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Incorporation of Microalgae Technology in the Built Environment

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Abstract: Buildings account for over 30% of energy use and emissions, necessitating sustainable design solutions. One potential solution is integrating microalgae bioreactors into buildings for renewable energy generation and enhanced environmental performance. However, there are technical and economic challenges to overcome. This study examined the best ways to incorporate microalgae systems to optimize productivity, energy benefits, and emission reductions. A techno-economic analysis was conducted on three scenarios: a commercial building, a detached house, and a community plant, comparing the UK with Europe and India. The findings revealed that high costs outweighed revenues over 25 years, making adoption difficult. The majority of emissions came from manufacturing, materials, and grid energy. Although renewable energy from microalgae mitigated some impacts, significant challenges persist. Factors affecting feasibility include climate's effect on algae growth, wastewater stream access, and the type of bioproducts produced. This research offers a foundation for future studies and policy recommendations.

Keywords: Algae as energy system, TEA, LCA, Integrating algae, scenario modelling

1. Introduction

Amid rising global energy needs and increasing greenhouse gas emissions, sustainable energy solutions are imperative. Microalgae have emerged as potential renewable sources for biofuels, biogas, and nutraceuticals due to their efficient photosynthesis, rapid growth, and adaptability to non-arable land and non-potable water (Pruvost et al., 2011). Large-scale microalgae cultivation for biomass, food, and eco-friendly products has gained momentum (Brune et al., 2009).

Integrating microalgae into buildings via photobioreactors (PBRs) and utilizing building waste like flue gas and greywater for cultivation could curb energy use and emissions (Edwards, 2012;), advancing sustainable architecture. Yet, translating this "algaetecture" concept confronts multifaceted technical, sustainability, and economic challenges (Raman & Anand, 2018). Optimizing microalgae PBRs across climates, achieving net energy gains, and managing maintenance remain unresolved. Economic feasibility, especially for biofuels, is uncertain despite flue gas coupling (Brune et al., 2009).

This dissertation aims to address these critical knowledge gaps by: Identifying optimal microalgae species, bioreactor designs, and cultivation conditions for productive building integration across geographic contexts; Modelling expected productivities and quantifying potential environmental benefits like CO2 mitigation; Conducting techno-economic and basic life cycle analyses to determine scenarios that could achieve net energy gains and commercial viability.

2. Literature Review

Buildings contribute over 30% of energy use and emissions, impacting climate change. Malik et al. (2016) highlights this significance. Photobioreactors (PBRs) are crucial for integrating microalgae cultivation into buildings. Tubular and flat panel closed-system PBRs are ideal for facades and rooftops due to their ability to maximize sunlight exposure while minimizing contamination risks (Slegers et al., 2013). The BIQ building in Hamburg serves as a testament to their potential, but a broader research scope is essential to understand their applicability across different building types and climates (Lakenbrink, 2013). The orientation of PBRs plays a pivotal role in sunlight interception and biomass productivity. Vertical configurations offer consistent illumination throughout the year, whereas horizontal PBRs exhibit seasonal variations (Pruvost et al., 2011). The challenge lies in striking a balance between light delivery, thermal management, and integration feasibility, which must be customized according to building geometry and function.

2.1 Microalgae for Energy and Emissions Savings

The primary motivation behind building integration is to offset carbon emissions through renewable energy generation from microalgae. However, there's a disparity in productivity projections. While some studies claim potential yields of up to 40 g/m2/day, real-world data suggests a range of 5-15 g/m2/day (Fernandez et al., 2012; de Vree et al., 2015). This discrepancy underscores the need for validation using demonstrated productivities.

From a qualitative standpoint, building integration appears to enhance the economic viability of microalgae cultivation by sharing infrastructure costs and tapping into waste resources (Stephens et al., 2010). However, techno-economic studies often conclude that algal biofuels may not be cost-competitive with conventional fuels, even with flue gas supplementation (Quinn et al., 2015). A more in-depth analysis, incorporating demonstrated productivity data, is imperative. Geography plays a significant role in determining the viability of cultivation and potential emissions reductions.

2.2 Techno-Economic Analysis

Techno-economic assessments are vital for understanding the feasibility of integrating microalgae systems into buildings. This review highlights the methodological constraints and knowledge gaps in current modelling studies. For instance, many studies estimate potential productivities based on assumptions that need validation (Fernandez et al., 2012; Slade & Bauen, 2013). Furthermore, biodiesel production cost analyses often cite high costs, but these estimates are based on varied processes and productivities (Slade & Bauen, 2013; Passell et al., 2013). Addressing these uncertainties with empirical data is crucial.

2.3 Life Cycle Analysis

Limited life cycle assessment (LCA) studies have been conducted in the context of building-integrated microalgae systems. Existing LCAs highlight the favourable energy balance of microalgae biodiesel production but also emphasize the high freshwater demands (Sills et al., 2012). Most investigations focus on the effects of the cultivation stage and lack empirical validation (Barlow, Sims, and Quinn, 2016). Building integration scenarios project energy and emission savings, but these are based on theoretical data (Fernández et al., 2012; Lundquist et al., 2010). A detailed analysis of system interactions is necessary to validate these projections.

2.4 Perspective, Research Gaps, & Future Outlook

Incorporating microalgae technologies into buildings holds significant promise for sustainable development. However, the literature review reveals an urgent need for more field demonstrations and pilot projects to generate empirical performance data. Research must also address economic viability challenges and explore innovative solutions. In Europe, the UK, and India, specific factors shape the viability of integrated microalgae systems. Europe leads in operational demos like SymBIO2 and Fuel4Me, while India's climate offers high potential. The UK faces climate and cost challenges, but urban demand is strong. Lower costs and incentives are needed in India. A multidisciplinary approach, combining various expertise, is essential to transition "algaetecture" from a conceptual promise to commercial reality. Future research priorities should focus on expanding field demonstrations, refining predictive models, discerning optimal integration arrangements, and catalysing commercialization through supportive policies.

3. Methodology

A comprehensive review was undertaken to determine the best microalgae strain for photobioreactors in urban settings. The focus was on strains with high lipid content for biofuel production, targeting three taxonomic groups: algae, cyanobacteria, and other microbes. The top five strains from each group were shortlisted based on lipid percentages from studies. Eleven parameters were used for comparison, including lipid content, space-time yield, photobioreactor design, and energy output potential. Data was standardized for uniform analysis. After a multi-criteria assessment, Chlorella sp. was identified as the optimal strain.

3.1 Techno-economic analysis

The techno-economic feasibility of algae photobioreactors (PBRs) combined with anaerobic digestion was analysed across three scenarios: a commercial building, a detached house, and a community plant, using the Chlorella sp. species.

Electricity costs were based on Octopus Energy rates, with purchase costs at £0.24/kWh, £0.18/kWh, and £0.20/kWh, and selling prices at £0.34/kWh, £0.31/kWh, and £0.35/kWh for the three scenarios respectively. PBR areas and production rates were specified for each scenario, with capital costs at £1000/m2 for commercial and community scenarios and £800/m2 for houses. Algae yields were 30 kg/day, 2 kg/day, and 160 kg/day, with methane yield at 0.25 m3 CH4/kg algae. Methane's heating value was 39 MJ/m3, with a 40% electrical conversion efficiency. Energy consumption rates and baseline usage were estimated for each building type. Costs were based on PBR area and per m2 costs, with additional costs and delivery costs as percentages of the capital payment. PBR electricity cost was 300 W/m3, with anaerobic digester consumption at 60% of PBR. Maintenance was 10% of the capital payment. Tax savings from renewable energy credits and carbon trading schemes were considered, with initial values and annual increases specified. Energy generation was based on methane content in biogas, with an average of 0.25 m3 CH4/kg algae. Building energy costs, net costs, and energy generated were calculated for various scenarios.

A 25-year projection was developed, detailing annual costs and revenues. Costs included PBR system capital cost, delivery & installation, and additional capital costs. PBR energy consumption was detailed, with rates and volumes specified. Anaerobic digester energy consumption was 60% of PBR. Maintenance and depreciation were also considered. Overall building costs minus electricity generated were calculated. Inputs for electricity generation included PBR volume, algae production rate, and methane production. Tax savings from renewable energy credits and emission reductions were also considered. Present value was derived from cash flow and discount rate, while net present value was the present value minus total capital cost.

3.2 Life Cycle Analysis

Photobioreactors, primarily made of plastic, glass, steel, aluminium, and concrete, contribute to greenhouse gas emissions during material extraction and production. The UK average emissions for these processes are 0.2 kg CO2e per kg of material (Passell et al., 2013). The commercial, house, and community setups produce 50,000 kg, 3,000 kg, and 250,000 kg of CO2e emissions, respectively. Manufacturing processes (emitting 10% of material impacts per m2) add 5,000 kg, 300 kg, and 25,000 kg CO2e for each setup (Pechsiri et al., 2023). Utilizing standard construction equipment, emissions for commercial and community constructions are 100 kg and 500 kg CO2e, respectively, while the house emits 20 kg CO2e (ECC, 2023). Grid electricity consumption leads to 110,000 kg, 7,400 kg, and 590,000 kg CO2e emissions for commercial building, house, and community plants, respectively (ECC, 2023). Material and component delivery contribute (0.1 kg CO2e per tonne-km) 5,000 kg, 300 kg, and 25,000 kg CO2e emissions for the commercial, house, and community setups (Department for Transport, 2021). Material disposal and replacements account for about 10% of manufacturing impacts (DEFRA, 2022). Renewable energy yields result in annual savings of 3,360 kg, 224 kg, and 17,500 kg CO2e for the commercial, house, and community plant.

4. Findings and Discussion

The commercial building's NPV starts at -£1,853,109, improving to £69,831 by year 25 due to high initial and maintenance costs. Year 1 revenue is only £24,080 from electricity sales and tax savings, covering a small portion of the building's electricity. To enhance viability, consider reducing initial costs, exploring alternative funding, lowering maintenance costs, and boosting revenue through increased algae productivity. The detached house scenario is unprofitable until year 24, even with lower initial costs. Improving viability requires cost optimization and revenue enhancement. The community plant, with the highest initial NPV of £10.8 million, only becomes positive by year 18. For all scenarios, strategies include cost reduction, revenue increase, and project extension.

The study assessed the impact of varying building energy costs and the percentage of energy generated on the net present value (NPV) breakeven points for commercial buildings, detached houses, and community plants. Three scenarios were evaluated for energy costs: a 10% increase, a 5% decrease, replicating the past 20 years' increase, and maintaining constant costs. For energy generation, the analysis tested a 10% lower starting percentage, a 5% higher percentage, duplicating historical changes, and keeping the percentage constant. Results indicated that higher building energy costs negatively affected NPV, delaying or preventing breakeven. Conversely, lower costs improved NPV outcomes. The percentage of energy generated significantly influenced project economics. Higher generation percentages enhanced revenues and improved breakeven points, while lower percentages had the opposite effect. For instance, commercial buildings achieved breakeven between year 18 (with 5% higher generation) and year 28 (with 10% lower starting percentage).

This study highlights the techno-economic challenges of building-integrated microalgae cultivation systems. Despite Europe's advancements in microalgae projects and robust sustainability policies, high costs and temperate climates pose barriers (Bhandari & Shrimali, 2018). Conversely, India's tropical climate and low labor costs offer potential advantages, but the lack of strong renewable energy policies hinders progress (Duarte et al., 2023). Targeting high-value products, such as nutraceuticals and aquaculture feed, could enhance revenue streams (Galasso et al., 2019). Innovative photobioreactor designs, optimized for building integration, are crucial for maximizing productivity and sustainability. Collaboration between architects, engineers, and sustainability consultants is imperative for successful integration. Policymakers should introduce robust incentives, renewable energy credits, and carbon trading schemes tailored for microalgae systems in architectural contexts. Research should focus on empirical validation of photobioreactor designs across varied climates and building types. Addressing the identified gaps in techno-economic evaluations, such as energy costs, equipment lifetimes, and potential co-products, is essential for validating the technology's feasibility. Field demonstrations across diverse environments are urgently needed, as many studies rely heavily on theoretical models without real-world validation (Fernandez et al., 2012; Lundquist et al., 2010). Comprehensive life cycle assessments, techno-economic evaluations, and comparative analyses against traditional energy sources will provide a holistic perspective (Pruvost et al., 2016).

5. Conclusion

The research explored the benefits of incorporating microalgae bioreactors in buildings for energy production, air purification, and enhanced performance. The literature highlighted advantages like renewable energy, CO2 reduction, shading, wastewater treatment, and aesthetics (Pruvost et al., 2011). However, challenges like high costs, unproven productivity, and lack of policies limit its adoption. The economic analysis showed that microalgae systems face financial challenges, with costs exceeding revenues over 25 years. The environmental impact varies with the system's size, but renewable energy production provides carbon savings. The study's uniqueness is its techno-economic and life cycle evaluations for different building scenarios, helping stakeholders identify research and policy areas. Limitations include relying on theoretical models and focusing only on bioenergy. Future research should emphasize field tests, sustainability metrics, and optimal integration strategies for various buildings and climates. Historically, technologies like solar panels and wind turbines took decades to become cost-effective (IRENA, 2019; IRENA, 2012). Similarly, microalgae systems might need years of enhancements and policy support to be economically viable. The community plant model could be profitable in 10-15 years, while commercial and residential models might take 15-25 years.

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