

## A-GATECH: GREEN INNOVATION OF IOT-PHOTOVOLTAIC MICROALGAE FROM E-WASTE-FOR- CAPTURE CO<sub>2</sub> DECARBONIZATION AND BIODIESEL PRODUCTION SUPPORTING LOW-CARBON ENERGY BUSINESS

Bayu Aji<sup>1</sup>

<sup>1</sup>Industrial Engineering Department, Faculty of Industrial Technology, Universitas Ahmad Dahlan  
e-mail : 2215019264@webmail.uad.ac.id

**Abstract.** Global carbon dioxide (CO<sub>2</sub>) emissions reached 36.8 billion tons in 2023, with industry and transportation contributing more than 65%. In Indonesia, emissions have increased by an average of 3.5% per year, highlighting the urgent need for effective mitigation solutions that also generate economic value. Therefore, this study focuses on the development of A-Gatech (Algae-based Green Technology), an innovation utilizing a tubular photobioreactor made from electronic glass waste (e-waste), powered by solar energy, and equipped with an IoT-based control system. The aim of this research is to design, test, and analyze the performance of A-Gatech in capturing CO<sub>2</sub> while simultaneously producing biodiesel as an economically valuable product. The research steps include a literature review, prototype design, laboratory validation, limited trials, field testing, and technical as well as economic feasibility analysis using the Technology Readiness Level (TRL) approach. Simulation and statistical results show that A-Gatech can capture up to 653 tons of CO<sub>2</sub> per hectare per year with an efficiency of 1.8 kg/m<sup>2</sup>/day, produce up to 198,000 liters of biodiesel per hectare per year valued at approximately IDR 1.98 billion, and reduce electronic waste by around 10 tons annually. Business feasibility analysis indicates that the production break-even point (BEP) can be achieved at 21 units per month, with a profit margin of around 65%. In conclusion, A-Gatech is feasible for implementation as it not only contributes to climate change mitigation but also supports the circular economy and creates green jobs. This innovation is aligned with the Sustainable Development Goals, particularly Goal 7 (Affordable and Clean Energy), Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action).

**Keywords:** circular economy, euglena gracilis, maritime biofuel, waste cooking oil

### INTRODUCTION

Climate change represents an increasingly evident global threat with direct impacts on the sustainability of life, ecosystems, and the world economy (Melo, 2024). Menurut Intergovernmental Panel on Climate Change 2023, According to the Intergovernmental Panel on Climate Change, the increase in average global temperature by 1.1°C since the pre-industrial era has triggered extreme weather events, sea level rise, and a decline in food productivity (IPCC, 2019). Indonesia, as a developing country whose economy remains heavily dependent on fossil energy, faces significant challenges in reducing greenhouse gas (GHG) emissions (Tsandra, 2023). Based on data from the Ministry of National Development Planning, total emissions reached 33 gigatons of CO<sub>2</sub> equivalent, with the energy sector being the largest contributor, accounting for more than 36% of global GHG emissions (Kementerian PPN, 2024). The country has set an emission reduction target of 31.89% through domestic efforts and 43.20% with international support by 2030, as outlined in the Enhanced Nationally Determined Contribution (NDC), which requires the adoption of effective, efficient, and sustainable decarbonization technologies (Perekonomian, 2022).

These challenges are further exacerbated by the decline in national oil reserves, which dropped from 3.77 billion barrels in 2012 to only about 2.25 billion barrels in 2022, leaving a reserve-to-production ratio (R/P) of less than 20 years (ESDM, 2022). On the other hand, the National Energy General Plan (RUEN) projects that national liquid energy demand will increase to 470 million barrels of oil equivalent (BOE) per year by 2050. Such a high dependency on oil imports threatens national energy security and may worsen the trade balance deficit. At the same time, Indonesia is facing a severe environmental challenge in the form of escalating electronic waste (e-waste). According to the United Nations University (2022), e waste in Indonesia reached 2.3 million tons per year in 2023, the highest in ASEAN, with a formal recycling rate of less than 15%. Most of this waste ends up in landfills or open environments, causing heavy metal pollution and posing public health

risks (Paminto, 2024). Pertamina, as the largest state-owned energy enterprise in Indonesia, has committed to achieving Net Zero Emission (NZE) by 2060 through strategies such as decarbonizing operations, developing renewable energy, and applying circular economy principles based on the kaizen approach (Energi, 2023). However, most available carbon capture technologies remain focused on Carbon Capture and Storage (CCS), which require high investment, complex infrastructure, and do not generate direct economic value (Shu, 2023). Therefore, there is an urgent need for Carbon Capture and Utilization (CCU) approaches that not only capture CO<sub>2</sub> but also convert it into value-added products, thereby creating new business opportunities while supporting Pertamina’s energy diversification portfolio.

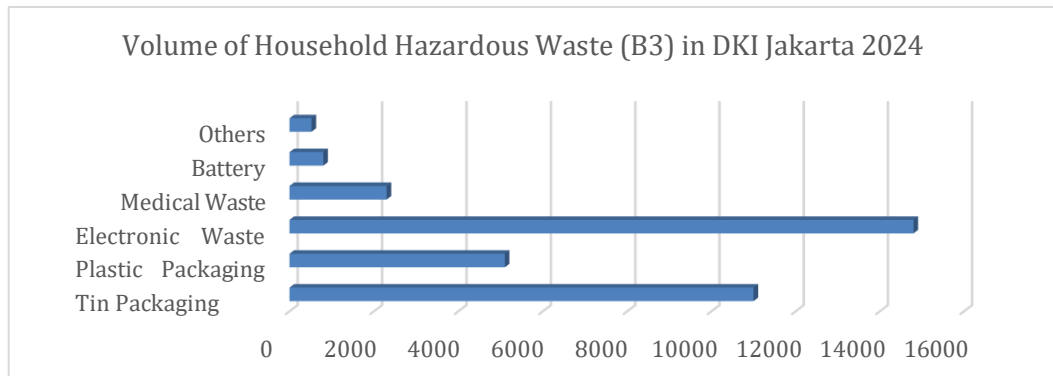
**Table 1.** Bioactive Compounds of Several Microalgae Species

| Source                           | Protein | Carbohydrated | Lipids |
|----------------------------------|---------|---------------|--------|
| <i>Chlorella Vulgaris</i>        | 51-55   | 12-17         | 14-22  |
| <i>Chlorella Pyrenoidosa</i>     | 57      | 26            | 2      |
| <i>Chlamydomonas Reinhardtii</i> | 48      | 17            | 21     |
| <i>Dunaliella Salina</i>         | 39-61   | 14-18         | 14-20  |
| <i>Spirulina Maxima</i>          | 26-63   | 8-14          | 4-9    |
| <i>Spirulina Platensis</i>       | 52      | 15            | 3      |

Source : Mendes et al. (2024)

In this regard, many local potentials based on the blue economy remain underutilized, one of which is microalgae, offering remarkable opportunities due to its multifunctional nature (Chamidah, 2025). According to Table 1, *Chlorella vulgaris* contains high protein levels (51–55%) and a significant lipid content (14–22%), as well as high-value bioactive pigments such as beta-carotene, astaxanthin, and phycocyanin (Mendes, 2024). This compositional diversity opens broad opportunities for the utilization of microalgae across various industrial sectors. In the food sector, microalgae have been applied as nutritional supplements, health beverages, and food fortification ingredients, with the global market projection for spirulina and chlorella expected to reach USD 1.1 billion by 2027 (Su, 2023). In the pharmaceutical and cosmetic sectors, natural pigments from microalgae are utilized as antioxidants, natural colorants, and anti-aging active ingredients, with the global market value estimated to reach USD 3.4 billion by 2025 (Shanaida, 2025). In the animal feed and aquaculture industries, nutrient-rich microalgal biomass can enhance livestock productivity while reducing reliance on imported fishmeal (Ahmad, 2022).

Despite these promising prospects, the most strategic contribution of microalgae in the energy transition era lies in the renewable energy sector, particularly as a feedstock for biofuels (Rial, 2024). Its lipid content can be processed into biodiesel and bio-aviation fuel through transesterification, with oil productivity reaching up to 58,700 liters per hectare per year—far exceeding that of palm oil (5,950 L/ha/year), jatropha (1,892 L/ha/year), and soybean (446 L/ha/year) (Monteiro, 2022). Another advantage of microalgae is its ability to grow on marginal or non-productive land, utilize wastewater or seawater, and act as a carbon-negative resource, where each ton of dry biomass can capture approximately 1.83 tons of CO<sub>2</sub> (Prussi, 2021). Based on interviews with 25 energy and environmental practitioners, 82% of respondents agreed that microalgae-based CCU technology has high implementation potential in large-scale industrial facilities such as oil refineries, power plants, and cement factories, owing to its modularity and adaptability to different emission capacities



**Figure 1.** Volume of Household Hazardous Waste (B3) in DKI Jakarta 2024 (Databoks, 2024)

Based on Figure 1, there is an unfavorable environmental situation in major urban areas of Indonesia, including Jakarta, where electronic waste and carbon emissions have significantly increased as a result of industrial activities and high energy consumption. Statistics indicate that the potential for carbon pollution continues to rise due to the uncontrolled combustion of fossil fuels. This presents a serious challenge, as carbon pollution contributes to climate change, which threatens ecosystems, the economy, and public health. A-Gatech (Algae-Based Carbon Capture Technology) emerges as a concrete solution by integrating carbon capture using immobilized *Chlorella vulgaris* microalgae in a glass tubular photobioreactor, manufactured from recycled glass sourced from e-waste. This system is connected to an IoT-based photovoltaic network, ensuring clean energy supply and real-time monitoring of the process. With a CO<sub>2</sub> absorption capacity of 1.8 kg/m<sup>2</sup>/day, A-Gatech is capable of capturing up to 657 tons of CO<sub>2</sub> per hectare annually, while producing approximately 58,000 liters of biodiesel. At a selling price of IDR 10,000 per liter, this represents a potential gross revenue of IDR 580 million per year, excluding additional carbon credit value estimated at IDR 49–98 million per hectare annually.

Aligned with the national energy sector’s vision, Pertamina acts as a key driver of the energy transition toward Net Zero Emission (NZE) 2060 through programs supporting SDGs 7, 11, 12, and 13, alongside ESG principles. This model provides effective emission mitigation while securing competitive renewable energy, expanding the low-carbon portfolio, and generating green revenue. From the triple bottom line perspective, A-Gatech delivers economic gains through revenue diversification, social value via green jobs and technology transfer, and environmental impact through CO<sub>2</sub> reduction, e-waste utilization, and ecosystem restoration. With its scientific, technical, and economic advantages, A-Gatech strengthens Pertamina’s energy transition strategy and contributes to Indonesia’s climate change mitigation efforts.

## METHODOLOGY

### Implementation stage

The method applied in this implementation is by developing a framework, in which the framework broadly outlines the sequence of activities to be carried out, as illustrated in Figure 2 below.

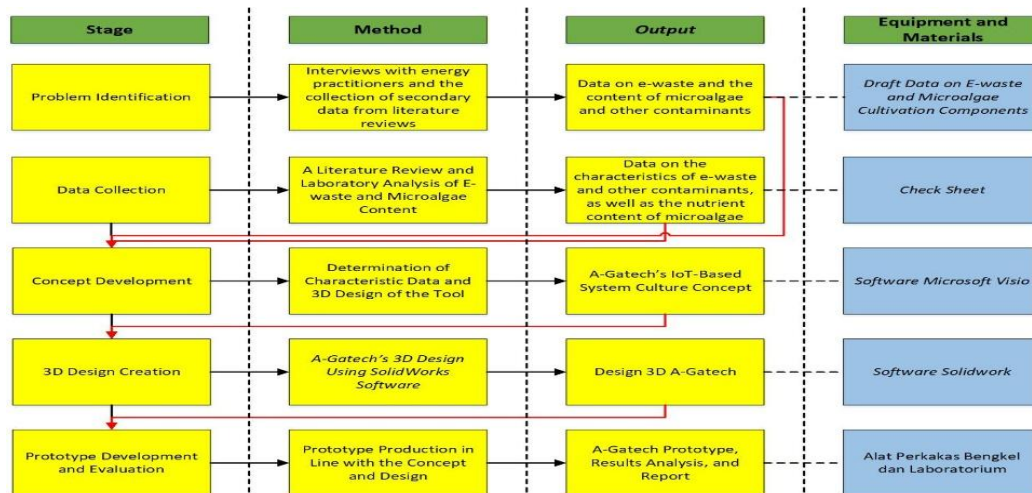


Figure 2. framework-based implementation stage

**a. Problem Identification**

This stage was carried out through a literature review and in-depth interviews with practitioners in the energy, environmental, and chemical industry sectors ( $n = 25$  respondents) to map the key challenges of carbon capture in Indonesia. The findings revealed the high cost of conventional CCS, the low utilization of CO<sub>2</sub>, and the suboptimal management of e-waste.

**b. Data Collection**

Primary data were obtained by measuring the characteristics of glass e-waste from CRT monitors using X-Ray Fluorescence Spectroscopy to ensure the material composition is safe for use in photobioreactors. Secondary data were collected from the Ministry of Environment and Forestry (KLHK), the Ministry of Energy and Mineral Resources (ESDM), and the FAO regarding national CO<sub>2</sub> emissions, microalgae potential, and energy reserves. System energy requirements and biofuel potential were calculated based on laboratory tests of microalgae lipid content using the Bligh & Dyer method (1959).

**c. Concept Development**

The concept development involved creating an initial sketch of the A- Gatech design based on the collected data as a guideline for the 3D design stage, with Microsoft Visio used to visualize the system conceptually. The output was a conceptual design of the filtration unit to be further developed.

**d. 3D Design Creation**

This process ensured that the equipment design met the technical criteria established in the previous stage. The output of this stage was a detailed 3D design prepared for prototype fabrication using SolidWorks 2020.

**Product and Service Development**

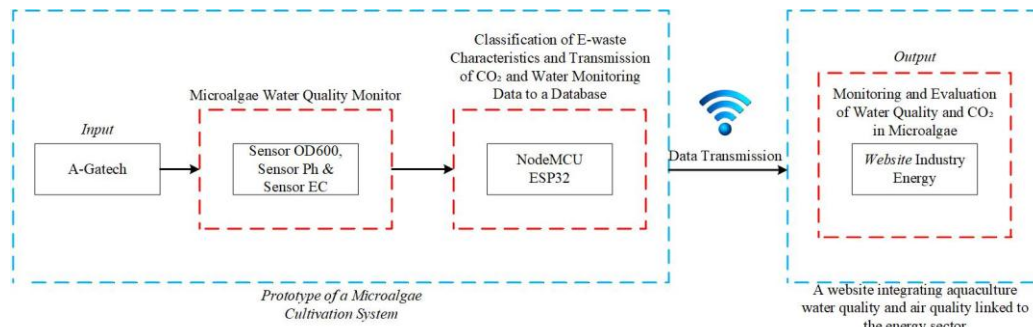
**a. Material Preparation Stage**

Recycled glass was cut and shaped into tubes, then sterilized at 121 °C for 15 minutes. The *Chlorella vulgaris* culture was prepared in an inoculum tank with gentle aeration until it reached a density of  $1 \times 10^7$  cells/mL. In addition, team coordination with third parties was conducted to achieve mutual agreement on the animation design and the development of the functional product.

**b. Tool Manufacturing Stage**

The equipment was manufactured according to established standards. At this stage, the team collaborated with third parties to produce a device that functions in accordance with the specified parameters.

### c. Instrumentation System



**Figure 3.** Real-Time Data Instrumentation System

The instrumentation system shown in Figure 3 was designed to monitor and evaluate aquaculture water quality and CO<sub>2</sub> absorption in real time. Data such as pH and CO<sub>2</sub> levels were measured using pH and EC sensors, then processed by an ESP32 microcontroller programmed to regulate lighting duration, CO<sub>2</sub> flow intensity, and medium circulation. The data were transmitted to the Blynk application, which displayed real-time graphs of microalgae growth, temperature, pH, and light intensity.

### Prototype Development and Evaluation

The prototype was tested for 30 days of operation with artificial CO<sub>2</sub> supply equivalent to refinery exhaust gas concentration (12–15% CO<sub>2</sub>). Microalgae growth was measured every 48 hours using a hemocytometer and a spectrophotometer at 680 nm wavelength. Lipid content was analyzed weekly, while biodiesel extracted from the biomass was tested for calorific value using a bomb calorimeter. CO<sub>2</sub> absorption efficiency was calculated from the difference between inlet and outlet CO<sub>2</sub> concentrations using an infrared gas analyzer.

A review of recent literature highlights that microalgae, particularly *Chlorella vulgaris*, continue to gain attention as a solution for energy diversification and carbon mitigation. Penloglou et al. (2024) emphasized various CO<sub>2</sub> conversion strategies based on microalgae, ranging from the selection of superior strains and advanced photobioreactor design to biorefinery integration and wastewater treatment techniques that underpin the development of A-Gatech as a sustainable CCU system (Penloglou, 2024). Several experimental studies reinforce its practical potential. Research by Krishnamoorthy et al. (2022) demonstrated that *Chlorella vulgaris* can grow in petroleum industry wastewater with biomass yields of 1.69 g/L and lipid content of approximately 21.5%, while simultaneously removing heavy metals and hydrocarbons (Krishnamoorthy, 2022). Meanwhile, pilot-scale tests in open ponds reported lipid productivity of 9.1 mg/L/day, CO<sub>2</sub> absorption efficiency of 63.2 mg/L/day, and biodiesel conversion rates of up to 93.3% through enzymatic transesterification (Liu, 2024).

Lipid enhancement strategies were also revealed by a recent study (2024), where exposure to heavy metal stress such as Co<sup>2+</sup> increased lipid accumulation to 283.3 mg/g CDW, compared to only 153.4 mg/g CDW in the control group (Saber, 2024). Other culture optimization methods, such as increasing light intensity and inoculum concentration, achieved lipid contents of up to 51.2% of dry weight and lipid productivity of 137.8 mg/L/day (Barua, 2021). Nevertheless, not all aspects of microalgal carbon capture are environmentally beneficial. A critical review in *Bioresource Technology* (2023) pointed out that the high energy demand during cultivation and processing may turn microalgae into a carbon source rather than a sink. Therefore, mitigation measures such as renewable energy use and cost-effective nutrients are essential to reduce indirect emissions (Politaeva, 2023). From a system design perspective, tubular photobioreactors remain the mainstream option. Their characteristics allow for high control, production of high-quality biomass, and efficient downstream processing commonly applied for the production of carotenoids or dietary supplements from *Chlorella vulgaris* (Bradley, 2023). Finally, digital transformation is increasingly influencing agriculture and bioenergy. Recent studies indicate the potential of IoT integration, particularly low-power photovoltaic systems, to support sensor devices (Nath, 2024). A comparison of previous studies is presented in detail in Table 2 below.

**Table 2.** Comparison with Previous Research

| Researcher                  | Research Focus  | Findings  | Limitations   | Triple Bottom Line Aspect |        |              |
|-----------------------------|---|---|---|---------------------------|--------|--------------|
|                             |   |   |   | Economic                  | Social | Enviromental |
| Penloglou et al. (2024)     | Algae-base CO <sub>2</sub> conversion strategies, biorefinery, and waste processing | Strain optimization, PB design, waste integration                                     | Does not address e- waste & renewable energy        | ✓                         | ✓      | ✓            |
| Krishnamoorthy et al (2022) | Utilization of <i>Chlorella vulgaris</i> in petroleum industry wastewater           | Biomass 1.69 g/L; lipids 21.5%; heavy metal removal                                   | Does not examine direct CO <sub>2</sub> utilization | ✓                         | -      | ✓            |
| Liu et al. (2024)           | Open-pond microalgae cultivation for biodiesel                                      | Lipids 9.1 mg/L/day; CO <sub>2</sub> uptake 63.2 mg/L/day; biodiesel conversion 93.3% | Susceptible to contamination and weather            | ✓                         | ✓      | ✓            |
| Saber et al. (2024)         | Lipid enhancement via heavy metal stress  | Lipids 283.3 mg/g CDW control 153.4 mg/g  | Heavy metal waste requires treatment                | ✓                         | -      | ✓            |
| Barua et al. (2024)         | Light & inoculum optimization for lipids  | Lipids 51.2% dry weight; productivity 137.8 mg/L/day                                  | No renewable energy integration                     | ✓                         | -      | ✓            |
| Bradley et al. (2023)       | Microalgae LCA  | Identification of indirect emissions  | High energy consumption                             | ✓                         | -      | ✓            |
| This study (2025)           | Tubular PBR design from e- waste and IoT  | High biomass production efficiency  | High borosilicate tube cost                         | ✓                         | ✓      | ✓            |

## RESULTS AND DISCUSSION

Based on simulation and projection calculations presented in Table 3. A-Gatech technology demonstrates significant potential for capturing carbon dioxide emissions while simultaneously producing renewable energy from microalgae.

**Table 3.** Simulation of A-Gatech Implementation Calculations

| Parameter                             | Value         | Unit                      | Description                                |
|---------------------------------------|---------------|---------------------------|--|
| CO <sub>2</sub> Absorption Efficiency | 1,8           | Kg/m <sup>2</sup> /Day    | According to literature                    |
| Absorption Capacity per Hectare       | 653           | Ton CO <sub>2</sub> /Year | Industrial scale                           |
| Dry Biomass Productivity              | 120           | Ton/ha/Year               | After 30 days of culture                   |
| Lipid Content                         | 40-45         | % dry weight              | Bligh & Dryer method                       |
| Biodiesel Production                  | ±198.000      | Liter/ha/Year             | Maximum potential                          |
| Biodiesel Calorific Value             | 37-39         | Mj/kg                     | Bomb calorimeter test results              |
| Potential Biodiesel Revenue           | IDR 1,98      | Billion/ha/Year           | Selling price IDR 10,000/liter             |
| E-waste Reduction                     | ±10           | Ton/Year                  | Utilization of CRT & neon lamp glass tubes |
| Potential Carbon Credit Revenue       | IDR 49-98     | Juta/ha/Year              | Price USD 5–10/ton CO <sub>2</sub>         |
| Production Break-Even Point           | 21            | Units/Month               | Production cost vs. selling price          |
| Production Cost per Unit              | IDR 1.763.000 | Rupiah                    | Prototype scale 30 units/month             |
| A-Gatech Selling Price                | IDR 2.199.000 | Rupiah                    | Profit margin ±65%                         |

## Duscussion

### Significance of Carbon Capture Performance

A-Gatech employs a closed tubular photobioreactor (PBR) as the “core” of CO<sub>2</sub> capture. The reported absorption capacities 653 and 657 tons CO<sub>2</sub>/ha/year represent complementary design and operational scenarios (conservative vs. optimum), both industrially relevant. Such high capacity makes A-Gatech promising for downstream applications at refineries, coal power plants, and cement factories, where CO<sub>2</sub> can be directly utilized as a photosynthetic substrate. Another advantage lies in energy self-sufficiency and real-time monitoring through PV + IoT integration, reducing indirect emissions and operational costs. Online sensing of pH, temperature, light intensity, and EC minimizes process deviation and facilitates early troubleshooting.

### **Biomass Conversion for Bioenergy**

Biodiesel production is projected in two scenarios: 58,000 L/ha/year (conservative) and 198,000 L/ha/year (intensive). At IDR 10,000 per liter, revenues are estimated at IDR 580 million/ha/year for the conservative scenario and up to IDR 1.98 billion/ha/year for the intensive case. Additionally, carbon credits contribute IDR 49–98 million/ha/year, ensuring that the business model is not solely dependent on biofuel sales. This combination of product revenue and environmental service revenue makes A-Gatech’s CCU model economically viable.

### **Manufacture Aspect, Cost, dan Business Feasibility**

On the production side, manufacturing 30 units/month results in a unit cost of IDR 1,763,888 and a selling price of IDR 2,199,000. The break-even point (BEP) is calculated at 21 units/month, indicating that planned production already surpasses BEP, enabling positive cash flow to support after-sales, services, and market development. For the first year, total program costs of IDR 635 million cover direct materials (e-waste glass, IoT, PV, etc.), labor, and overhead, offering transparency on investment scale for initial rollout.

### **Validation and Test Plan**

A 30-day test plan using synthetic flue gas (12–15% CO<sub>2</sub>) and instrumented validation (hemocytometer, OD680, IR gas analyzer, bomb calorimeter, lipid analysis) follows a robust pipeline: process parameters → biomass → lipids → biodiesel (calorific value). Such chain-of-custody data reduces scale-up uncertainty.

### **Triple Bottom Line Aspect**

A-Gatech simultaneously addresses CO<sub>2</sub> emissions and e-waste, targeting 10 tons/year reduction of electronic waste through the reuse of CRT and fluorescent glass as PBR tubes. This supports the circular economy while creating green jobs and technology transfer. The research highlights the triple bottom line economic, social, and environmental as a rationale for implementation.

### **Implementation Readiness & Governance**

The partnership framework local government, research institutions, renewable energy companies, local communities, and financing bodies and development timeline validation and commercialization 12 prototype + 3 months go-to-market reflect realistic governance for deployment in high-emission areas.

### **Performance Indicators**

The key performance indicators of A-Gatech highlight its technical, environmental, and economic potential. The system demonstrates high CO<sub>2</sub> capture efficiency, reaching approximately 653–657 tons per hectare per year, supported by traceable operational metrics. In addition, A-Gatech provides dual benefits by simultaneously contributing to emission mitigation and generating economic value through biodiesel production and carbon credit opportunities, thereby transforming carbon capture and utilization (CCU) from a cost center into a potential revenue stream. From a circular economy perspective, the technology utilizes approximately 10 tons of electronic waste per year, reducing environmental footprint while lowering material costs. The integration of photovoltaic energy and IoT-based monitoring also enables energy self-sufficiency and real-time control, which helps reduce indirect emissions and operational expenditures (OPEX). Furthermore, business feasibility analysis indicates a break-even point (BEP) of 21 units per month, providing

a viable pathway for production scale-up. The technology also demonstrates a strong level of implementation readiness, supported by a 30-day prototype testing plan, collaboration with strategic partners, and a structured adoption roadmap spanning 12 months of validation followed by 3 months of commercialization preparation.

**Key Risks and Mitigation Strategies**

Challenges include high upfront investment, sustained e-waste supply, and low public awareness. Mitigation strategies include leasing models to reduce financial barriers, public education and demonstration for acceptance, and partnerships with waste managers to secure recycled glass feedstock.

**A-Gatech Concept Idea**

The A-Gatech concept integrates three main components: closed tubular PBRs, e-waste glass as reactor structure, and PV + IoT integration for power and control. With projected absoIDRtion of 653 tons CO<sub>2</sub>/ha/year and biodiesel yields up to 198,000 L/ha/year, A-Gatech enables climate mitigation (CO<sub>2</sub> sequestration), fossil fuel substitution, and economic value creation. For Pertamina, this positions the technology as CCU that generates revenue rather than mere compliance cost.

**A-Gatech Innovation Concept**

In the development of A-Gatech (Algae-Based Carbon Capture Technology), various technologies and multi-sensors are used to support the microalgae-based decarbonization process. The details of the innovations offered are as follows:

1. Glass Tubular Photobioreactor utilizing glass tubes from neon lamp waste as microalgae culture vessels that absorb CO<sub>2</sub> through photosynthesis.
2. Artificial Light to ensure photosynthesis runs optimally, especially under conditions of low natural lighting.
3. IoT-Based Monitoring for real-time monitoring of parameters such as pH, temperature, light intensity, and Electric Conductivity (EC).
4. Electric Pump and Electric Turbine to drive water and algae circulation using solar energy, while utilizing the flow to generate additional energy sustainably.
5. Dual Axis Solar Tracker to optimize solar energy absoIDRtion using LDR (Light Dependent Resistor) sensors to adjust the position of solar panels.
6. Photovoltaics to provide independent energy for the entire system, supporting green energy sustainability.
7. Multi-Sensor for Environmental Quality to ensure system efficiency by monitoring time and environmental parameters in real-time.
8. Web-Based IoT Application to enable remote monitoring and system control using smart devices

**Formulation of SMART Development Targets**

The formulation of development targets is described using the SMART principle (Specific, Measurable, Acceptable, Realistic, Time-bound). SMART development targets can be seen in Table 4

**Table 4.** Formulation of SMART Principle Targets

| <i>Spesific</i>   | <i>Measurable</i>   | <i>Acceptable</i>  | <i>Realistic</i>  | <i>Time-Bound</i>   |
|---|---|--|---|---|
| Developing a Glass Tubular Photobioreactor based on used neon lamp waste capable of facilitating CO <sub>2</sub> absoIDRtion using <i>Chlorel vulgaris</i> integrated with IoT. | Increasing carbon absoIDRtion efficiency up to 1.8 kilograms of CO <sub>2</sub> per liter of microalgae culture per day, while reducing electronic waste by 10 tons per year. | The technology is accepted by user communities, including local governments, industry sectors, and academia, due to its cost effectiveness and environmental friendliness. | Utilizing 10% of used neon lamp waste in Indonesia, with the initial implementation scale focused on urban areas with high emission levels. | The TRL approach ranges from TRL 1–7 for concept development to limited-scale testing, TRL 8 for industrial-scale feasibility testing, and TRL 9 for full implementation and commercialization. |

### Extended Impacts of A-Gatech Concep

The expected further impact is the reduction of electronic waste and improvement of air quality in high-mobility urban areas. The extended impact is explained in Figure 4 as follows:

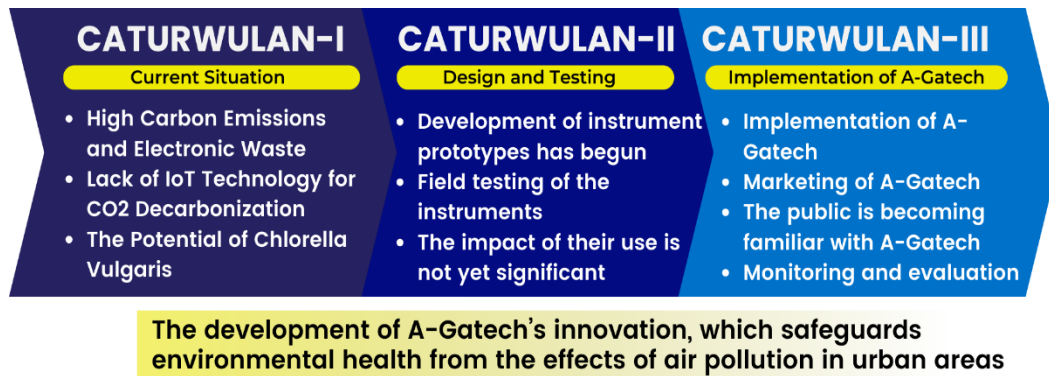


Figure 4. A-Gatech Extended Impacts

### Possible Approaches to Achieve Targets

A SWOT analysis was conducted to identify internal and external factors influencing target achievement see Figure 5.

|          |             | STRENGTH   | WEAKNESS   |
|----------|-------------|--|--|
| INTERNAL | OPPORTUNITY | <ul style="list-style-type: none"> <li>Using electronic waste to reduce CO2 emissions and support SDGs 11 and 13</li> <li>Real-time, automated multi-sensor monitoring</li> <li>Energy efficiency to optimize renewable energy</li> <li>Multifunctional: CO2 capture, microalgae derivatives</li> <li>Creating green business opportunities with economic value</li> </ul> | <ul style="list-style-type: none"> <li>Requires a significant initial investment</li> <li>Depends on the availability of electronic waste, which varies</li> <li>Requires specialized expertise and trained personnel</li> <li>Requires government permits or compliance with environmental standards</li> </ul> |
|          | TREATH      | <ul style="list-style-type: none"> <li>Microalgae-based photobioreactor technology remains distinct from other methods such as ORP</li> <li>Lack of public and industry understanding of the benefits of A-Gatech technology</li> <li>Ever-changing government policies regarding electronic waste treatment or EBT reduction</li> </ul>                                   | <ul style="list-style-type: none"> <li>Securing research grants and CSR funding to reduce production costs and develop alternative materials for tubular glass</li> <li>Providing a simple and portable version to boost adoption in the household and SME markets</li> </ul>                                    |
|          |             | S - O  | W - O  |
|          |             | S - T  | W - T  |

Figure 5. A-Gatech SWOT Analysis of Internal & External Factors

Based on the SWOT analysis results, the supporting factors in the development of the A-Gatech instrument include the utilization of electronic waste as the main material, energy efficiency through renewable energy optimization, as well as regulatory support and global trends toward decarbonization. These opportunities are utilized by accelerating technology adoption through government funding, collaboration with academia, and the development of attractive business models for the green industry.

On the other hand, inhibiting factors that need to be addressed include high initial investment, limited raw materials, and low public understanding of this technology. Therefore, strategies that can be implemented include developing a leasing system to reduce financial barriers, increasing public education through product demonstrations, and cooperating with waste managers to ensure a sustainable supply of raw materials. With approach, A-Gatech is expected to achieve broader implementation targets to effective carbon emission reduction.

### Cost Benefit and Time Considerations

In the design of this innovation tool, cost–benefit analysis and budget justification have been carefully considered to ensure the economic feasibility of the A-Gatech system. The calculation of production costs and the break-even point (BEP) analysis demonstrate that the innovation can be developed with relatively low investment while providing promising financial returns. In the design of the A-Gatech Smart Culture System with a production capacity of 30 units per month, a total production cost of IDR 52,916,000 is required, with a contribution margin of IDR 1,421,222 and a break-even point of 21 units per month, equivalent to IDR 45,773,102. The production cost for a single unit is estimated at IDR 1,763,000 with a selling price of IDR 2,199,000, resulting in a profit margin of approximately 65% of the unit production cost. At this price, urban environmental managers obtain a complete A-Gatech system package, including the equipment set, tool manual, program code manual, a compact disk containing instructional videos and explanations, and access to the A-Gatech website. The development timeline of the tool is estimated to span approximately three years, beginning from the initial design concept, environmental needs observation, experimentation and testing, evaluation of tool performance, and continuing to the commercialization stage. During the design and testing phases, collaboration with several government stakeholders will be conducted to support the implementation process. Furthermore, the commercialization and dissemination of this innovation to the public are planned within three months through promotional media and advertising. Within three years after commercialization, the broader impacts of A-Gatech implementation are expected to be realized, including reducing the negative effects of waste and producing useful products for agriculture and the environment.

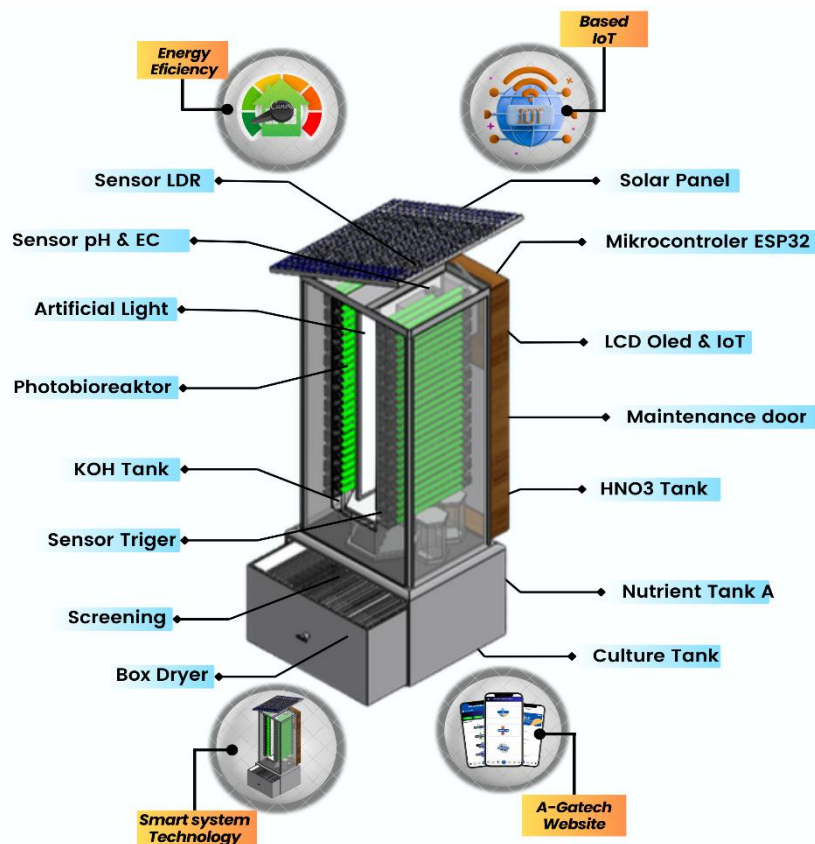
### A-Gatech Design Analysis

A-Gatech was developed using NASA’s 2003 TRL approach to ensure measurable, tested, and independently audited progress from concept to implementation, as outlined in Figure 6.

| TRL Stage | Main Activities  | Time Target | Output   |
|-----------|--|-------------|--|
| TRL 1-2   | Observation of fundamental principles, literature review, formulation A-Gatech concept based on PBR tubular technology from e-waste        | Month 1-2   | Concept and initial design documents   |
| TRL 3     | Preliminary analytical tests and design simulations (CFD, SolidWorks, calculations of CO <sub>2</sub> absorption and biodiesel production) | Month 3-4   | Technical simulation data, 3D designs  |
| TRL 4     | Validation of core components in the laboratory (e-waste glass tubes, IoT sensors, mini solar panels, 10-20 L microalgae cultures)         | Month 5-6   | Lab-scale component prototype  |
| TRL 5     | The integration of components → the A-Gatech breadboard system was tested in a relevant environment (the campus PV mini-plant)             | Month 7-8   | Limited-scale integrated prototype   |
| TRL 6     | Demonstration of a medium-scale prototype (50-100 L culture) in a relevant environment (artificial CO <sub>2</sub> emissions of 12-15%)    | Month 9-10  | Data on CO <sub>2</sub> sequestration, biomass production and biodiesel production |
| TRL 7     | Full-scale prototype demonstration (1-5 m <sup>2</sup> /1000 L) in a semi-industrial setting   | Month 11-12 | Field-scale performance validation   |
| TRL 8     | Field testing with industry partners (refineries/coal-fired power stations) → “system qualified”   | Years to-2  | Industry performance data, feasibility reports                                     |
| TRL 9     | Large-scale system implementation at partner sites, ongoing operations   | Years to-3  | “Flight-proven” system & ready for commercialisation                               |

**Figure 6.** Development Stages Using the TRL Method

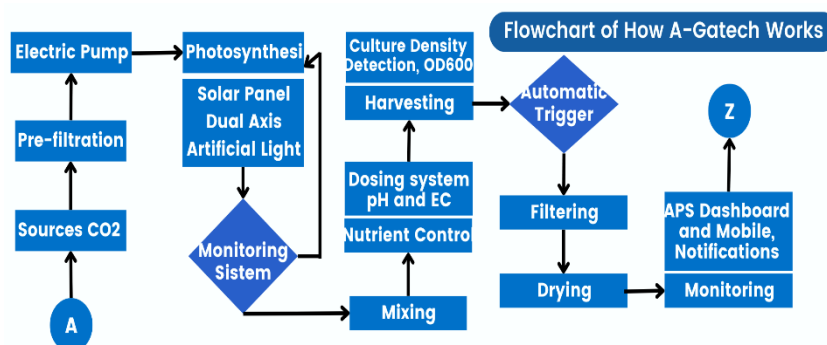
The A-Gatech tool is based on the Internet of Things and connected to a website, allowing remote monitoring without risk to operators and surrounding communities. A-Gatech is designed with dimensions of 90 cm × 70 cm × 203 cm, taking into account human ergonomics in the initial design using SolidWorks 2020 software. The placement of A-Gatech components is carried out with various considerations including pH & EC sensors as well as OD600 to regulate the quality standards of biodiesel produced from microalgae cultivation. The tool components can be seen in Figure 7.



**Figure 7.** 3D Design and A-Gatech Components

Air pollution and electronic waste caused by high mobility are significant environmental problems because they can contaminate air and groundwater if not properly managed. Therefore, the development of an effective system to absorb CO<sub>2</sub> into O<sub>2</sub> is very important. A-Gatech is an innovative solution to manage electronic waste into a valuable product, namely as a glass tubular PBR, utilizing a closed culture system and IoT connectivity. Although it has challenges and risks, the environmental and economic benefits expected from this project are substantial.

### Operational Analysis of the Concept



**Figure 8.** A-Gatech Operational Analysis

In general, A-Gatech is divided into several main parts consisting of CO<sub>2</sub> absorption and distribution, microalgae photosynthesis, nutrient control, automatic harvesting, and IoT-based monitoring. This process begins with the absorption of CO<sub>2</sub> from free air or industrial emissions, where carbon dioxide gas first passes through a preliminary filtration system to filter out impurities before being pumped using an electric pump into the Glass Tubular Photobioreactor (PBR). Next, microalgae photosynthesis occurs in the PBR with the support of dual-axis solar panels that optimize natural lighting as well as artificial light (IoT-based LED) activated during low light intensity. The system is equipped with IoT-based monitoring that tracks important parameters such as pH, temperature, light intensity, and CO<sub>2</sub> levels, ensuring the environment remains optimal for the growth of *Chlorella vulgaris*. To ensure microalgae obtain sufficient nutrients, the automatic dosing system adds nutrients A, B, HNO<sub>3</sub>, and KOH, while pH and EC (Electric Conductivity) sensors maintain nutrient balance.

Automatic water pumps mix the culture for uniform growth. When microalgae reach optimal density, the OD600 sensor triggers automatic harvesting. The system filters and dries the biomass for bioenergy, fertilizer, or animal feed. Controlled via an IoT dashboard and mobile app, it allows real-time monitoring and alerts. A-Gatech thus captures CO<sub>2</sub> and converts it into valuable biomass, promoting decarbonization and sustainability through renewable energy and efficient automation.

### Work Plan Schedule

In planning this research to be properly implemented, a work schedule has been created, as shown in Table 6.

**Table 6.** Work Plan Schedule

| Stage | Activity Development Product  | Month- |   |   |   |   |   |   |   |   |    |    |    | Years-2 | Years-3 |                                 |
|-------|---|--------|---|---|---|---|---|---|---|---|----|----|----|---------|---------|---------------------------------|
|       |   | 1      | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |         |         |                                 |
| TKT 1 | Research and Introduction<br><i>Brainstorming</i> for Device Development  | █      | █ |   |   |   |   |   |   |   |    |    |    |         |         |                                 |
| TKT 2 | Environmental Observation<br>Review Existing Innovation Literature  |        | █ | █ |   |   |   |   |   |   |    |    |    |         |         |                                 |
| TKT 3 | <i>Focus Group Discussion</i>   |        |   | █ | █ |   |   |   |   |   |    |    |    |         |         |                                 |
| TKT 4 | Development of Conceptual Framework<br>Device Fabrication Experiment  |        |   |   | █ | █ |   |   |   |   |    |    |    |         |         |                                 |
| TKT 5 | Limited-Scale Testing   |        |   |   |   | █ | █ |   |   |   |    |    |    |         |         |                                 |
| TKT 6 | Device Error Correction<br>Retesting  |        |   |   |   |   | █ | █ |   |   |    |    |    |         |         |                                 |
| TKT 7 | Large-Scale Testing<br>Deficiency Analysis  |        |   |   |   |   |   | █ | █ |   |    |    |    |         |         |                                 |
| TKT 8 | Improvements<br>Large-Scale Re-Test<br>Final Refinement   |        |   |   |   |   |   |   | █ | █ |    |    |    |         |         |                                 |
| TKT 9 | Commercialization<br>Dissemination to Stakeholders/Partners<br>Device Usage Training<br>Monitoring and Evaluation of Device |        |   |   |   |   |   |   |   |   |    |    |    | █       | █       | █                               |
|       |   |        |   |   |   |   |   |   |   |   |    |    |    |         |         | Every 3 months after monitoring |

### Key Partners (Stakeholders) in the Development Program

In the program, collaboration with partners is essential for developing and utilizing the innovation, with their roles detailed in Table 9.

**Table 9.** Program Collaboration Partners

| No | Partner Type  | Description  |
|----|---|--|
| 1. | Local Government Environmental and Agriculture Departments                | Responsible for regulations and permits for developing infrastructure and operational activities of the A-Gatech program at specific locations.  |
| 2. | Environmental Research Institutions and Environmental Management Agencies | Validate the effectiveness of the new technology used and provide guidance to ensure the program is sustainable and has a positive environmental impact.   |
| 3. | Technology Industry   | Collaboration with the technology industry ensures the availability of necessary equipment and technical support.  |
| 4. | Renewable Energy Companies  | Renewable energy companies, especially those involved in developing and installing solar cell systems, support the program by providing clean energy solutions for water filtration system operations.                       |
| 5. | Local Communities   | Involving the community in planning, implementation, and monitoring ensures strong public acceptance and support.  |
| 6. | End Users in Energy and Other Sectors                                     | End users of the program's final products, such as biodiesel from cultivation, particularly in the energy sector, play a key role in providing feedback and validating the quality and effectiveness of the produced energy. |
| 7. | Financial and Investment Institutions                                     | Provide funding for the development and implementation of the A-Gatech program. They can also advise on financial models and investment strategies to ensure the program's long-term sustainability.                         |
| 8. | Media and Communication   | Disseminate information about the A-Gatech program to the wider public and help raise awareness of environmental and sustainability issues highlighted by the program.   |

## CONCLUSIONS AND SUGGESTION

### Conclusions

Based on research results and discussion, it can be concluded that A-Gatech is a green technology innovation effective in capturing carbon dioxide while simultaneously generating economic value through biodiesel. The tubular photobioreactor system made of electronic waste glass with solar energy and IoT support has been proven to achieve an absorption capacity of up to 653 tons CO<sub>2</sub>/ha/year and biodiesel production of up to 198,000 L/ha/year. This demonstrates alignment with research expectations emphasizing efficiency, sustainability, and circular economy implementation.

Furthermore, business feasibility analysis with a production break-even point of 21 units per month and a profit margin of around 65% shows that A-Gatech is not only technically feasible but also has high economic prospects. Thus, A-Gatech has the potential to become an alternative solution to support the 2060 Net Zero Emission target and the implementation of Sustainable Development Goals (SDGs), particularly Goals 7, 11, 12, and 13.

### Suggestion

A-Gatech offers several implications and recommendations for various stakeholders. For government and policymakers, this technology can be considered as a supporting solution for industrial decarbonization programs and the development of carbon trading mechanisms. In the energy and manufacturing sectors, the implementation of A-Gatech may serve not only as an emission mitigation strategy but also as a potential new revenue stream through the production of bioenergy and carbon credit opportunities. For educators and research institutions, A-Gatech can function as a transdisciplinary learning platform that integrates technical, environmental, economic, and social perspectives. To strengthen its practical application, industrial-scale trials

are required to confirm the consistency of A-Gatech's performance under real operational conditions, particularly in high-emission facilities such as coal-fired power plants, cement factories, and refineries. Furthermore, future research may focus on optimizing microalgae strains, improving the efficiency of modular photobioreactor designs, and exploring the utilization of by-products beyond biodiesel, including organic fertilizers and animal feed. In addition, Life Cycle Assessment (LCA) studies should be further expanded to comprehensively evaluate the overall carbon footprint from upstream to downstream processes, thereby providing a more complete assessment of the environmental sustainability of the A-Gatech system.

## REFERENCES

- Ahmad, A. W. (2022), "An overview of microalgae biomass as a sustainable aquaculture feed ingredient: food security and circular economy", *Bioengineered*, Vol.13, No.4, hal. 9521-9547.
- Barua, V. B. (2021), "A review on synchronous microalgal lipid enhancement and wastewater treatment", *Energies*, Vol.14, No.22, hal. 7687.
- Bradley, T. R. (2023), "Life cycle assessment of microalgae-derived biodiesel", *The International Journal of Life Cycle Assessment*, Vol.28, No.5, hal. 590-609.
- Databoks. (2024), Types and volume of household hazardous waste (B3) in DKI Jakarta, 2024. Diambil dari <https://databoks.katadata.co.id/lingkungan/statistik/fd2438f427dd9a3/sampah-elektronik-jadi-limbah-b3-rumah-tangga-terbanyak-di-dki-jakarta-2022>.
- Energi, P. H. (2023), Encouraging Green Strategy, PHE Intensively Strives for Decarbonization. Diambil dari <https://phe.pertamina.com/en/media/encouraging-green-strategy-phe-intensively-strives-for-decarbonization>.
- ESDM, K. (2022), Menteri ESDM: Cadangan Minyak Indonesia Tersedia untuk 9,5 Year dan Cadangan Gas 19,9 Year. Diambil dari <https://www.esdm.go.id/id/media-center/arsip-berita/menteri-esdm-cadangan-minyak-indonesia-tersedia-untuk-95-Year-dan-cadangan-gas-199-Year>.
- IPCC, I. P. (2019), PEMANASAN GLOBAL (GLOBAL WARMING). Diambil dari <https://dlh.bulelengkab.go.id/informasi/detail/artikel/pemanasan-global-global-warming-76>.
- Ir Anies Chamidah, M. P. (2025), *Chlorella vulgaris Mikroalga Kecil BeIDRotensi Besar*, DKI Jakarta: Media Nusa Creative (MNC Publishing).
- Kementerian PPN, B. (2024), Low Carbon Development Indonesia. Diambil dari <https://lcdi-indonesia.id/grk-energi>.
- Krishnamoorthy, A. R. (2022), "Sustainable approaches to microalgal pre-treatment techniques for biodiesel production: A review", *Sustainability*, Vol.14, No.16, hal. 9953.
- Liu, W. S. (2024), "Development of microalgal dual-cultures for enhanced productivity in sewage: an experimental study", *Biomass and Bioenergy*, Vol.180, hal. 106994.
- Melo, R. H. (2024), "Tantangan Pembangunan Sumberdaya Alam di Indonesia: Dampak Lingkungan dan Ekonomi dalam Pencapaian Keberlanjutan", *Geosfera: Jurnal Penelitian Geografi*, Vol.3, No.2, hal. 149-154.
- Mendes, A. R. (2024), "Chemical compounds, bioactivities, and applications of *Chlorella vulgaris* in food, feed and medicine", *Applied Sciences*, Vol.14, No.23, hal. 10810.
- Monteiro, R. R.-L. (2022), "Production of jet biofuels by catalytic hydroprocessing of esters and fatty acids: a review", *Catalysts*, Vol.12, No.2, hal. 237.
- Nath, D. C. (2024), "Internet of Things integrated with solar energy applications: a state-of-the-art review", *Environment, Development and Sustainability*, Vol.26, No.10, hal. 24597-2465.
- Paminto, A. K. (2024), "Evaluasi pengelolaan limbah elektronik di Indonesia", *Waste, Society and Sustainability*, Vol.1, No.1.
- Penloglou, G. P. (2024), "Recent advancements in photo-bioreactors for microalgae cultivation: a brief overview", *Processes*, Vol.12, No.6, hal. 1104.
- Perekonomian, K. (2022), Akselerasi Net Zero Emissions, Indonesia Deklarasikan Target Terbaru Penurunan Emisi Karbon. Diambil dari <https://ekon.go.id/publikasi/detail/4652/akselerasi-net-zero-emissions-indonesia-deklarasikan-target-terbaru-penurunan-emisi-karbon>.
- Politaeva, N. I. (2023), "Carbon dioxide utilization using *chlorella* microalgae", *Environments*, Vol.10, No.7, hal. 109.

- Prussi, M. W. (2021), "Are algae ready to take off? GHG emission savings of algae-to-kerosene production", *Applied Energy*, Vol.304, hal. 117817.
- Rial, R. C. (2024), "Biofuels versus climate change: Exploring potentials and challenges in the energy transition", *Renewable and Sustainable Energy Reviews*, Vol.196, hal. 114369.
- Saber, H. G.-E. (2024), "Enhancing the biodiesel production in the green alga *Chlorella vulgaris* by heavy metal stress and prediction of fuel properties from fatty acid profiles", *Environmental Science and Pollution Research*, Vol.31, No.24, hal. 35952-35968.
- Shanaida, M. M. (2025), "Carotenoids for Antiaging: Nutraceutical, Pharmaceutical, and Cosmeceutical Applications", *Pharmaceuticals*, Vol.18, No.3, hal. 403.
- Shu, D. Y. (2023), "The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment", *Renewable and Sustainable Energy Reviews*, Vol.178, hal. 113246.
- Su, M. B. (2023), "Applications of microalgae in foods, pharma and feeds and their use as fertilizers and biostimulants: Legislation and regulatory aspects for consideration", *Foods*, Vol.12, No.20, hal. 3878.
- Tsandra, N. A. (2023), "Pengaruh Konsumsi Energi dan Aktivitas Ekonomi Terhadap Emisi CO<sub>2</sub> di Negara G20", *e-Journal Ekonomi Bisnis dan Akuntansi*, Vol.10, No.2, hal. 69-79.