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# Prospects of Industry 5.0 in algae: Customization of production and new advance technology for clean bioenergy generation

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ABSTRACT

There is a high demand for clean, affordable and sustainable source of energy due to the limitation in fossil fuel supplies. The algae industrial revolutions have proved to be a significant step to realize the growing need for energy and achieving the sustainable development goals (SDGs). In this review, the production and processing of algae from an industry point of view and the algae processing in Industry 4.0 as well as a paradigmatic shift from Industry 4.0 to Industry 5.0 were well-delineated. Moreover, numerous aspects in the algae industry have been discussed, including economic and environmental analysis of algae bioenergy production, customization of the algae-derived bioenergy, algae cultivation and modifications in the cultivating approach. Genetic engineering tools implemented in the algae culture for bioenergy and by-products generation was also studied, and area of focusing such as the desired algae strain and its detection through automated genetic manipulation and genetic modification. Furthermore, the impacts of the Industry 5.0 on the new market opportunities and environment aspect as well as the possibility of achieving SDGs were significantly studied.

## 1. Introduction

Algae are a diverse group of chlorophyll-containing eukaryotic organisms found in marine and freshwater habitats. They are ranged from micro (single-cell organism) to macro level (hundred feet in length). Their capabilities for food and energy production have gained lot of research attention. The creation of algae that is naturally highly efficient owing to the ability to endure the macro-panel spectrum of temperature, light intensity, pH and salinity value [1]. At present, it is known the environmental and energy sustainability are the main two problems faced by the society. This is due to the unsustainable dependency on fossil fuels. Apart from these, the emission of greenhouse gases (GHGs) to the atmosphere also occurs as the side impacts from high utilization of fossil fuels [2]. Therefore, many researchers world-wide have identified alternative renewable energy options such as algae. Accordingly, the use of algae to generate bioenergy (i.e., third generation biofuels) as a viable feedstock by further research with advanced technologies, that produces a fourth generation of more personalized and customized microalgae, could effectively produce valid, cost effective and reliable source of energy [3]. Table 1 compares the features of first, second and third generation of biofuels.

Algae bio-refineries integrated with Industry 4.0 approach presented

*Abbreviations:* AI, Artificial Intelligence; APS, Algae Production System; BHT, Butylated Hydroxytoluene; CNNs, Convoluted Neural Networks; CPD, Continuing Professional Development; DL, Deep learning; EOS, Electro-Optical Systems; GHGs, Greenhouse Gases; GRAS, Generally Regarded as Safe; IR, Industrial Revolution; LCAs, Long Chain Assessments; ML, Machine Learning; NADP, Nicotinamide adenine dinucleotide Phosphate; PBR, Photo-bioreactor; RE100, Renewable 100 percent; ROS, Reactive Oxygen Species; SDGs, Sustainable Development Goals; SVM, Support Vector Machines; TAIR, The Arabidopsis Information Resource; UN, United Nations.

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**Table 1**
Characteristics of different generations of biofuels.

| First generation biofuels | Second generation biofuels | Third generation biofuels |
|---|---|---|
| *Sources* | | |
| Edible oils such as vegetable oils, sugarcane, corn etc. | Non-edible oils such as agricultural oil crops (e.g., Jatropha seeds), municipal solid waste, forest residue etc. | Algae such as macroalgae and microalgae |
| *Advantages* | | |
| Environmentally friendly | Do not compete with food crops | Higher biomass productivity and oil content |
| Safe to use | Cheaper cost of biomass compared to edible oil crops | Can utilize wastewater and $CO_2$ to cultivate algae |
| Simple reactions involved in biofuels production (e.g., fermentation and transesterification) | Multiple biofuel products (e.g., bioethanol, bio-char, bio-oil and syngas) | Valorization of end-products for biofuels and other biological by-products |
| *Limitations* | | |
| Compete with food supply | Utilization of arable land | High energy consumption |
| Only for bioethanol and biodiesel production | Complex reactions involved in biofuels conversion | Technical hindrances from cultivation and biomass recovery processes |

that no matter how the biomass is processed in an optimized bio-refinery that allows for the production of the greatest numbers of goods and co-products (Fig. 1) and the lowest residual quantity, downstream capital is always assured for optimal returns [4,5]. This implies that in an algae bio-refinery, it can automate the algae growth and harvesting system in order to reduce operational costs, and also enable operators to track growth and output of algae in real time via a network of Internet of Things (IoTs) plug-and-play sensors [6]. The Industry 4.0 idea goes a step forward by creating a replica or digital duplicate of the device from the sensor data of the algae population. In the attempt to satisfy anticipated commodity demand, and minimize waste, such simulations will allow a forecast of potential cellular performance in real time basis [7,8]. Figs. 1 and 2 illustrate the incorporation of microalgae biomass in several processes to produce various by-products that could be possibly utilized in our daily life with minor side effects in the long term on the wellbeing and environment.

Industrialization has contributed to a fast urbanization that proceeds to escalate in contemporary times, where it influenced the average life expectancy that represented an enormous enhancement in industrial nations. Hence, average incomes have increased as well, which proves that industrialization has improved human's lives in many ways and

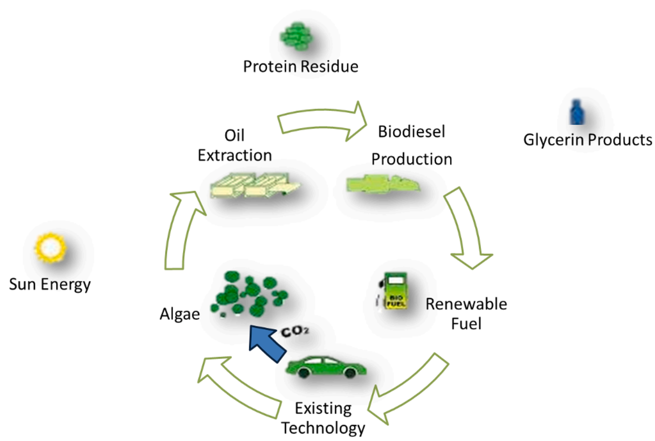


**Fig. 1.** Flow cycle of algae of microalgae biomass.

that from a population perspective as a bulk and not from an individualist perspective per person [9]. Throughout the transition period, emphasis of Industry 5.0 is on the restorations of human hands, brains and intuitions in the manufacturing senses, which stresses transformations of factories into smart IoT facilities, which uses semantic processing and interconnect systems via cloud servers. The Industry 5.0 has the capability that could reconcile humans and machines and seeks ways to operate together in order to increase the manufacturing capacity and performance [10,11]. Implementation of a modern technological development is unpredictable, since its possibility of building, and its likelihood of deconstruction, is the product of a specific transition. The industrial revolution represents an immense move from the decision-maker towards settling the endless needs conditions, such as collective community commitment and willingness, civic influence, market risk reduction and financial stability.

The pattern shift for algae industry follows the increment model. This is because it is a biochemical process that has been modified by chemical engineers continually ever since it had started. Market segmentation may contribute to a few minor structural changes in the market. Though, it is not a good strategy of segmenting the industry and to take shelter in an untapped area of the marketplace. Rather, a change is essentially caused by a stronger comparative offer for a defined market than the previous model standard product.

The 17 sustainable development goals (SDGs) are part of a program to alleviate global poverty and inequality by development, bringing the world into greater consideration. The SDGs are an immediate call for action and international cooperation between all countries generated by the United Nations (UN), and provides crucial milestones for a sustainable climate and atmosphere for everyone. Table 2 provides suitable SDGs that would make a change after the implementation of the new advances in technology that could lead to influence on the mankind and the world. Therefore, this review aims to provide insight on the prospects of Industry 5.0 in the algae industry. The customization of production and processing for clean bioenergy generation was well-delineated.

## 2. Algae industry

### 2.1. Algae processing in Industry 4.0

Industry 4.0 manages goods, businesses' practices and the control of its output. It is a huge leap for innovation manufacturing which uses intelligent devices to control machines on the shop floor, communicating device-to-device autonomously to manage and disperse manufacturing operations. Industry 4.0 extends the whole production supply chain and can be tracked from definition to execution and later steps. Particularly where industrial symbiosis is taken to foster sustainable growth in the field will help small and medium-sized food companies.

As an example, technical developments from the Fourth IR would help the current food infrastructure to become greener and longer-term. Industry 4.0 eliminates and reduces uncertainty by removing biases and unrealistic predictions, allowing a comparable degree of practical information and fresh perspectives. The usage of digital technologies such as specific planting and irrigation would organically increase production. Transportation would increase dramatically in speed, quality and sustainability while mobile IT would boost farmers' awareness about the land they are cultivating and their respective markets.

For instance, food network digitalization should recognize all the facets of developing, harvesting, refining, storing and delivery of foods from the area in order to maximize their role in encouraging human welfare. Food network digitalization will also help to change the local economy by increasing the availability of conventional values, increase the yield of natural resources and develop innovative food goods with health benefit properties, for improving local environment; manufacturers' buying power will rise and food and human health in the area

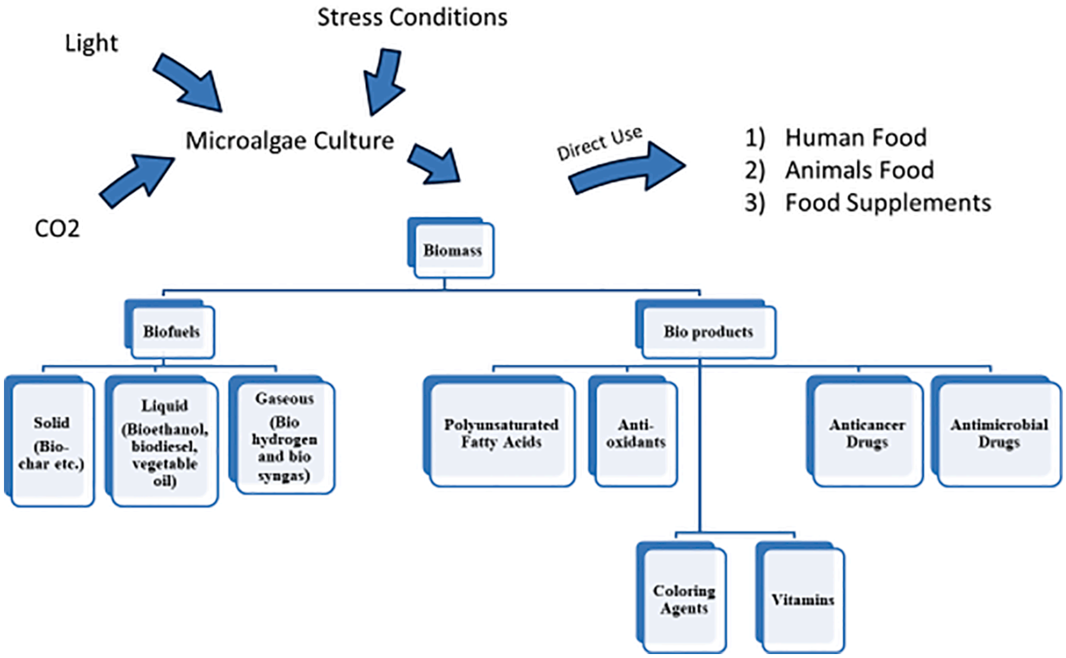


**Fig. 2.** The potential by-products produced from microalgae biomass.

will get better [12].

## 2.2. A paradigm shift in the Industry 4.0 to Industry 5.0

Based on a recent study, it is discovered that high-dimensional phenotypical data acquisition on a whole-organism scale is known as phenomics [13]. However, algae phenomics have a tremendous potential for food conservation (food and nutraceuticals), bioremediation (algae biodegradation of emergent toxins) and agriculture (food and nutraceuticals, feedstocks, high-value items and biopolymers) [14]. By conceiving a database of G × E = P [where G, genome, E, environment and P, phenotype] interactions for a given algae species, researchers can screen natural and artificial diversity for the combination of gene alleles that will combine essential phenotypes [15], such as rapid growth and high product yield.

The possible implications of the phenomenon techniques and innovations in microalgae have been illustrated in recent advances in plant phenomics. A recent phenomics analysis on *Arabidopsis thaliana*, for example, resulted in a mutant that showed increased pathogen protection and photosynthesis production, supposed exchange between production and protection among plant researchers, a near-dogma [16]. Such a phenomics method may also generate drastic combinations of beneficial phenotypes in micro-algae, like a strain utilizing cloture sensing to cause auto-flocculation [17,18] and induction of product synthesis [19,20] when the culture reaches harvest density.

The lack of searchable phenomics repositories is a significant drawback in modern microalgae phenomics. The Arabidopsis Information Resource (TAIR) [21] repository is used by plant and yeast scientists in planning and conducting silico experiments. These tools speed up work by demonstrating how specific genes are connected by a common phenotype [22] or by distinguishing the role of apparently redundant genes [23]. This intensity would demand investments in the development of a broad range of algae science in constructing a comprehensive phenotypic database.

Plant phenomics have also established guidelines for data exchange, data processing and ontology classification, which can be modified to algae [24,25]. The latest analytical data methods for model microbes, for instance yeast, in which can be used with the usage of regular microbiological sensors [26] and hyper spectral cameras [27] to calculate phenotype data from extremely output algae culture formats (such as agar plates, micro planes) [28,29]. The scanning of images with Support Vector Machines (SVM) and Convoluted Neural Networks (CNNs), as shown in [30,31] respectively, were achievable automatically to search only morphological phenotypes by utilizing machine learning technology (ML) approaches.

The option of growth conditions under which the microalgae exhibits a variety of phenotypes is dependent upon their genetic predisposition and is one of the challenges under creating the microalgae phenotypic database, for example a huge amount of work has been carried out utilizing high and low carbon dioxide concentrations to know the photosynthesis genes' function [32], however it is more challenging to elucidate phenotypes relating to stress and repair [33]. Inadequate segregation of phenotype can result in a risk of poorly selected algae phenomics [34]. The restricted capacity to control genetics of a variety of non-model microalgae organisms is another challenge to algae phenomics. The diverse life cycles of many microalgae are often broad and highly repeated, and the genomes of many microalgae challenge the genome sequencing and assembly techniques commonly used for shotgun sequencing [35]. However, the logjams in the third-generation processes that require long-lasting series, such as Nanopore and PacBio, yet efficient to utilize.

If these problems have been overcomed, algae phenomics will - provide a significant effect on algae biotechnology by allowing the processing of microalgae for one reason, i.e., to achieve high value products as new bioproducts designed by pharmaceutical companies. In this scenario, the yield of the desired commodity is regarded as a phenotype in a search for productivity and reliability in engineered strains. In addition, the maturation of resources for algal phenomics would potentially transform the outlook of researchers in biotechnology.

Currently, algae biotechnology investigators are choosing a single strain synthesized by the drug of interest to maximize their production environment, which is frequently expensive and requires complicated photobioreactor (PBR) design [36]. During the moment of algae phenomena, researchers must evaluate their processing culture and refine the ecosystem in the context of algae, as with a plant breeding corporation for industrial crops [37].

**Table 2**
Suitable SDGs with objectives after IR implementation.

| SDG's number | SDG's call to action | Objectives |
|---|---|---|
| 6 | Ensure access to water and sanitation for all. | The continuing professional development (CPD) offers an overview into tracking, controlling and stimulating progress to reach sustainable development goal 6 utilizing the world's largest corporate water dataset. |
| 7 | Ensure access to affordable, reliable, sustainable and modern energy. | The CPD has goals to improve sustainable energy output or use and to help businesses in transition to renewable energy through programs such as Renewable 100 per cent (RE100). In the meanwhile, businesses and creditors will track worldwide advancement towards a renewable energy future via the transparency phase of CPD. |
| 11 | Make cities inclusive, resilient, safe and sustainable. | The CPD offers sustainable enterprise creation. Approximately 620 and more are subscribing for a disclosure nowadays as a crucial first move in the growth of community resistance, whilst the Accessible Data Platform for the CPD provides a vital snapshot of city behaviour globally. |
| 12 | Ensure sustainable consumption and production patterns. | The goal is to concentrate on the relation between the private and public sectors and to encourage sustainable practice and incorporate sustainable knowledge in the reporting process by businesses, and large and transnational corporations. CPD monitoring will maintain compatibility with SDG 12 and can help identify ways to pursue greater ambition. |
| 13 | Take urgent action to combat climate and its impacts. | On behalf of more than 650 global investors, the CPD gathers the data in environment risks and low carbon prospects from the world's biggest businesses and enables industries to increase rates for energy and figure out technical pollution reduction goals; to take aggressive steps. |
| 15 | Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss. | Around 80% of the world's earth relies on them; they provide safe water and avoid surface degradation and flooding; one third of all emissions mitigation attempts to maintain the temperature increase below 20 °C. Approximately 1.6 billion people rely on forests for fruit, duels and herbs, and around 10000 people throughout the world for forestry industry.The CPD gathers the company's related data to monitor the adoption of the SDGs in the private sector and allow businesses to disclose their progress. |

### 2.3. Energy and economy analysis

Net energy research was performed in two methods such as biodiesel and biogas processing systems developed in raceway ponds and strongly optimistic expectations and significant energy deficits. Sensitivity analyses have shown that even though higher algae yields and oil content are used, carbon shortages can also be attained. Carbon processing activities such as cell drying and intervention were at the highest energy load [38]. According to a recent study it has been observed that only if a wet extraction method was implemented would a good net energy balance be achieved [39]. The study indicated that none of the systems analyzed will be practicable as solely energy generating systems; that is to suggest systems designed only to use photosynthesis to produce energy for human. By comparison, accurate full chain energy analysis of methyl esters developed using current technologies showed favorable energy balances in the jatropha, palm oil, rapeseed oil and used cooking oil.

Cost analyzes are a valuable instrument to measure both the total costs and method elements that gives the best output and therefore help to guide potential research and growth. The drawbacks of the cost of algae development are close to those faced with life cycle evaluations which involve data restrictions and the emphasis on criteria extrapolated from laboratory analyzes [40,41,42]. It is also not possible to capture the current state of the art for microalgae culture. Potential expectations might also be expressed in forecasts for algae growth, carbon dioxide capture performance and device capacity rather than existing achievements. Like for long chain assessment (LCA), co-products or co-services are development projects that emphasizes on enhancing economic feasibility, which is significantly impacted.

### 2.4. Algae production

An enclosed illuminated culture vessel built for guided biomass processing can be defined as a PBR that applies to be locked, environmentally-free structures without active transfer of gases and pollutants as illustrated in Fig. 3. Despite PBR's prices, it has some important advantages over open systems such as reduced contamination and monoculture axenic algal production. Also, PBR provides greater control over pH, temperature, light intensity, carbon dioxide rates, etc. Less carbon dioxide loss and water evaporation minimization could permit the production of higher concentrations of complex bio-pharmaceuticals products. Different types of PBR have been designed and developed to cultivate algae for bioenergy and bioproducts generation [43].

The reactor should allow different microalgae species to be cultivated universally. The reactor architecture will guarantee that the culture surface is illuminated equally and that the mass of carbon dioxide and oxygen are spread rapidly. Microalgae cells are extremely adhesive and allow the light exchanging surfaces of reactors. That also ends in automatic washing and sterilization of the reactors once switched off. Hence, the architecture of the reactor will prevent or reduce 30–40% of the reactor fouling, particularly the light transmission surfaces [44]. Therefore, fast mass transfer levels can be reached by not

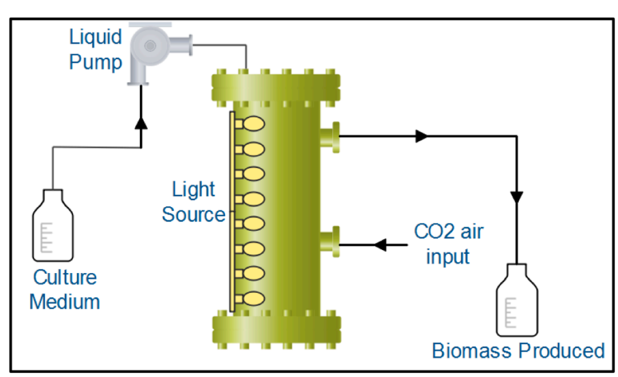


**Fig. 3.** Illustration of the basic requirement for a photo bioreactor (PBR) operation.

damaging or repressing cultivated cells.

### 2.5. Future projections

The future lies in cities with photosynthetic membranes and vertical gardens, energy harvesting from the sun and the development for the communities of urban people of food and bioproducts. Over the last 30 years, thousands of modern algae-based goods were launched with the commercialization of microalgae starting in the 1970s [45]. Due to its 20 times the processing potential and usage of inexpensive and abundant materials, nature's first photo-synthetic model of life is rapidly understanding the abundance of algae in supplying sustainable and locally grown food and electricity.

About few billion dollars has been invested into the production of algae biofuels over the last five years. Although sustainable industrial algae biofuels can be found years away, this expenditure produces creative approaches and innovations, improving the sustainability of algae processing and increasing interest in algae development for other goods. Our future food and its own packaging are to expand with big investments in algae development.

The objectives of algae competition are to develop an open cooperation to expand and share a future view on algae through concepts for algae production landscapes, sustainable and affordable algae production systems for medicinal products, food products, feeding stuffs, energy, nutrients, water remediation and new algae feeds. Competition in building algae food development and recipes, algae production systems (APS), algae landscape and architecture design.

## 3. Customization of bioenergy in the algae industry

### 3.1. Bioenergy

#### 3.1.1. Solid biofuels

Solid biofuels provide renewable, solid, biologically originated non-fossil material that also referred to as biomass that can be used to produce or generate electricity. Solid biofuels are a chemical composite of energy statistics comparable to the volumes of biomass, fuel wood, wood residues and by products, black liquor, bagasse, livestock wastes, food and other waste materials, and commercial green fraction [46]. Moreover, algae can be converted into solid bio-char with the application of thermochemical technology which initiates the bond breaking and reforming of organic matter. Studies also indicates that torrefaction is also an important thermal pre-treatment method to produce solid biofuels [47].

#### 3.1.2. Liquid biofuels

Liquid biofuels contain all fluid fuels that are of renewable origin, such as biomass and biodegradable waste fractions, and are ideal for blending with or eliminating fossil-based fuels. Liquid biofuels are the sum of bio gasoline, biodiesels, bio-jet kerosene and other liquid biofuels in the energy statistics [48].

Several downstream processing from microalgae are required in the production of liquid fuels. The initial step is cultivation then followed by harvesting such as filtration, flocculation and centrifugation of microalgae that contributes possibly almost up to 20–30% of the total production cost of microalgae's biomass. Consequently, dewatering of microalgae biomass which requires constituting up of almost 84.9% of the total energy consumption; this varies prior to the conversion steps in the process. For instance, biodiesel production requires lipid extraction and filtration for purity and quality of the product [49].

#### 3.1.3. Gas biofuels

Biogas is a gas created primarily of methane and carbon dioxide from anaerobic biomass combustion or biomass thermal processes like waste biomass [50]. Biogas is a chemical quantity of energy statistics equal to the volume of deposit gas, waste sludge gas, and biogas from anaerobic degradation and thermal cycle biogas.

One of the most efficient ways to produce biogas is through the hydrothermal gasification (HTG) thermochemical process to change wet biomass to $CO_2$, $H_2$, $CH_4$ and CO containing biogas, whereas high pressure, for instance more than 22.1 MPa and temperature, for instance 374 °C are required to be applied in this procedure. The reaction conditions are moderate compared to conventional gasification, as well as, it has high significance due to its avoidance of dewatering step for the microalgae biomass in the procedure. Different model compounds were carried out using the hydrothermal gasification methodology such as cellulose and humic acid for instance [8]. The evaluation of different strains and catalysts to raise yields and decrease high reaction temperature are the main objectives in few studies that deal with microalgae biomass [51].

## 4. Algae cultivation in Industry 5.0

### 4.1. Tools for alternating cultivation mode

For cultivation of photoautotrophic algae, there are two key alternatives: raceway pond systems and PBRs. A standard raceway pond has a pool of 0.25–0.40 m in depth, exposed to the sun, combined with a paddled wheel to pump water and avoid sedimentation, besides of its shallowness that restrict light penetration into the algae crust as can be illustrated in Fig. 4 below [52]. In PBRs, a transparent series of tubes or plaques hold the culture medium and a central reservoir circulates the micro algal broth. The systems allow for greater management of the ecosystem for algae cultivation but are typically more costly than raceway ponds.

### 4.2. Multipurpose and specific medium for cultivation

Nitrogen, phosphorus, calcium, potassium, magnesium, microelements and vitamins are basic ingredients of a culture medium for microalgae. Also, carbon is required to cultivate the microalgae, and it is usually inorganic and may initially be applied to or supplied as carbonate-containing material.

For certain situations, the isolation of microalgae from cultivation fluid is needless. Nevertheless, surplus and off-season production may be optimized and sustained. Studies has also initiated and explored the various methods used to extract microalgae [53]. The production of high-density algal may be intensified by either chemical growing or centrifugation. Cells coagulate and precipitate to the floor or float to the top, utilizing materials such as aluminium sulphate and ferric chloride. Algae biomass recovery is then carried out by combing off the surface of the skimming cells.

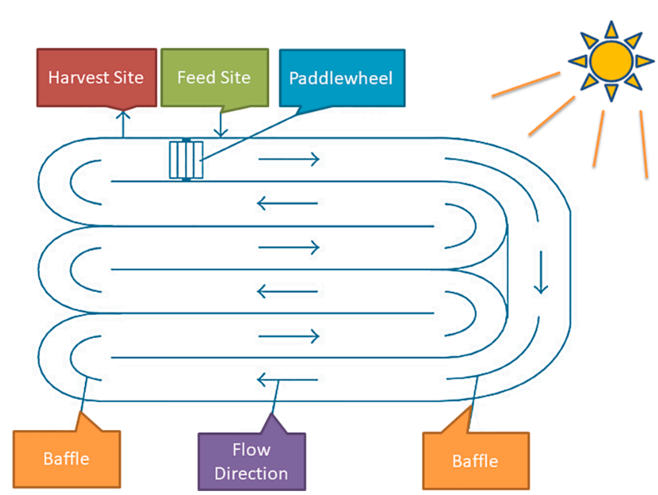


**Fig. 4.** Schematic race way pond diagram.

### 4.3. Cultivation condition and adaption of algae

The algae need nutrients and the optimum pH for the productive growth. Carbon, hydrogen, oxygen, nitrogen, fibers, sulphide, iron and trace elements are required for an autotrophic development. Production declines dramatically under nutrient-limiting conditions and thus influence the lipid accumulation. The main step is to develop algae, which involves site preference, collection of algae crops and method optimization. Algae favor a pH from neutral to alkaline. The design of processes involves the production of the bioreactor and essential algal cell growth components such as nutrients, light and mass transmission. The adaptation of algae is dependent on the several factors such as light intensity, temperature, osmotic stress and nutrient limitation [54].

Light intensity is marked as one of the key inducers of antioxidants. Although electron transfer devices have been saturated or NADP cell supply restricted in photosystems, photo inhibition and the arousing energy transferred to oxygen have occurred and reactive oxygen derivative products are generated. Several adaptation mechanisms, including minimizing the size of the antenna, dispersing energy as heat, carbon dioxide fixation in storage material styles such as storage starch and lipids for redeeming electron transport chain's pressure and lastly by purifying the reactive oxygen species (ROS) through the processing of antioxidants have been taken in such challenging environments. Photo inhibition and the overproduction of oxidants are increased when microalgae are under the stressful conditions of development, due to nutritional restriction or other adverse conditions of culture. Light stress may also enable algae to produce antioxidants, such as carotenoids, certain vitamins and butylated hydroxytoluene (BHT) [55,56].

Another strategy to urge the production of antioxidants in microalgae is low temperature cultivation approach. In order to cope with the cold climate, algae generate unsaturated fatty acids which are applied to the membranes. Many adaptation mechanisms are involved, including cold-shock and antifreeze proteins, which reduce the defective basic enzyme function and involved in differential energy partitioning. Salinity differences are one of the main causes of osmotic shifts which may impact the microalgae cells with hypo- or hyperosmotic tensions. This requires water pump, ion transfer, processing of vacuoles for ion separation and manufacturing of one or more organic osmolytes (such as glycerol).

Deprivation of certain key nutrients contributes to the termination of the development process of microalgae and shifts the production of certain cells. Therefore, microalgae take various modification pathways. They are enzyme control linked with pathways to limit nutrient absorption, reduced photosynthetic activity, hindered by the oxidative stress of the Calvin cycle, substantial amounts of carotenoids produced, major increases in the number of defense pigments (e.g., astaxanthin; mostly due to key deficits in nutrients like N, P or S), raise lipid cellular content (which is often used to react to desperation for nitrogen) and boosting the amount of polyunsaturated fatty acid [57].

### 4.4. Advanced PBR for customization

Hybrid PBR is commonly used, taking advantage of two separate reactor styles and eliminating each other's disadvantages. The combined airlift system and external tubular loops in a thermo-static water pool have been added [58]. The overall volume of the reactor was 200 L. The external loop, on the one side, works like a light harvesting machine as it offers a large surface area to volume ratio and regulates crop temperature. The airlift method is often a degassing device, where tests may also be placed in to control the other variables of community. Owing to a low land demand, stronger carbon dioxide transition from gas phase to liquid phase occurs. The helical form of the bioreactor often has an advantage over the other bioreactors, but the key downside is that this reactor is floating in and energy is required for a centrifugal pump to circulate with the associated shear stress that restricts its usage in manufacturing.

In recent developments of helical PBR represented a promising advancement in the bioreactor cultivation efficiency. Recently a helical-tubular PBR has been built to monitor the continuous development of *Nanochloropsis* species [59]. The key advantages are: incorporating a large culture volume to surface ratio with efficient light penetrator range, simple temperature and pollutants monitoring, successful fresh air and carbon dioxide spatial delivery, improved carbon dioxide - transfer by means of the extensive surface interface between fresh air and culture-liquid median and a modern integrated fluid sensor offering a continuous transmission. Comprehensive knowledge of light propagation, mass transfer, shear stress, scalability and algae cell biology are needed for the designed PBR. None of the single bioreactor satisfies all the bioreactor criteria. For industrial processing of algae relative to single PBR, though, hybrid reactors have proven to be effective. Efforts should be made to combine various PBRs in order to build the most suitable reactor for the development of mass microalgae production.

## 5. Algae genetic engineering

### 5.1. Genetic modification for desired strain

In the logical nature of living cells, synthetic biology follows engineering concepts. A biological structure is described in this discipline as a set of identified genetic pieces that can be modified and reassembled to modify or create current roles in alternative institutions. Genetics prototypes are tested by a design built as to test learning cycle variations to refine the metabolism process in biotechnology applications [60]. This important new method would be paired with the advantages of a microalgae's photosynthesis host in synthetic biology in order to generate new developments for strains suited to the climate. Microalgae are rapidly emerging resources for genetic engineering, which enable the greater availability of sequenced genomes across multiple algal lines. The decoding of genomes in the green algae has enabled the creation of genetic resources *Chlamydomonas reinhardtii*, *stramenopiles*, *Phaeodactylum tricornutum*, *Nannochloropsis gaditana*, *cyanobacteria* and among others [61,62]. In addition, genetic translation methods in microalgae for a variety of animals have been refined, which include natural transformation, electroporation, bead beating, biolistic transformation and plasmid conjugation [63].

Genomic data of these organisms allowed the discovery of an effective transformation of natural genetic elements required for genetic engineering. Many fundamental and inducible endogenous promoter/terminator pairs, including bidirectional promoters for gene stacking or co-expression, were demonstrated to efficiently express transgenes in model species [64]. Furthermore, heterologous sequences or synthetic promoter have been established [65]. Many regulating factors have been identified and established as instruments to control gene expression in *cyanobacteria* and *C. reinhardtii*, such as ligand-binding Riboswitches [66]. Better characterization of transcription-related sequences would be necessary to switch from step-by-step genetic modification to several locations, multi-gene pathways and the construction of individual circuits. In addition to sequences that modulate transcription, the molecular toolkit in microalgae also includes a useful suite of selectable markers, reporter genes, protein tags, and peptide sequences for ribosomal skipping or protein localization [67]. The scientific community has introduced endonuclease cloning restriction systems in order to standardize the widely used genetic sections and promote collaboration. This method enables successful modular assembly through a library of domesticated components of complex plasmids and is commonly used in many models, including plants [68].

Different molecular approaches are used in microalgae for manipulating native gene expression or attacking different areas of the genome. Gene knockdown has been introduced in several structures by the implementation of antisense, engineered small RNAs and CRISPRi [69]. Although comprehensive genome editing technology, like zinc-finger - nucleases, has been recorded in various microalgae, including, transcription activator-like effector nucleases (CRISPR/Cas9). There are many problems related to controlled, effective and toxicity still need to be tackled fully [70] Temporary Cas9 production [71], direct ribonucleoprotein (RNP) distribution and usage of Cas variants are methods to overcome such problems [72]. This breakthrough marks a step towards the production and assembly in microalgae of individual artificial chromosomes. Yeasts have already demonstrated a reconstruction of a native *P. tricornutum* chromosome [73], and a related method can be utilized to establish entirely re-edited chromosome sequence.

### 5.2. Automated genetic manipulation, estimation and computing of proper strain detection

The algae may be categorized as macroalgae or microalgae in an aquatic environment depending on the algae morphology and size [74]. Carbohydrates, lipids and proteins that can be transformed to various forms of biofuel are the major biochemical components of algae biomass. The prototypes which can combine are limited for genetic engineers due to the insufficient data accumulated. Nevertheless, an improved combination of computer design and biological automation is anticipated to shift this model rapidly. For instance, the optimization of terpenoid output in cyanobacteria [75] indicates computational modeling can be used for predicting non-intuitive approaches to optimize metabolic flows through heterologous pathways.

In automation, highly performing bio-foundries which attract grants investment acceptance from research institutions worldwide. This is to create novel biological designs or complex combinatorial libraries that is quickly installed and evaluated [76]. In order to test clone libraries on a scale, strain production should be combined with advanced small molecular detection techniques, such as modern biosensor technology and developments in multi-dimensional phenotyping that are studied in phenomics

Synthetic biology is not limited to the production of existing natural compounds, since the deconstruction of biology into its basic genetic components permits systems to be redesigned free from pre- constraints. An exciting avenue of synthetic biology will be the creation of novel, new-to-nature compounds with potential new functions and applications [77]. Synthetic biology may also be used in order to boost farming results for microalgae production, including photosynthesis enhancement and carbon consumption [78]. For instance, computer-based scenarios were predicted for synthetic redesign of more effectively photosynthetic carbon fixation [79]. In view of these advances, synthetic biology is highly capable of reinventing traditional industries such as fruit, high-value goods and chemicals by this invention it could - minimizes cost and environmental impacts.

## 6. Algae Industry 5.0

### 6.1. The impact of Industry 5.0

Microalgae medications represent a significant development to produce new health goods, which due to their ability to generate nutrients, minerals, trace elements and other bioactive [80]. The microalgae industry with an approximately global net worth of USD 1 – 1.5 billion still has retained their maximum growth ability [81]. The cyanobacteria *Spirulina* sp., the green algae *Chlorella* sp. and *C. reinhardtii* have been well-documented as health supplement and recognized as “generally regarded as safe” (GRAS) compound globally, which is a certification legislated under the United States of Food and Drug Administration. Other certified GRAS species included the green algae *Haematococcus* sp. and *Dunaliella* sp. [82].

Products and goods derived from microalgae can be found in many industrial food markets, for example, bulk proteins, carbohydrates and lipids [83]. Microalgae protein is a promising source for sustainable agricultural production. The majority of the world’s protein intake is currently allocated to higher plants, with vast amounts of arable soil, water and the use of herbicides and fungicides being needed for plants [83]. Due to the improved protein content and desirable amino acid compositions it may be a high-quality protein in human diet, and a nutritious substitute for soy-based protein [84]. Latest research displayed positive performance in terms of changes in physical and chemical properties of the protein blends of *Spirulina* [85].

Many types of microalgae are involved as a source of secondary bioactive metabolites that may intensify diseases and trigger disease effects, such as inflammation or prevent neurodegenerative disorders [85]. The most widely ingested powder is dry algae biomass from GRAS-certified species, and it is now sold as a nutritional substitute that is frequently blended into other products such as mixed beverages [86]. In a variety of clinical studies with certain positive results, powdered food additives have been tested [86]. According to a recent study, both - *Spirulina* sp. and *Chlorella* sp. have clinically shown the ability to positively affect lipid profiles, various immune variables and have antioxidant capacities [86].

Microalgae pigments have an attractive proposition against synthetic pigments with a growing market demand for natural product additives. The extracted pigments are a collection of intrinsically bioactive compounds. They function as radical scavengers and minimize oxidative harm, and thereby known to promote human wellbeing [87]. This is opposed to synthetic pigments, which, while not providing any healthful benefit for them, may pose increasing questions regarding to their toxicity and potential adverse health consequences [87].

### 6.2. Algae revolutionization in Industry 5.0

GHGs generally cause climate change like global warming, although this phenomenon occurs naturally, humans have massively increased the release of GHGs after the IR. As to attaining a low carbon environment, algae could play a crucial part owing to their superb efficient natural carbon capture process system. The electro-optical systems (EOS) bioreactor prototype combined with artificial intelligence (AI) technology for an algae system to reduce carbon emissions, which was initially developed by hypergiant industries. Similarly, the algae biotech company, Helios-NRG, aimed to accelerate this pattern in energy production by utilizing algae. Using tanks of microalgae, Helios-NRG intends to both raise algae output whilst minimizing carbon emissions.

Currently, algae cultivation is feasible as they can be cultured in numerous ecosystems such as reservoirs, rivers, oceans and closed-loop networks. The potential of algae to generate biofuels besides acting as effective carbon capture agent ensuring environmental protection by reducing carbon mitigation and supplying biofuels. Algae revolution is deviated towards achieving the UN’s SDGs which promoting a better living standard for the wellbeing and could be accomplished by the incorporation of science and engineering research.

### 6.3. Environmental impact on Industry 5.0

Large scale of microalgae manufacturing may have multiple environmental impacts in the manufacturing process beyond energy consumption, whereas many may restrict the design and activity of the device. The emissions of nutrients feed the production of toxic algae blooms that have detrimental effects on marine environments. Harmful blooms of algae, which are called eutrophication sometimes, contain toxins that damage fish and other species. These pollutants travel up the food chain and may affect bigger species such as sea-lions, turtles, dolphins, ducks and other animals after being eaten by these living organisms. Even if algae is not harmful, it can adversely affect marine life by blocking the sunlight penetration to the ecosystem, thus, suffocating aquatic living organisms from lowering the oxygen level (hypoxia). On top of that, the production of such air pollutant, such as ground-level ozone, which can be a smog factor, leads to the formation of airborne nitrogen compounds such as nitrogen oxides. Ozone from urban to rural areas will carry wind and atmosphere for several miles. Pollution of the ozone will kill trees and destroy plants and the environment [88].

However, these problems could be possibly avoided with the use of new advance technologies such as green technology that is incorporated with AI, ML and deep learning (DL) applications, which would show promising solutions in maintaining positive environmental impact [89]. Pollution of nutrients (eutrophication) may produce unwanted changes in the structure and operation of the environment. It may have a favorable or detrimental effect on algal aquaculture. If residual nutrients are released into the local aquatic environments in spent cultivation products, negative impacts can occur. In the other side, it could have beneficial consequences if algae growth were introduced into the management of bodies of water already exposed to the availability of excess nutrients. Apart from these, the application of life cycle analysis (LCA) could be utilized to determine the variables that would have impact the energy balance and environmental performance of the entire biodiesel production. This has been proven in a recent study that uses LCA to identify the potential of microalgae as an energy source by comparing first generation biodiesel and oil diesel [90].

Genetic modification is one of the potential choices in the quest for algae that can simultaneously yield high biomass productivity and lipid rates [91]. Molecular genetic applications, including acceleration of sampling, discovery of suitable strains, large-scale production of the modified algae and increased tolerance to high light levels. For instance, algae with herbicide resistance are desired in order to prevent contamination of cultures by wild type organisms. These are some major risks to produce genetically engineered algae. In open pond systems, culture leakage and transfer are unavoidable. In contrast, closed bioreactors appear to be more secured but the scientist [92] comments that as far as containment is concerned, PBRs are only cosmetically different from open ponds and some culture leakage is inevitable.

## 7. Challenges and prospective

Throughout the transition period, emphasis of Industry 5.0 is on the restoration of human hands, brains and intuition in the manufacturing sense, which stresses transformation of factories into smart IoT facilities, which use semantic processing and interconnect systems via cloud servers. Industry 5.0 has the capability that could reconciles humans and machines and seeks ways to operate together in order to increase manufacturing capacity and performance [93]. Implementation of a modern technological development is unpredictable, since its possibility of building, and its likelihood of deconstruction is the product of a specific transition. The IR represents an immense move from the decision-maker towards settling the endless needs conditions, such as collective community commitment and willingness, civic influence, market risk reduction and financial stability.

Virtual testing could be applied to promote sensible choices in areas like optimizing production processes. Within the future, employing a digital illustration of a machine with the associated producing methodologies applied in the manufacturing processes. AI is going to be able to acknowledge whether the work presently being factory-made meets the quality needs. Moreover, it determines the assembly parameters that require being custom-made to ensure that this remains the case throughout the continuous manufacturing processes. As a result, production is formed with even additional reliable, more economical and firms even to be more competitive.

The Internet of Things is connecting devices on the plant floor that was introduced by the Industry 4.0 that works coincidently with Industry 5.0 (which emphasize on the interaction between humans and machines to produce collaborative robots (cobots)) that are integrated with AI and machine learning. Experts state that still there is a lot of facilities need to be implemented to reach to the Industry 5.0, although it is already initiated by observing humans working alongside with machines. Working under connected smart manufacturing plants through using devices integrated with current technology had been ascribed and put into application.

These technologies could be integrated in the microalgae industry to promote and optimize the genetic modification tools that re-engineer the microalgae strains to make it more productive and efficient. This is achieved by the application of the AI and ML concepts to decide the most suitable strain to focus on to alter its genetic sequence that would have a possibility to change the microalgae phenotypic shape which makes it more suitable to work under stress and to adapt in producing more useful by-products with massive quantity with the use of only small amount of microalgae biomass. For instance, these new technologies could easily find a way to produce a more effective and sensitive CRISPER CAS-9 genetic re-engineering modification tool that could use less energy from the environment while processing and to be more eco-friendly to the environment as well as to match with the sustainable development goals guidelines.

The Industry 5.0 could implement cobots that would help in the manufacturing processes like packaging and transferring the products from one place to another. It provides a more civilized digitized society and workers that are adaptable enough to use and implement the new advances in technology into actual work. Hence, the most efficient outcome out of a manufacturing process with almost no harm to relevant parties can be produced.

## 8. Conclusions

Microalgae industry is a large scale industry and provides an alternative and sustainable by-product that shows high interdisciplinary work of microalgae biomass that could interfere in more than one sector. Using the advantages of new technologies that could see after the Industry 5.0 in the microalgae industry would be a great benefit to the environment and to the product quality which would assumingly reflect a better living standard of society. Besides that, applying the new advanced PBR models in microalgae culture is hoped to greatly reduce carbon emissions and even achieve zero carbon releases from industry. Moreover, moving forward to Industry 5.0 also contribute hugely on the algae genetic engineering for modification of strain. The Industry 5.0 also have influence on the algae economy by affecting the algae production due to modified cultivation practices, changing in biofuels need through customization of bioenergy and transforming the market and fulfilling the SDGs.

## CRediT authorship contribution statement

**Omar Ashraf ElFar:** Writing - original draft, Writing - review & editing. **Chih-Kai Chang:** Conceptualization, Writing - review & editing, Visualization. **Hui Yi Leong:** Conceptualization, Writing - review & editing, Visualization. **Angela Paul Peter:** Writing - review & editing, Visualization. **Kit Wayne Chew:** Conceptualization, Writing - review & editing. **Pau Loke Show:** Conceptualization, Project administration, Funding acquisition.

## Declaration of Competing Interest

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

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