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# Design and Development of an Automated Portable Bioreactor for Algae Cultivation with Ageing Analysis

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***Abstract***— ***Algae are booming as promising solution for biofuels, carbon capture process, waste water treatment, dye extraction etc., However, traditional methods of cultivating the same suffers from lack of portability, manual intervention for nutrient supply and monitoring etc., Hence, this paper discusses on the design and development of portable, automated, table top bioreactor that would enable the cultivation of algae in a smart manner. The proposed system involves the design of a table top, closed reactor system of 25 litres capacity with inbuilt provisions for light, aeration and temperature maintenance. The sensors, to monitor key environmental parameters such as light intensity, temperature and pH are integrated and sent to a microcontroller unit. An image capturing mechanism is also integrated and processing of the above is exerted by the microcontroller to indicate the nutrient requirement for the growth of the algae. Depending on the growth prediction, the microcontroller enables the automated delivery of required nutrients. Real time implementation of the same is done and validated in the laboratory. The sensors are coupled with Digilent - Analog Discovery data acquisition module and coupled with microcontroller for automated prediction and nutrient delivery. The entire process and development are validated for the efficacy of algae growth. After the entire process, the extracted third generation bio-oil is aged under multiple stresses to produce a good quality bio-oil.***

***Index Terms— Algae cultivation, portable automated bioreactor, nutrient supply for algae, ageing analysis.***

## I. INTRODUCTION

With the advancement and empowerment of sustainability and clean green technology, efforts have been encouraged to develop alternative options in place of the currently used first and second-generation transformer oil. Despite the widespread of application, mineral oils are faced with disadvantages such as non-biodegradability, high rate of flammability and toxic environmental effects. Thus, biofluids that have greater biodegradability and high flash points. This lowers environmental impacts have proved to be better alternatives [11]. There has been a growing focus and empowerment on using algae as a third-generation source to produce oil owing to their fast growth and lipid accumulation, as well as efficient use gases like carbon dioxide. Unlike the sources of first- and second-generation oils, algae will not conflict with food requirements and can be grown indoors. Due to their potential for biofuels and hydrocarbons generation, algae can serve as an ideal material for producing advanced transformer insulation fluids [4]. However, to maximize biomass production, optimum environmental conditions, such as light intensity, duration, and nutrients, are vital. Research has shown that optimized photobioreactor conditions have improved the productivity of algae [1].

To increment and enhance the efficiency of the cultivation process, several efforts have been made by recent researchers to incorporate sensors into bioreactors for measuring important parameters such as oxygen, temperature, mass produced, etc. Integrating sensors with IOT enabled ESP32 microcontroller helps to measure important parameters such as pH level, nutrient concentration, growth rate, etc. [3]. Furthermore, Internet of Things has been used for large scale sensing and monitoring processes in algae cultivation facilities [5]. Sensing techniques like the usage of CMOS-based sensors for monitoring growth and the use of optical imaging methods are also in trend which helps to increase efficiency and provide more precise and accurate information [6], [7]. One of the most innovative sensing techniques is the impedance-based biosensors that helps in quick measurement of lipid content and other important components in intracellular space without damaging cells and hence can help determine potential oil yield [8]. Apart from cultivation, the most challenging part is how to efficiently extract oil from algae. Traditional methods of extraction involve high energy consumption or the use of harmful chemicals. PEF (Pulsed Electric Field) technique has emerged as a sustainable method for hydrocarbon extraction through electroporation technique [4]. To use bio-oils in transformers, it is necessary to conduct the assessment of aging properties under multiple stresses simultaneously like thermal, electrical, vibrational, oxidative and moisture stress. In relation to vegetable oils, it can be concluded that oxidation is the most significant factor in aging that causes the formation of peroxides, acids and other compounds, which affect dielectric properties of the transformer oil [9]. Moreover, aging due to the joint impact of temperature, moisture, and oxygen reduces transformer service life [10].

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While there is numerous research into the application of vegetable oils and natural esters, there are few publications related to multi-stress aging tests of algae-based transformer oils.

This study describes the development of a portable bioreactor for algae cultivation with simultaneous ageing tests of algae-based transformer oil. It involves the use of a controller based on a Raspberry Pi and ESP32 for management of cultivation processes and real-time monitoring. The bioreactor allows for accelerated aging of the oil sample due to five stresses: electrical, mechanical, thermal, oxidation (interaction with oxygen) and moisture stresses.

The major contributions of this study are: (a) Design and development of an economical, automatic, and portable bioreactor setup, (b) Incorporation of IOT based monitoring and control for improved growth of algae and (c) Comprehensive multi-stress aging evaluation of transformer oil synthesized from algal biomass.

## II. LITERATURE REVIEW

### A. Overview of Existing Work

Inoculation of algae has received considerable attention because of its use in biofuel generation without any harmful effects. Growth of algae is very much influenced by environmental factors like light intensity, duration of light period, temperature and nutritional requirements. It has been found that optimum light and dark periods greatly influence biomass yield in the case of controlled photobioreactor environments [1]. There has also been an attempt made to develop new methods using magnets-controlled photobioreactors [2].

To enhance the ability to monitor and regulate the cultivation process, several sensing and automation methods have been devised. The use of wireless sensors allows for the tracking of biochemical factors like pH and nutrient levels inside the bioreactor [3]. Pulsed electric fields (PEF) are effective in harvesting hydrocarbons efficiently without the use of harmful substances [4]. In addition, the integration of Internet-of-Things (IoT) technologies has made it possible to gather, store and analyse massive amounts of data from industrial algae cultivation systems [5].

Sensing techniques can also be advanced to ensure precise and efficient growth measurement. CMOS sensor-based monitoring devices accurately and promptly identify the growth phase of algae, minimizing the reliability on conventional time-consuming growth measurements [6]. In addition, image processing techniques and optical sensing methods have been employed to calculate and find out the population and biomass density of algae in real-time [7]. The latest technology with regards to impedance biosensing can be applied to quantify biomolecules such as lipids, proteins, and carbohydrates efficiently and without harm to cells. This method is vital in measuring the efficiency of oil production [8].

Another crucial factor that affects the production and efficiency of algal biomass growth is oil harvesting. Traditional methods of oil harvesting employ hazardous chemicals that consumes significant amounts of energy.

When considering the use of bio-based algae derived insulating oils in transformers, it has been found that there is a vast amount of research available in this regard. It has been observed that vegetable oils age due to oxidation, which causes acidification, peroxides and other degrading agents, resulting in poor dielectric behaviour [9]. Moreover, thermal stress, humidity and oxygen play a crucial role in accelerating the degradation process that directly impacts the efficiency and lifespan of the transformers [10]. It has also been reported that natural ester-based oils i.e. the second-generation bio-oils outperform the mineral oils in terms of their dielectric strength and thermal behaviours [11].

### B. Research Gap

Although tremendous and remarkable progress has been made in growing algae, analysing their growth and harvesting oils from them, only few studies have looked into developing these technologies within an integrated automated and mobile platform. Studies that have concentrated solely on optimizing cultivation processes and improve the sensing methods, rather than combining them, dominate more significantly.

While the development of transformer oils from biological origins based on vegetable oils has attracted much attention, there is a scarcity of research done on oils extracted from third-generation algae. Specifically, very little information exists about the aging process of these oils under various stress combinations, which include electrical stress, mechanical stress, thermal stress, oxygen exposure and moisture, basically a multi-stress real time environment.

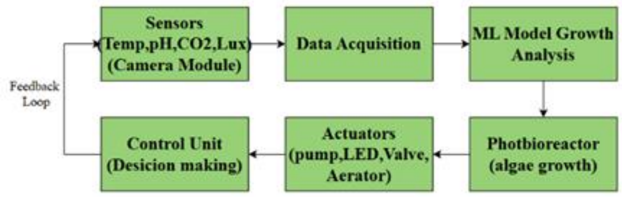
### C. Contribution of This Work

To bridge these gaps, this research work aims at providing:

- A portable automated bioreactor for algae *Chlorella vulgaris* growth
- Real-time monitoring and control of the algae growth
- Production of the third-generation transformer oil from the algal biomass
- The effects of multiple stresses and strains in aging process under:
    - Electrical stress
    - Mechanical stress
    - Thermal stress
    - Oxygen exposure
    - Humidity

## III. METHODOLOGY

### A. System Overview




The suggested topology includes two major processes: (i) automation of algae cultivation in a portable bioreactor and (ii) extraction of third generation bio - oil and its analysis for various stresses on the transformer oil obtained. This process involves algae cultivation, monitoring of various parameters, harvest of the biomass, extraction of the oil and testing of aging properties in various stress environments.

### B. Automated Bioreactor Design

This unique photobioreactor is designed to simulate the real time environment that supports maximum algae development. This system relies on a transparent bioreactor in which all light is evenly distributed. Artificial light (LED) is provided to ensure a controlled photoperiod, while an air pump provides a continuous flow of oxygen throughout the process.

ESP32 is used to control all processes automatically.

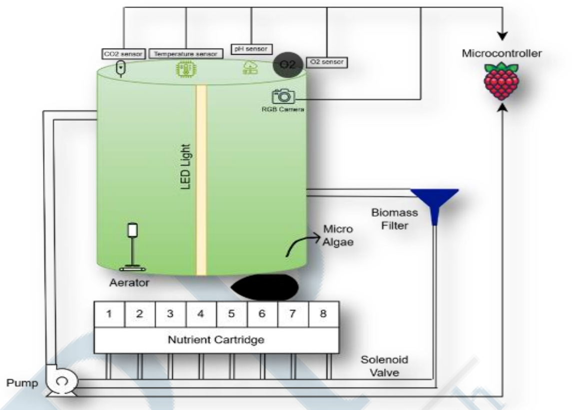



**Figure 1.** Topology of the Bioreactor

The sensors measure the required parameters such as pH levels, temperature and optical density. The sensor information is continuously processed in real-time to assess the current status of the growing algae. On the basis of the sensor output, the lighting, oxygen supply rate and environmental conditions can be adjusted accordingly.

**Table 1:** Sensor Conditions

| Parameter | Minimum value | Optimum Value | Maximum Value | If Exceeds Then Action Taken |
|---|---|---|---|---|
| Temperature | 25°C | 28°C | 30°C | Aerator and water pumps turned on |
| pH | 6.8 | 7.0 | 7.2 | Add Base / Reduce $CO_2$ or Inject $CO_2$ / Add Acid |
| $CO_2$ Level | 20,000 ppm | 25,000 ppm | 30,000 ppm | Increase Aeration / Vent Excess $CO_2$ |
| Dissolved Oxygen (DO) | 5 mg/L | 7 mg/L | 10 mg/L | Increase or decrease Aeration |
| Light Intensity | 3,000 lux | 4,500 lux | 6,000 lux | Increase/Reduce LED Brightness |

### C. Monitoring and Data Aquisition

The real-time monitoring was done integrating sensors that were connected to the ESP32 module. The temperature and humidity sensors were used to monitor the stable temperature, while the pH sensors helped determine the chemical environment of the culture medium. On the contrary side, optical density was used to estimate biomass concentration and growth rate.

The data collected from these devices was recorded using an Analog Discovery 2 Module (DAC). This makes it possible to observe growth patterns. The various stages of growth are, the lag phase, exponential phase and stationary phase. With the help of collected data from the sensors ML prediction models can be built to monitor the growth more accurately.

### D. Biomass Harvesting and Oil Extraction

When algae enter the stationary stage, inoculation occurs inside the bioreactor. Biomass is dried and processed to eliminate all the moisture content present inside. Subsequently, oil extraction occurs through an appropriate technique like mechanical and electrical extraction.

In this research, sophisticated extraction methods, such as pulsed electric field (PEF), are incorporated for enhanced efficiency. This process breaks down cell membranes through the process of electroporation, resulting in efficient extraction of lipids without significant energy and chemical input.

### E. Ageing Analysis of Bio-Transformer Oil

The extracted algae-derived oil is subjected to accelerated ageing analysis in a real-world simulation scenario to evaluate its suitability as a transformer insulating fluid. The ageing process is conducted under five critical stresses:

- **Thermal Stress:** Oil samples are exposed to elevated temperatures (150-300°C) to simulate operating conditions inside transformers.
- **Electrical Stress:** High-voltage conditions (up to 10kv) are applied to evaluate dielectric strength and insulation performance.
- **Mechanical Stress:** Agitation and amplified vibration (100kHz) are introduced to simulate mechanical disturbances.
- **Oxygen Stress:** Exposure to air promotes with the help of oxygen inlet leads to oxidation which results in degradation of oil properties.
- **Moisture Stress:** Controlled moisture levels are introduced with the help of humidifying chamber to analyse the effect of water contamination on insulation characteristics.

**Table 2:** Types of Stresses

| Stress | Minimum | Applied / Experimental | Optimum | If exceeded |
|---|---|---|---|---|
| **Thermal** | ~20°C | 300°C | 160°C | Accelerated oxidation and degradation |
| **Electrical** | 0 kV/cm | 100 kV/cm | 87.5 kV/cm (50 pulses) | >100 pulses → ~99% cell damage |
| **Moisture** | <30 ppm (oil) | 0.5–3% (paper) | ~1–2% (paper) | >3–4% → accelerated hydrolysis |
| **Oxygen** | ~0 ppm (sealed) | 2000–30000 ppm | Controlled low exposure | High $O_2$ → oxidation, acidity >0.1 mg KOH/g |
| **Mechanical** | ~50 Hz | 50–120 Hz | ~50–60 Hz | High amplitude → fibre fatigue & defect formation |

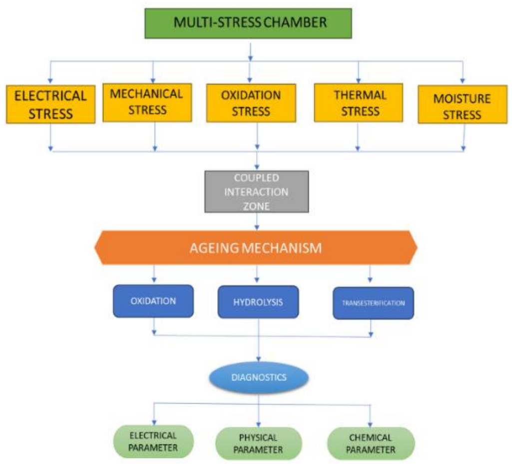



**Figure 2.** Types of Stresses

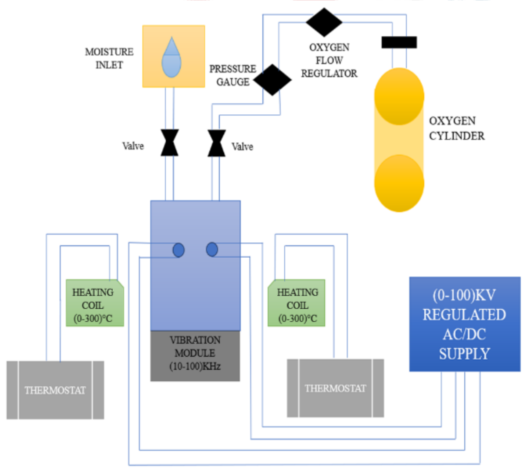



**Figure 3.** Aging Chamber for Multistress Conditions

## F. Performance Evaluation

The quality of the aged oil is determined on the basis of key parameters like dielectric strength, viscosity and acidity. Variations in these parameters determine the aging behaviour of the oil under various stress conditions.

The acquired data through the aging process are compared with other traditional transformer oils to prove whether this third-generation bio-oil can be used as an eco-friendly substitute for traditional oils.

# IV. RESULTS AND DISCUSSIONS

## A. Algae Growth Performance

The automatic controlled bioreactor system maintains favourable conditions for algae growth. Variations in dissolved oxygen with respect to time indicates that the growth behaviour of the organism had three phases, namely initial lag phase, exponential phase and stationary phase. During the exponential phase, there was a substantial increase in dissolved oxygen readings. This output indicates that algae growth took place effectively as a result of proper lighting, aeration, and nutrients.

Continuous observation of the growth process facilitates a better regulation of environmental conditions such as temperature and pH. Ideal growth occurred as a result of optimum photoperiod and aeration.

## B. Sensor Performance and Monitoring Accuracy

The Data acquisition done by the embedded sensing system that is Analog Discovery 2 by DIGILENT (DAC) was very efficient and accurate. The temperature and pH sensors consistently gave stable and desired readings, guaranteeing ideal growing conditions. Optical density was consistent with the anticipated biomass process, indicating the reliability of the system's data acquisition capability.

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### C. Oil Extraction Efficiency

The resulting biomass from the harvest provided bio-oil that was measurable enough for further investigation. The results of the extraction process indicate a successful lipid extraction, thus confirming that algae can be used as raw material for producing bio-transformer oils of third generation.

In terms of future development and advancement, more advanced methods of extraction like pulsed electric field (PEF) are likely to enhance the efficiency of extraction due to higher cell disruption rates and less energy usage. The obtained oil proved to have better characteristics of bio-insulating fluid as compared to first- and second-generation bio-oil.

### D. Oil Yield values:

- Lipid content ~ 20-30% of dry biomass (10g dry algae – (2-3g oil)
- Breakdown Voltage = 50kV
- Flashpoint = 3°C


**Figure 4.** 300ml Chloroform+ 150ml Methanol □ To Dried Algae Powder, Then Heated in Heating Mantle FOR 2 Hours.

**Figure 5.** Crude Bio-Oil Produced

### E. Ageing Characteristics Under Multi-Stress Conditions

The ageing analysis revealed significant changes in oil properties under different stress conditions:

- **Thermal Stress:** Increased temperature leads to accelerated degradation which results in increase in viscosity and acidity content.
- **Electrical Stress:** Dielectric strength shows rapid reduction under prolonged high electrical stress exposure which indicates insulation degradation.
- **Oxygen Stress:** Oxidation resulted in the formation of peroxides and acidic compounds that contributes to chemical instability that affects the rate of reaction.
- **Moisture Stress:** Presence of water significantly reduced dielectric strength and further increased conductivity.
- **Mechanical Stress:** Agitation along with vibrations causes minor structural changes in the bio-oil.

The combined effect of these stresses resulted in more pronounced degradation compared to individual stress conditions, highlighting the importance of multi-stress analysis for realistic transformer applications.

### F. Comparative Analysis with Conventional Transformer Oil

Comparison between the efficiency of bio-oil derived from algae and mineral oil was made based on certain criteria:

- **Biodegradability:** Better biodegradability is achieved in the case of bio-oil.
- **Thermal Stability:** Similarity in terms of thermal stability at moderate temperatures was found.
- **Dielectric Strength:** Slightly lower dielectric strength but still within permissible limits.
- **Oxidation Stability:** More susceptible to oxidation, needs further optimization.

In conclusion, it can be said that bio-oil from algae holds promise for being a sustainable choice, albeit with some room for improvement.

**Figure 6.** Aging Chamber with Inside View

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**Figure 7.** Spherical Rods Inside the Aging Chamber That Will Provide the Pulsed Electric Field

## V. DISCUSSIONS

From these highly better and accurate results, it can be concluded that a combination of the automated bioreactor along with constant real-time monitoring of the algae effectively increases the efficiency of algae cultivation. Controlling the conditions of growing algae enables stable and enriched biomass production.

This system will provide a solution to link the process of bio-oil generation and its utilization in transformer insulation.

## VI. CONCLUSION

From the results we can understand that the suggested approach allowed for controlled cultivation of algae through automated adjustment of temperature, pH, and optical density of the solution by utilizing ESP32-based device.

During accelerated aging test, the oil extracted from the algae was subjected to the following stress factors: thermal, electrical, mechanical, oxidative and moisture stress. It became evident that thermal and oxidative stresses had considerable effect on oil stability causing changes in viscosity, acidity and dielectric properties. Furthermore, moisture was shown to have negative effect on insulating capabilities of oil, however, mechanical stress had a relatively small effect.

Based on comparative analysis, it can be stated that the suggested bio-oil demonstrates high potential as a substitute for traditional transformer oils due to its natural origin. It may also serve as an environmentally friendly alternative, although there still exists an issue related to stabilization.

In conclusion, it can be said that the proposed approach covers all steps from bio-resource creation to testing of transformer oils.

### A. Future Scope

Furthermore, studies can be conducted to increase the oxidation resistance of the third-generation bio- oil by means of adding antioxidants or nanomaterials to the mixture. Improved methods for extracting algae-based oil can also be studied in addition to the genetic modification of algae for better results. In addition, prolonged testing in transformers under real operating conditions using IoT technology can be conducted for further analysis.

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