "Economic assessment of microalgae-based co2 utilization in power plant sector in Malaysia," Chemical Engineering Transactions, 56, 643-648. (2017), https://doi.org/10.3303/CET1756108

115) H. Kargbo, J.S.Harris, A.N. Phan "Drop-in" fuel production from biomass: Critical review on techno-economic feasibility and sustainability," Renewable and Sustainable Energy Reviews, 135, 110168 (2021). https://doi.org/10.1016/j.rser.2020.110168

116) M. Rizwan, J. H. Lee, R. Gani, "Optimal design of microalgae-based biorefinery: Economics, opportunities and challenges," Applied Energy, 150, 69–79, (2015). https://doi.org/10.1016/j.apenergy.2015.04.018

117) A. I. Barros, A. I. Gonçalves, M. Simões, J. C.M. Pires,"Harvesting techniques applied to microalgae: A review," Renewable & Sustainable Energy Reviews, 41, 1489–1500 (2015). https://doi.org/10.1016/j.rser.2014.09.037

118) Alibaba.com, Isopropanol price alibaba.com/showroom/price-isopropanol.html, accessed 15.05.17.(2017), https://www.amazon.com/s?k=isopropyl+alcohol+ipa&adgrpid

119) G. Thomassen, U. E.Vila, M.Van Dael, B. Lemmens, S. Van Passel, "A techno-economic assessment of an algal-based biorefinery," Clean Techn Environ Policy, 18, 1849–1862, (2016). https://doi.org/10.1007/s10098-016-1159-2.

120) W. A. W. Mahari, W. A. W. Razali, H. Manan, M. A. Hersi, S. D. Ishak, W.Cheah, D. J. C. Chan, C. Sonne, P. L. Show, S. S. Lam," Recent advances on microalgae cultivation for simultaneous biomass production and removal of wastewater pollutants to achieve circular economy," Bioresource Technology, 364, 128085, (2022). https://doi.org/10.1016/j.biortech.2022.128085

121) R. Davis, J. Markham, C. Kinchin, N. Grundl, E. C. D. Tan, and D. Humbird, "Process design and economics for the production of algal biomass: algal biomass production in open pond systems and processing through dewatering for downstream conversion, 2016, nrel.gov/docs/fy16osti/64772.pdf, accessed 23.06.17.

122) R. L. Pastor, M. P. Hernández, G. F. G. Acién Fernández, "Technical and economic viability of using solar thermal energy for microalgae drying," Energy Reports, 10, 989-1003, (2023). https://doi.org/10.1016/j.egyr.2023.07.040

123) P. L. Show, "Global market and economic analysis of microalgae technology: Status and perspectives," Bioresour. Technol. 357, 127329, (2022). https://doi.org/10.1016/j.biortech.2022.127329Show 2022.

124) M. Bamaarouf, M. Slaoui, Y. Addach, F. Dahawi, "Influence of the time of flocculation in the tertiary treatment of wastewater by an integrated system," Eau, l'Industrie, les Nuisances, 416, 95-102, (2018). https://196.203.79.254/record/126226?ln=en

125) C. G. Gutiérrez-Arriaga, M. Serna-González, J. M. Ponce-Ortega, M. M. El-Halwagi,"Sustainable Integration of Algal Biodiesel Production with Steam Electric Power Plants for Greenhouse Gas Mitigation," ACS Sustainable Chemistry & Engineering, 2, 1388–1403, (2014). https://doi.org/10.1021/sc400436a

126) O. M. Hernández-Calderón, J. M. Ponce-Ortega, J. R. Ortiz-Del-Castillo, M. E. Cervantes-Gaxiola, J. Milán-Carrillo, M. Serna-González, E. Rubio-Castro E., "Optimal design of distributed algae-based biorefineries using CO2 emissions from multiple industrial plants," Industrial & Engineering Chemistry Research, 55, 2345–2358, (2016). https://doi.org/10.1021/acs.iecr.5b01684

127) J. Maroušek, B. Gavurová, O. Strunecký, A. Maroušková, M. Sekar, V. Marek, "Techno-economic identification of production factors threatening the competitiveness of algae biodiesel," Fuel, 344, 128056, (2023) https://doi.org/10.1016/j.fuel.2023.128056.

128) B. Vázquez-Romero, J. Perales, H. Pereira, M. Barbosa, J. Ruiz, "Techno-economic assessment of microalgae production, harvesting and drying for food, feed, cosmetics, and agriculture," Science of the Total Environment, 837, 155742, (2022). https://doi.org/10.1016/j.scitotenv.2022.

129) B. Behera, K. V. Supraja, B. Paramasivan, "Integrated microalgal biorefinery for the production and application of biostimulants in circular bioeconomy," Bioresource Technology, 339, 125588, (2021). https://doi.org/10.1016/j.biortech.2021.125588.

130) Y. Y. Qin, M. Z. Liang, S. C. Liang, and H. I. Zheng," Effect of shrimp aquaculture effluent on mangrove sediment in Beibu Bay," Pol. J. Environ. Stud. 31, 795–802, (2022). https://doi.org/10.15244/pjoes/140174

131) P. Zhao, E. Sanganyado, T. Wang, et al.," Accumulation of nutrients and potentially toxic elements in plants and fishes in restored mangrove ecosystems in South China," Sci. Total Environ. 838(1), 155964, (2022). https://doi.org/10.1016/j.scitotenv.2022.155964

132) Schmautz, F. Loeu, F. Liebisch, A. Graber, A. Mathis, T. G. Bulc, and R. Junge, "Tomato Productivity and Quality in Aquaponics: Comparison of Three Hydroponic Methods Zala," Water, 8(533), 1-21, (2016). https://doi.org/10.3390/w8110533 (2016).

133) B.T. Sabarudin, and S. Kartohardjono, "The Combination of coagulation-flocculation and membrane processes to minimize pollution of tofu wastewater," Evergreen, 7 (1), 56–60, (2020). https://doi.org/10.5109/2740942

134) C. H. Gao, S. Zhang, M. Y. Wei, Q. S. Ding, Q.S., Ma, D.N., Li, J., et al., "Effects of shrimp pond effluent on functional traits and functional diversity of mangroves in Zhangjiang Estuary," Environ. Pollut., 297(15), 118762, (2021). https://doi.org/10.1016/j.envpol.2021.118762

135) W. K. Alazzai, M. K. Obaid, B.S. Z. Abood, L Jasim, "Smart agriculture solutions: harnessing AI and IoT for crop management," E3S Web of Conferences 477, 00057 (2024) STAR'2023. https://doi.org/10.1051/e3sconf/202447700057

136) H. R. Seireg, Y. M. K. Omar, F. E. A. El-Samie, A. S. El-Fishawy and A. Elmahalawy, "Ensemble Machine Learning Techniques Using Computer Simulation Data for Wild Blueberry Yield Prediction," in IEEE Access, 10, 64671-64687, (2022). https://doi.org/10.1109/ACCESS.2022.3181970

137) A. Katyayan, S. Mashelkar, and S. Morajkar, "Design of smart agriculture systems using artificial intelligence and big data analytics. In 2021 3rd International Conference on Advances in Computing, Communication Control and Networking," (ICAC3N), IEEE, 592-595, (2021). http://dx.doi.org/10.1109/ICAC3N53548.2021.9725672

138) M. Hori, E. Kawashima, and T. Yamazaki, "Application of cloud computing to agriculture and prospects in other fields," Fujitsu Sci. Tech. J, 46(4), 446-454, (2010). https://www.fujitsu.com/global/documents/about/resources/publications/fstj/archives/vol46-4/paper15.pdf

139) M. S. Goraya, and H. Kaur, "Cloud computing in agriculture," HCTL Open International Journal of Technology Innovations and Research (IJTIR), 16, 2321-1814, (2015). http://ijtir.hctl.org/

140) D. J. Reddy and M. R. Kumar, "Crop Yield Prediction using Machine Learning Algorithm," 5th IEEE International Conference on Intelligent Computing and Control Systems (ICICCS), 1466-1470, (2021). http://dx.doi.org/10.1109/ICICCS51141.2021.9432236

141) A. Khanna, and S. Kaur, "Evolution of Internet of Things (IoT) and its significant impact in the field of Precision Agriculture," Computers and electronics in agriculture, 157, 218-231, (2019). https://doi.org/10.1016/j.compag.2018.12.039

142) M. Ayaz, M. Ammad-Uddin, Z. Sharif, A. Mansour, and E. H. M. Aggoune, "Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk," IEEE access, 7, 129551-129583, (2019). https://doi.org/10.II09/ACCESS.2019.2932609

143) M. Javaid, A. Haleem, I. H. Khan, and R. Suman, "Understanding the potential applications of artificial

intelligence in agriculture sector," Advanced Agrochem, 2(1), 15-30 (2023). https://doi.org/10.1016/j.aac.2022.10.001
144) S. A. Ansar, K. Jaiswal, P. C. Pathak, and R. A. Khan, "A step towards smart farming: unified role of AI and IoT," In International Conference on Computer Vision and Robotics, 557-578), (2023). Singapore: Springer Nature Singapore. http://dx.doi.org/10.1007/978-981-99-4577-1_46
145) C. Heldreth, D. Akrong, J. Holbrook, and N. M. Su, "What does AI mean for smallholder farmers? a proposal for farmer-centered AI research," Interactions, 28(4), 56-60, (2021). https://doi.org/10.1145/3468004
146) M. Chandraprabha, and R. K. Dhanraj, "Ensemble Deep Learning Algorithm for Forecasting of Rice Crop Yield based on Soil Nutrition Levels", ICST Transactions on Scalable Information Systems, 2023. https://doi.org/10.4108/eetsis.v10i3.2610
147) A. Sharma, A. Jain, P. Gupta and V. Chowdary, "Machine Learning Applications for Precision Agriculture: A Comprehensive Review," in IEEE Access, 9, 4843-4873, (2021). https://doi.org/10.1109/ACCESS.2020.3048415
148) Y. Cai, K. Guan, D. Lobell, A. B. Potgieter, S. Wang, J. Peng, T. Xu, S. Asseng, Y. Zhang, L.You, B. Peng, "Integrating satellite and climate data to predict wheat yield in Australia using machine learning approaches," Agricultural and Forest Meteorology, 274, 144-159, (2019. https://doi.org/10.1016/j.agrformet.2019.03.010
149) S. Agarwal, and S. Tarar, "A hybrid approach for crop yield prediction using machine learning and deep learning algorithms," Journal of Physics: Conf. Ser. 1714 012012, (2021). https://doi.org/10.1088/1742-6596/1714/1/012012
150) M. Doshi, and A. Varghese, "Smart agriculture using renewable energy and AI- powered IoT. In AI, edge and IoT-based smart agriculture," 205-225, (2022). Academic Press. https://doi.org/10.3390/en17235984
151) Z. Li, L. Ding, D. Xu, "Exploring the potential role of environmental and multi-source satellite data in crop yield prediction across Northeast China," Science of The Total Environment, 815, 152880, (2022). https://doi.org/10.1016/j.scitotenv.2021.152880
152) H. Ashraf, M. T. Akanbi, "Sustainable agriculture in the digital age: Crop management and yield forecasting with IoT, Cloud, and AI Tensorgate," Journal of Sustainable Technology and Infrastructure for Developing Countries, 6(1), 64-71(2023). https://orcid.org/0000-0002-2419-4626
153) E. Alreshidi, "Smart sustainable agriculture (SSA) solution underpinned by internet of things (IoT) and artificial intelligence (AI)," arXiv preprint arXiv:1906.03106. (2019). https://doi.org/10.48550/arXiv.1906.03106
154) S. Qazi, B. A. Khawaja, and Q. U. Farooq, "IoT-equipped and AI-enabled next generation smart agriculture: A critical review, current challenges and future trends," IEEE Access, 10, 21219-21235, (2022). https://doi.org/10.1109/ACCESS.2022.3152544
155) G. Mariammal, A. Suruliandi, S. P. Raja, and E. Poongothai, "Prediction of Land Suitability for Crop Cultivation Based on Soil and Environmental Characteristics Using Modified Recursive Feature Elimination Technique With Various Classifiers," in IEEE Transactions on Computational Social Systems, 8(5),1132-1142, (2021). https://doi.org/10.1109/TCSS.2021.3074534
156) P. Tomar, and G. Kaur, "Artificial Intelligence and IoT-based technologies for sustainable farming and smart agriculture. IGI Global. (Eds.). (2021). https://doi.org/ 10.4018/978-1-7998-1722-2
157) R. Kumar, D. Sinwar, A. Pandey, T. Tadele, V. Singh, and G. Raghuwanshi,"IoT Enabled Technologies in Smart Farming and Challenges for Adoption. Internet of Things and Analytics for Agriculture, 3, 141-164, (2022). http://dx.doi.org/10.1007/978-981-16-6210-2_7
158) M. K. Jhariya, R. S. Meena, A. Banerjee, "Ecological intensification of natural resources towards sustainable productive system." Ecological intensification of natural resources for sustainable agriculture 1-28, (2021). https://doi.org/10.1007/978-981-33-4203-3_1
159) S. Kumar, K. Siva Shanmugam, and G. Rayavel, "Smart environmental waste water monitoring system and analysis using big data," International Journal of Innovative Technology and Exploring Engineering 8(6),1310-1314, (2019).https:// https://www.ijitee.org/portfolio-item/f3848048619/
160) N. Ahmed, and G. Turchini, G. "Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation," Journal of Cleaner Production 297,1-14 (2021). https://doi.org/10.1016/j.jclepro.2021.126604
161) A. Reddy, "Utilisation of Aquaculture in Agriculture Using Image Processing," International Journal of Scientific Research and Review 8(3), (2019).
162) V. K. M. Putri, "Eco-farming: Definition and Examples. (2022) https://www.kompas.com/skola/read/2022/03/11/070000669/eco-farming-pengertian-dan-contohnya.
163) M. S. Gill, J. P. Singh, and K S Gangwa, "Integrated farming system and agriculture sustainability." Indian Journal of Agronomy, 54(2),128-139, (2009). https://doi.org/10.59797/ija.v54i2.4790

164) E. S. Mohamed, A. A., Belal, S. K. Abd-Elmabod, Mohammed, A. El-Shirbeny, A. Gad, and M. B. Zahran, “Smart farming for improving agricultural management,” The Egyptian Journal of Remote Sensing and Space Science. 24(3,2), 971-981, (2021). https://doi.org/10.1016/j.ejrs.2021.08.007
165) C. E. Boyd, Claude, L. R. D'Abramo, B. D. Glencross, D. C. Huyben, L. M. Juarez, G. S. Lockwood, A. A. McNevin et al.,"Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges," Journal of the World Aquaculture Society, 51(3), 578-633, (2020). https://doi.org/10.1111/jwas.12714
166) G. Luo, X. Chen, J. Tan, G.Abakari, and H. Tan, “Effects of carbohydrate addition strategy and biofloc levels on the establishment of nitrification in biofloc technology aquaculture systems,” Aquaculture, 514, 734441, (2020). https://doi.org/10.1016/j.aquaculture.2019.734441
167) S. Al-thawadi, “Public perception of algal consumption as an alternative food in the kingdom of bahrain,” Arab Journal of Basic and Applied Sciences, 25 (1) 1–12 (2018). https://doi.org/10.1080/ 25765299.2018. 1449344.
168) S. Sinha, N. Patro, and I.K. Patro, “Maternal protein malnutrition: current and future perspectives of spirulina supplementation in neuroprotection,” Frontiers in Neuroscience, 12 (December) 1–18 (2018). https://doi.org/10.3389/fnins.2018.00966.
169) N. C. Eli-Chukwu, “Applications of Artificial Intelligence in Agriculture: A Review”, Eng. Technol. Appl. Sci. Res., vol. 9, no. 4, pp. 4377–4383, (2019). https://doi.org/10.48084/etasr.2756
170) V. Udutalapally, S. P. Mohanty, V. Pallagani and V. Khandelwal, "Crop: A Novel Device for Sustainable Automatic Disease Prediction, Crop Selection, and Irrigation in Internet-of-Agro-Things for Smart Agriculture," in IEEE Sensors Journal, vol. 21, no. 16, pp. 17525-17538, (2021). https://ieeexplore.ieee.org/iel7/7361/9650682/09686561.pdf
171) Z. Liu, R. N. Bashir, S. Iqbal, M. M. A. Shahid, M. Tausif and Q. Umer, "Internet of Things (IoT) and Machine Learning Model of Plant Disease Prediction–Blister Blight for Tea Plant," IEEE Access, 10, 44934-44944, (2022). https://doi.org/ 10.1109/ACCESS.2022.3169147
172) S. Bhansali, P. Shah, J. Shah, P. Vyas and P. Thakre, "Healthy Harvest: Crop Prediction And Disease Detection System," IEEE 7th International Conference for Convergence in Technology (I2CT), 1-5 (2022). https://www.proceedings.com/content/064/064715webtoc.pdf
173) R. Donde, G. Gouda, S. Sabarinathan, M. K. Gupta, G. K. Dash, N. Rajesh, S. K. Dash, K. K. Sahoo, P. Sanghamitra, C. Parameswaran, R. Vadde, and L. Behera, "Artificial Intelligence and Machine Learning in Rice Research." Applications of Bioinformatics in Rice Research, 239-275, (2021). https://doi.org/10.1016/j.nexus.2021.100022
174) Sethi, S.S., Sharma, P. New Developments in the Implementation of IoT in Agriculture. SN COMPUT. SCI. 4, 503 (2023). https://doi.org/ 10.1007/s42979-023-01896-w.
175) K. Slimani, S. Khoulji, A. Mortreau, and M. L. Kerkeb, “From tradition to innovation: The telecommunications metamorphosis with AI and advanced technologies,” Journal of Autonomous Intelligence, 7(1), 1-11, (2024). https://doi:10.32629/jai.v7i1.1099
176) R. K. Goel, C. S. Yadav, S. Vishnoi, and R. Rastogi, “Smart agriculture–Urgent need of the day in developing countries,” Sustainable Computing: Informatics and Systems, 30, 100512, (2021). https://doi.org/10.1016/j.suscom.2021.100512
177) D. Chittora, M. Meena, T. Barupal, P. Swapnil, and K. Sharma, “Cyanobacteria as a source of biofertilizers for sustainable agriculture,” Biochemistry and Biophysics Reports, 22,100737, (2020). https://doi:10.1016/j.bbrep.2020.100737.
178) Zhu N Y, Liu X, Liu Z Q, Hu K, Wang Y K, Tan J L, et al. “Deep learning for smart agriculture: Concepts, tools, applications, and opportunities,” Int J Agric & Biol Eng,11(4): 32–44, (2018). https://doi.org/10.25165/j.ijabe.20181104.4475
179) Valdovinos-Garcia E. M., J. Barajas-Fernandez, M. de los A. Olan-Acosta, M.A. Petriz-Prieto, A. Guzman-Lopez, and M.G. Bravo-Sanchez, “Technoeconomic study of CO_2 capture of a thermoelectric plant using microalgae (chlorella vulgaris) for production of feedstock for bioenergy,” Energies, 13 (41) 1–19 (2020). https://doi.org/10.3390/en13020413
180) A. Crane-Droesch, “Machine learning methods for crop yield prediction and climate change impact assessment in agriculture,” Environ. Res. Lett., 13, 114003, (2018). https://doi.org/10.1088/1748-9326/aae159
181) N.K.Z. AlFadhly, N. Alhelfi, A.B. Altemimi, D.K. Verma, F. Cacciola, and A. Narayanankutty, “Trends and technological advancements in the possible food applications of spirulina and their health benefits: a review,” Molecules, 27 (17) 1–40 (2022). https://doi.org/10.3390/molecules27175584.
182) A.E.M. Hussian, “The Role of Microalgae in Renewable Energy Production: Challenges and Opportunities,” Marine Ecology, Intech Open, Rijeka, 2018. https://doi:10.5772/intechopen.73573.
183) H. Aghighi, M. Azadbakht, D. Ashourloo, H. S.

Shahrabi and S. Radiom, "Machine Learning Regression Techniques for the Silage Maize Yield Prediction Using Time-Series Images of Landsat 8 OLI," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11(12)(2018), 4563-4577. https://doi.org/10.1109/JSTARS.2018.2823361

184) L.Boukhris, J. Ben Abderrazak, H. Besbes, “Tailored Deep Learning based Architecture for Smart Agriculture,” International Wireless Communications and Mobile Computing, 964–69, (2020). https://doi.org/10.1088/1742-6596/1767/1/012026

185) K. Sujatha, N. P. G. Bhavani, V. S. George, T. Kalpatha Reddy, N. Kanya, A. Ganesan, “Innovation in Agriculture Industry by Automated Sorting of Rice Grains,” Evergreen, 10(01), 283-288 (2023). https://doi.org/10.5109/6781076

186) J.M. Rutar, M.J. Hudobivnik, M. Nečemer, K.V. Mikuš, I. Arčon, and N. Ogrinc, “Nutritional quality and safety of the *Spirulina* dietary supplements sold on the Slovenian market,” Foods, 11(6),(2022). https://doi.org/10.3390/foods11060849.

187) M. Ayundyahrini, D. Agus Susanto, H. Febriansyah, F. M. Rizanulhaq, G. H. Aditya, “Smart Farming: Integrated Solar Water Pumping Irrigation System in Thailand,” Evergreen, 10(01),553-563(2023). https://doi.org/10.5109/6782161

188) R. Ciolac, T. Iancu, I. Brad, T. Adamov, and N. Mateoc-Sîrb, "Agritourism A business reality of the moment for Romanian rural area’s sustainability," Sustainability, 13(11), 6313, (2021). https://doi.org/10.3390/su13116313

189) D. Elavarasan and P. M. D. Vincent, "Crop Yield Prediction Using Deep Reinforcement Learning Model for Sustainable Agrarian Applications," in IEEE Access, vol. 8, pp. 86886-86901, (2020). https://doi.org/doi: 10.1109/ACCESS.2020.2992480

190) A.T. Nugraha, G. Prayitno, A.W. Hasyim, F. Roziqin, “Social Capital, Collective Action, and the Development of Agritourism for Sustainable Agriculture in Rural Indonesia,” Evergreen, 8(01),01-12(2021). https://doi.org/10.5109/4372255

191) N. Kim, K.-J. Ha, N.-W. Park, J. Cho, S. Hong, Y.W. Lee, ‘‘A comparison between major artificial intelligence models for crop yield prediction: Case study of the midwestern United States, 2006–2015,’’ ISPRS Int. J. Geo-Inf., vol. 8, no. 5, p. 240, (2019). https://doi.org/10.3390/ijgi8050240

192) G. Swaminathan, G. Saurav, “Development of Sustainable Hydroponics Technique for Urban Agribusiness,” Evergreen, 9(03),629-635(2022). https://doi.org/10.5109/4842519

193) S. Ramadhanty, M.H. Amirullah, M.H. Faturrahman, R. Dhelika, and T. Abuzairi, “Development of small scale electrohydrodynamic drying device for rough rice using dc plasma generator,” Evergreen, 6 (2) 103–107 (2019). https://doi.org/10.5109/2321000.

194) A.M. Ali, M. Abouelghar, A.A. Belal, N. Saleh, M. Yones, A. I. Selim, M. E.S. Amin, et al., “Crop Yield Prediction Using Multi Sensors Remote Sensing,” The Egyptian Journal of Remote Sensing and Space Science, Volume 25, Issue 3, Pages 711-716, ISSN 1110-9823, (2022). http://dx.doi.org/10.1016/j.ejrs.2022.04.006

195) H. Pariaman, G.M. Luciana, M.K. Wisyaldin, and M. Hisjam, “Anomaly detection using lSTM-autoencoder to predict coal pulverizer condition on coal-fired power plant,” Evergreen, 8 (1) 89–97 (2021). https://doi.org/10.5109/4372264.

196) B. Prasetyo, Suyanto, M.A.M. Oktaufik, “Smart Farming: Integrated Solar Water Pumping Irrigation System in Thailand Himawan, “ Design, construction and preliminary test operation of bppt-3mw condensing turbine geothermal power plant,” Evergreen, 6 (2) 162–167. http://dx.doi.org/10.5109/6782161

197) A.A.A. Putri, S. Hartini, and R. Purwaningsih, “Sustainable value stream mapping design to improve sustainability performance of animal feed production process,” Evergreen, 8 (1) 107–116 (2021). https://doi.org/10.5109/4372266.

198) L. M. Z. Ash-Shalehah, C. Anggraeni, E. Gloria, Dianursanti, “Development of Microalgae-microbial Fuel Cell (MmFC) Technology using Microalgae Consortium of *Chlorella vulgaris* and *Spirulina platensis*.“ Evergreen, 9(02), 476-483 (2022). https://doi.org/10.5109/4794175

199) S. Mopidevi, V. Singitham, B. Thippani, R. Shamanthula and N. S. P. Vallabhaneni, "Plant growth and yield prediction using ML and DL Algorithms," 2022 IEEE International Conference on Electronics and Renewable Systems (ICEARS),1470-1477,(2022). https://doi.org/10.1109/ICEARS53579.2022.9751906

200) P. Bhatt, M. Singh, “Industry 4.0 and Sustainability-Leveraging Community Engagement for Achieving Partnership for Common Goals,” Evergreen 10(04), 2483-2489 (2023). https://doi.org/10.5109/7162011

201) U. Rai, and M. Saif, “Smart Agro: Agriculture with Technology and Management Utpal,” International Journal for Research in Applied Science & Engineering Technology (IJRASET). 11(3), (2023). https://doi.org/10.22214/IJRASET.2023.49996

Cite: T. Handayani et al., "Opportunity of Smart Aquaculture and Eco-Farming Integration in POME Bioremediation and Phycoremediation System for Environmental Sustainability". Evergreen, 12 (02) 903-931 (2025). https://doi.org/10.5109/7363484.