Application of Artificial Intelligence in microalgae culture: review

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Abstract
Microalgae has many applications; such as in biofuel production, carbon capture and utilization, and assorted microalgae production due to their high nutrient content, wastewater treatment, and bioremediation that make algae cultivation extremely popular in industries. Microalgae produce a variety of substances with high value-added potential such as health-promoting omega-3 fatty acids, carotenoids with antioxidant effects, pigments or polymeric storage substances. Therefore, they are an excellent sustainable source for the production of food, cosmetics, chemicals, pharmaceuticals and biofuels. Because of economic and ecological aspects, microalgae should be cultivated outdoors and on a large scale, using natural daylight as an energy source. The major challenge is that no robust and proven fully automated control system for the algae reactors has yet been established. This is mainly due to the lack of models that can control the algae growth and product formation in their cells. With the recent acceleration of AI researches, large and complex data from microalgae research can b e properly analyzed by combining the cutting_edge of both fields.The utilization of AI algorithms in microalgae cultivation, system optimization, and other aspects of the supply chain is also discussed. Artificial intelligence is helping set a new world record for producing algae as a reliable and economic source sustainable of biofuel and potentially, animal feed. The aim of this paper is introducing data-based algorithms – generated by machine learning methods – to control the cultivation of algae in order to develop an economical, ecological and robust algae production process on an industrial scale.
Keywords: algae, artificial intelligence, culture.

Introduction

The applications of algae, such as in biofuel production, carbon capture and utilization, and assorted microalgae production due to their high nutrient content, wastewater treatment, and bioremediation, make algae cultivation extremely popular in industries. Various process parameters such as algal characteristics and operating conditions of the process affect the yield and productivity. The operating conditions and feedstock characteristics are directly correlated to the product. For example, bio-oil yield produced is directly related to ultimate and proximate analysis; similarly, wastewater treatment with algae is dependent upon the organic and inorganic content in the water. Therefore, it is essential to optimize these processes to enhance productivity and identify the efficient method for producing high-quality products with minimal wastage. This can be accomplished by using machine learning (ML), one of the most recently developed tools for modeling a process with multiple inputs to predict output accurately without conducting tedious experiments. ML is widely applied in predictive modeling for growth optimization, nutrient recovery, real-time decision support systems, quality control in algal biomass, energy efficiency optimization, and many more. The incorporation of ML is playing a critical role in the evolution of these algae farming applications. This chapter examines the different applications of artificial intelligence (AI) and ML-based algorithms for product enhancement, process optimization, and gaining important insights into algal biotechnology.

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The aim of the paper is introducing different usages of AI in algae culture special data-based algorithms – generated by machine learning methods – to control the cultivation of algae in order to develop an economical, ecological and robust algae production process on an industrial scale.

Application of Machine learning techniques in different methods of algae

Microalgae production can be carried out in two different technologies, namely closed or open reactors. The latter, generally known as raceway reactors, are the most widespread option at the industrial level due to their simpler scalability and lower cost, despite the greater difficulty in controlling their conditions . When using closed photobioreactors the risk of contamination is usually one of the most frequent reasons for failures, and control of contamination in microalgae cultures is a major challenge for large-scale production facilities. Moreover, certification of the quality of biomass being produced is also a significant issue for the development of this industrial sector. In this regard, adequate monitoring methods are not very widespread.Traditionally, the characterization of cultures has been carried out by manual analysis of samples by an expert eye capable of discerning morphological differences between species under an optical microscope. This is a laborious task, whose replacement is desirable given the need for highly skilled workers, the difficulty of the analysis, and the time taken. Alternative methods encompass the analysis of the biomass biochemical composition, which involves assessing the pigment or fatty acid profile. While these approaches provide valuable information, they are time-consuming and primarily confirm the suitability of the biomass composition rather than identifying the specific strain being produced. Furthermore, 'omic' tools capable of completely characterizing the microorganisms present in biological samples have been developed in the last few years. These methods require the extraction of DNA and replication of sequences, and application of bioinformatics to recognize specific sequences corresponding to each microorganism, thus allowing determination of their presence and abundance. However, these methods are still expensive and require a long time, making them unfeasible for continuous monitoring of microalgae cultures at an industrial scale. Thus, having fast and precise methods to characterize microalgae cultures is essential. Machine learning techniques are experiencing a remarkable increase in popularity in recent years, mainly related to the growth of existing computational capacity, combined with the increasing volume of data being processed. These techniques learn directly from data, successfully solving very specific problems without being explicitly programmed to do so, often outperforming humans on some tasks (Mafat *et al.*, 2023; Chong *et al.*, 2023). In the field of microalgae production, these techniques have been used for different purposes. Some authors have developed models for pH prediction based on neural networks or regression trees . While others have obtained models for productivity prediction based on the same techniques. However, the field in which they have found the most use is microalgal classification for culture characterization. Hyperspectral imaging of three species of microalgae has been performed using a support vector machine for its classification, with a minimum accuracy of

94.4% . Others achieved a 97.69% accuracy model using digital holographic microscopy - fully convolutional networks. Salmi et al. trained and validated a convolutional neural network using absorbance spectra, validating the model with monocultures and pairwise cultures, with a minimum accuracy of 95%, while predicting the biomass for the pairwise cultures. Others have developed a convolutional neural network for algal classification with an accuracy higher than 93.9% , or a methodology based on image segmentation, feature extraction, and support vector machine classification . A deep neural network for harmful algal bloom detection combined with an AI-chip-based system has been proposed. Some convolutional neural network and support vector machine models for classification between Cyanobacteria and Chlorophyta have also been proposed, with a minimum accuracy of 99.66%. There is previously developed a study to analyze the viability of applying this type of technique to the problem at hand. Two models for culture classification corresponding to two species from different genera (*Chlorella vulgaris* and *Scenedesmus almeriensis*) were developed, one based on images, and the other on descriptive features of the cells, using *FlowCam* as an acquisition device. In the study, the potential of neural networks for culture characterization and the feasibility of using classification thresholds were demonstrated, and good results were obtained in the characterization of pure samples as well as mixtures. Both images and features proved to be sufficient information to determine the composition of a culture. Based on previous experience, here an artificial neural network (ANN) model has been developed for the characterization of microalgae cultures. The model uses images of the culture acquired using the *FlowCam* device, from which it classifies each detected cell individually, determining the composition of the culture (fig 2). The decision to use images as input is justified by the results of the previous work, in addition to being simpler to obtain than the descriptive features of the cells. According to previous results, in this work, a more advanced tool has been developed with greater utility in the identification of cultures. The developed model extends the classification to 6 different genera of microalgae, having been trained with 9×10^5 cell images. In addition, multiple species have been grouped into each genus, making the model more general and applicable. It is complemented with classification thresholds that improve the accuracy of the model while discarding any organisms that do not correspond to any of the classes, which makes it more appropriate for the characterization of real cultures. The main contribution of this work is the development of a tool for the characterization of microalgae cultures capable of differentiating a relatively large number of genera concerning those classified by other models in the literature, trained with multiple species that give it a great generalization ability, and that uses as input a type of data that can be easily acquired using optical devices and artificial vision techniques. The final accuracy of the model with the test set is 83.43%, and up to 97.27% with classification thresholds (Paul Peter *et al.*, 2023).

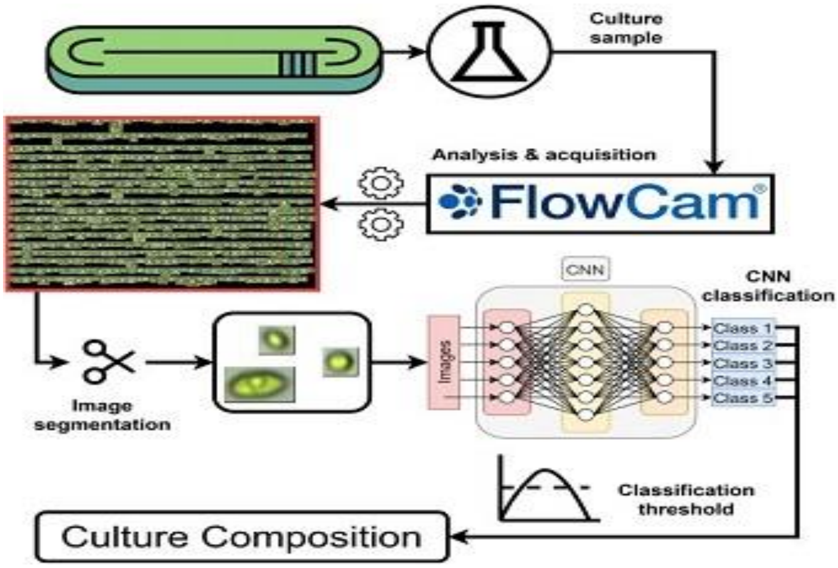

Fig 1: The model uses images of the culture acquired using the FlowCam device.

Industrial revolution has the ability to break down traditional barriers and allow for sustainable growing conditions with quick testing on biomass growth. In previous years, photo-bioreactors are widely investigated on its design structure, in terms of sustainable and economical aspects. With the use of technology, photo-bioreactors would often provide a consistent optimum biomass production by monitoring microalgae development with a variety of linked sensors, altering conditions as necessary, and using machine learning to discover the perfect growth parameters. However, implementation of artificial intelligence able to overcome the tough challenge, by identifying the best time to harvest the algae before it degraded. The current UV– Vis's methods are too tedious, costly and time consuming which prevents stake holders in venturing into large scale algae growth. Hence, this study also includes the application of custom vision service in monitoring the algae growth via image classifiers (Guzmán *et al.*, 2023).

Improving monitoring of algae growth

The most popular method for monitoring the growth of microalgae is the OD (optical density) sensor, which measures the light adsorption, scattering caused by algae cells to calculate the biomass concentration. However, algae cells can change their size, shape and pigment content under different growth conditions, which has a major effect on the accuracy of measurements with the OD sensor. The other challenge in the cultivation of microalgae is the big difference of the growth behavior (Paul Peter *et al.*, 2023).

Modeling of algae growth

Besides monitoring, modeling the growth of microalgae is a cornerstone for improving the productivity of a cultivation. To achieve the highest possible productivity, microalgae should be cultivated with high cell density. However, this also leads to the so-called "self-shading" effect of microalgae, which is very difficult to describe in a model. To overcome this challenge, researchers have simulated the light distribution in the FPA reactor based on the Lambert-Beer law, as shown in Figure 1. This simulation of the light distribution was then used in modeling with the Monod model, which provided a correlation coefficient of 82 percent for the prediction of algae growth in outdoor cultivation. In addition, researchers used a machine learning algorithm called Support Vector Machine (SVM) to predict the algae growth rate with a correlation coefficient of 88 percent. Both SVM and Monod models can then be used to optimize the control of microalgae cultivation. The Monod kinetic model provides a better understanding of algal growth with biological sense, while the SVM model promises a better prediction. Therefore, we will combine the advantages of both methods in our future control system (Oruganti *et al.*, 2023).

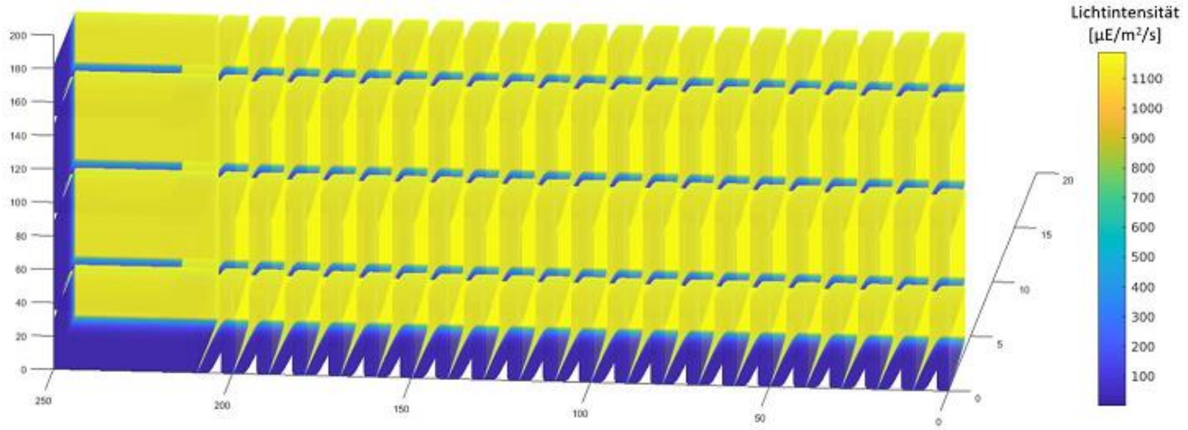

Fig2: Simulation of light distribution in a FPA reactor.

Optimization of the harvesting strategy

Another important aspect for cultivation is to optimize the harvest strategy. In outdoor cultivation, the harvest strategy should be dynamically adapted to the weather conditions. When light intensity is too high, we can increase the cell density in the reactors to protect algae from light inhibition conditions. On the other hand, we can harvest part of the algae biomass at low light intensity, so that all the algae cells will have more light available to growth (Long *et al.*, 2022).

AI to detect harmful algal blooms

In the presence of concentrated nutrient sources, some species of algae can grow exponentially, forming harmful algal blooms (HABs). These blooms can have harmful effects on people, birds, marine mammals, fish, shellfish and other aquatic organisms. In addition, some species that can form HABs also produce toxins.

Blooms occur in marine and freshwater environments throughout the world, with damaging ecological, social, and economic effects. Identifying algae can be slow and labour-intensive. First, water samples are collected in the field and delivered to a lab. Next, an analyst views each sample under a microscope and identifies the species present. Each sample can take more than an hour to analyse and the results can be inconsistent between different analysts. This means it is difficult to get accurate results and to analyse samples from large areas as frequently as desired. To solve these problems, scientist are using machine learning to train computers to automatically detect important types of harmful algae. This involves collecting a large image dataset.then manually annotate the data by drawing bounding polygons around each algae cell. Next, they iteratively train deep neural networks to learn structures and patterns in the data. researchers are building smart machines capable of performing tasks that typically require human experts, such as being able to differentiate between species of algae that look extremely similar (Guzmán *et al.*, 2023).

they are taking thousands of photos of our living algae collection at ANACC and training AI systems to detect and classify different species of harmful algae. Ther arealso developing human-in-the-loop systems that can identify where the machine learning model is not performing well, allowing algae experts to improve the model. Using an efficient human-centered AI approach, coupled with powerful deep neural networks, they are combining the best capabilities of humans and computers to build effective detection systems. A high-tech underwater device that scans water samples for potentially dangerous algae blooms – the first of its type to be deployed in UK waters – has been operational for over a year at a Scottish Sea Farms site in Shetland. The Imaging FlowCytobot (IFCB) uses a combination of lasers and cameras to detect, photograph, and identify phytoplankton species with the aim of alerting fish farm operators of potential harmful algal bloom (HAB) threats. While phytoplankton are a critical part of the ocean ecosystem, some species can cause environmental issues when present in large numbers. Humans eating shellfish that have absorbed these toxic phytoplankton can become ill and blooms can also be fatal to farmed fish. Early warning of such phytoplankton blooms is therefore crucial to the aquaculture industry. Since entering the water in spring 2023, the IFCB has photographed phytoplankton around the clock at 20-minute intervals and has already identified trends in the structure of the phytoplankton community from more than 38 million images. Thanks to funding from the Sustainable Aquaculture Innovation Centre (SAIC), researchers hope the observations made by the device will help them to better understand seasonal trends in harmful phytoplankton blooms. The artificial intelligence developed for the IFCB marks significant progress in the world of phytoplankton taxonomy. Compared to traditional methods, which rely on the expertise of phytoplankton taxonomists and can take days of processing, the IFCB can provide near real-time information to farm-managers. It is notoriously difficult to predict when an algal bloom will occur, given the various environmental factors involved in its formation. The more warning we can give fish and shellfish farmers, the better the chance they have of mitigating the impact.With the IFCB, we have a virtual taxonomist on duty around the clock, identifying potential risks before a scientist has even looked down a microscope. It's already showing us rapid changes over the courses of a day that we've never seen before. Traditional sampling methods use fixatives to preserve the sample for analysis but that can damage the cell. Being able to see live samples shows us the structure of the cell as it's meant to be. Algae cultivation in a controlled environment requires maintaining proper conditions to extend healthy culture growth and life cycles. Terrestrially, relatively large facilities (raceway ponds) cultivate algae. This is not adequate for the integration into spacecraft or buildings due to mass and volume constraints. These large terrestrial systems do not fully utilize artificial intelligence (AI), based on data analysis, to achieve optimal growth. Hypergiant developed a small-scale bioreactor prototype as a commercial and open-source platform, focused on addressing life support systems in space and the growing concern of climate change. This autonomous system is grouped into several design aspects such as mechanical, electronics, sensors, and data monitoring. Sensor clusters collected measurements about the biological and environmental status. Then, AI algorithms utilized these data, such as the concentration of O_2 and CO_2, pH, turbidity, temperature, and optical density to automatically adjust the cultivation environment by cascade control. Algal biofuel is regarded as one of the ultimate solutions for renewable energy, but its commercialization is hindered by growth limitations caused by mutual shading and high harvest costs. Researcgers overcome these challenges by advancing machine learning to inform the design of a semi-continuous algal cultivation (SAC) to sustain optimal cell growth and minimize mutual shading. An aggregation-based sedimentation (ABS) strategy is then designed to achieve low-cost biomass harvesting and economical SAC. The ABS is achieved by engineering a fast-growing strain, *Synechococcus elongatus* UTEX 2973, to produce limonene, which increases cyanobacterial cell surface hydrophobicity and enables efficient cell aggregation and sedimentation. SAC unleashes cyanobacterial growth potential with 0.1 g/L/hour biomass productivity and 0.2 mg/L/hour limonene productivity over a sustained period in photobioreactors. Scaling-up the SAC with an outdoor pond system achieves a biomass yield of 43.3 g/m^2/day, bringing the minimum biomass selling price down to approximately $281 per ton. The researchers developed two machine-learning models. One predicts how, based on the light intensity falling on algae in water and the density of algal cells, light gets scattered and distributed through the cell mass. Unlike previous models, this one predicts light distribution in 3D. The second model predicts how this light availability affects growth rate. By combining the two models, reserchers can calculate the highest algae concentration that does not produce too much shade, allowing algae to grow at maximum speed in changing light conditions (fig 3).

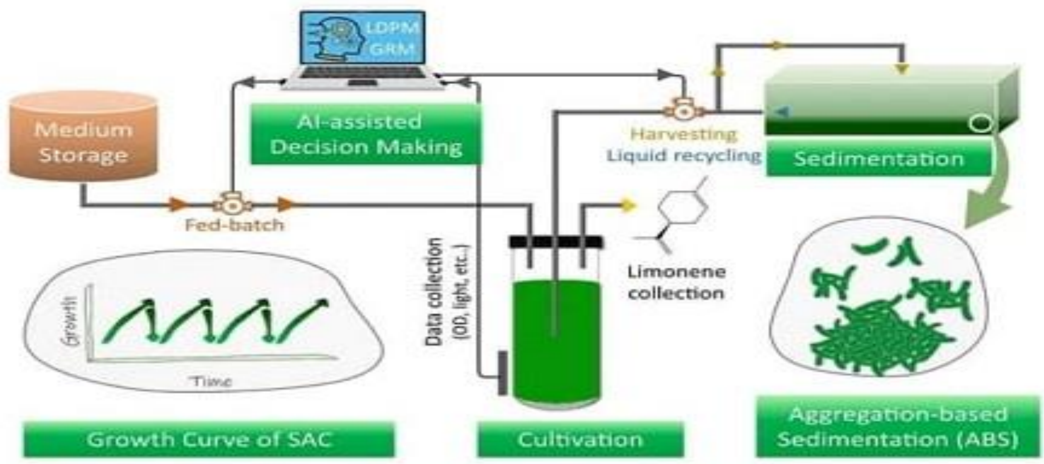

Fig 3: This illustration shows the integration of the machine-learning informed semi-continuous algal cultivation (SAC) and aggregation-based sedimentation (ABS) for biofuel production.

Pigment extraction by AI models

Fucoxanthin is a carotenoid that possesses various beneficial medicinal properties for human well-being. However, the current extraction technologies and quantification techniques are still lacking in terms of cost validation, high energy consumption, long extraction time, and low yield production. To date, artificial intelligence (AI) models can assist and improvise the bottleneck of fucoxanthin extraction and quantification process by establishing new technologies and processes which involve big data, digitalization, and automation for efficiency fucoxanthin production. This review highlights the application of AI models such as artificial neural network (ANN) and adaptive neuro fuzzy inference system (ANFIS), capable of learning patterns and relationships from large datasets, capturing non-linearity, and predicting optimal conditions that significantly impact the fucoxanthin extraction yield. On top of that, combining metaheuristic algorithm such as genetic algorithm (GA) can further improve the parameter space and discovery of optimal conditions of ANN and ANFIS models, which results in high R^2 accuracy ranging from 98.28% to 99.60% after optimization. Besides, AI models such as support vector machine (SVM), convolutional neural networks (CNNs), and ANN have been leveraged for the quantification of fucoxanthin, either computer vision based on color space of images or regression analysis based on statistical data. The findings are reliable when modeling for the concentration of pigments with high R^2 accuracy ranging from 66.0% − 99.2%. This review paper has reviewed the feasibility and potential of AI for the extraction and quantification purposes, which can reduce the cost, accelerate the fucoxanthin yields, and development of fucoxanthin-based products (Lee *et al.*, 2021).

Conclusion

By using new sciences and technologies, creating new models for culture and harvesting, all industries will develope quickly. During this revolution we will reach to accuracy data and managemnent for algae farm and other sections of aquaculture business.

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مروری بر کاربرد هوش مصنوعی در پرورش جلبک

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چکیده

ریزجلبک‌ها کاربرد فراوانی در تولید سوخت زیستی، صنایع مختلفی چون آبزی‌پروری و غذایی، مواد بهداشتی آرایشی، تصفیه فاضلاب... دارند. همچنین ریزجلبک‌ها با هدف استخراج مواد مغذی، اسیدهای چرب، کاروتنوئیدها و سایر ترکیبات زیستی مفید کشت داده می‌شوند. کشت انبوه ریزجلبک‌ها با دو روش سیستم بسته در فتوبیوراکتورها و سیستم باز در استخرها انجام می‌شود. بیشترین چالش برای راکتورها سیستم تمام اتوماتیک کنترل شاخص‌ها و شمارش ریزجلبک‌ها برای سنجش میزان رشد، تولید و شرایط محیط کشت آنها می‌باشد و تا کنون مدل مشخصی برای کنترل تولید وجود ندارد. با توسعه تحقیقات هوش مصنوعی در علوم مختلف، شاهد پیشرفت این علوم در زمینه آبزی‌پروری و پرورش جلبک‌ها می‌باشیم. هوش مصنوعی می‌تواند داده‌های بزرگ و پیچیده در زمینه تحقیقات ریزجلبک‌ها را به درستی با ترکیب کردن جدیدترین روش‌های به روز تجزیه و تحلیل کند. استفاده از الگوریتم‌های هوش مصنوعی در کشت ریزجلبک، بهینه‌سازی سیستم و سایر جنبه‌های زنجیره تامین نیز مورد بحث قرار دارد. هوش مصنوعی به ثبت رکورد جهانی جدید برای تولید جلبک به عنوان یک منبع قابل اعتماد و اقتصادی پایدار از سوخت زیستی و به طور بالقوه خوراک حیوانات کمک خواهد کرد .هدف این مقاله معرفی کاربردهای هوش مصنوعی در صنعت کشت جلبک برای کنترل شرایط پرورش جلبک‌ها به منظور توسعه یک فرآیند تولید جلبک اقتصادی، زیست‌محیطی و قوی در مقیاس صنعتی است.

واژگان کلیدی: جلبک، هوش مصنوعی، پرورش.