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OPTIMIZATION OF AN ADAPTIVE ALGAE FAÇADE BASED ON SOLAR RADIATION SIMULATION

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ABSTRACT

Due to the climate crisis, extreme fluctuations in temperature are caused by the high sources of energy, and carbon consumption have a great impact on both construction and water resources management. Accordingly, the world today is paying attention to searching for cleaner energy resources. In Egypt, the extreme heat of the summer seasons causes constant air-conditioner (AC) usage in building to provide cooling, which produces outlet wastewater. The continuous flow of this outlet wastewater results in cracks and erosion among the facades that need maintenance.

As a way to search for environmentally friendly material that can reuse this outlet water and reduce the solar radiation on the façade providing more cooler spaces, algae are suggested due to their availability in water from several sources in Egypt. This paper presents the assessment of an innovative façade element photobioreactors (PBR) made from algae on a real administrative building facade in Cairo. The aim is to evaluate digitally by simulation the solar radiation reduced from the façade that acts as a double green skin and self-watering system with an appealing aesthetic form preventing any erosion on the façade surfaces.

The method of assessment is done using Ladybug plug-in simulation in Grasshopper plug-in in Rhino software based on the climatic data from EnergyPlus. Four main phases are followed: 1) the form generation of the façade using Rhinoceros software, 2) the simulation to assess the solar radiation before and after adding the PBR, 3) the evaluation phase to calculate the thermal conductivity and water temperature mathematically, and 4) fabrication of small-scale façade using the 3D-printed technique with algae filament.

The results recorded a reduction in the solar radiation from 301 to 75 kWh/m^2 comparing the current case of the building façade, while the thermal performance was 0.36 W/m^{2}K, which is better than the most common materials used in arid climates such as rammed earth, fired brick, and concrete. The optimization of the algae tube length was based on the required outlet temperature that is suitable for plantation 15°C to help in reducing the water temperature.

The finding addresses the significant role of using algae that can generate biomass to explore their benefits regarding their O_2 production and CO_2 absorption through 3D printing, which is considered a cleaner technology.

Keywords: 3D printing, additive manufacturing, algae, adaptive façade, bioenergy, bioprinting, digital fabrication, green façade.

1 INTRODUCTION

Due to the extreme fluctuations and changes in climate and population growth, the world today consumes resources and energy more than ever before causing a shortage in many resources. As a result, the construction field is now being considered to be one sector with highest energy consumption and carbon emissions, which reach 40% [1, 2], as industrial materials such as concrete and fired bricks started to replace the environmentally friendly material causing extreme fluctuation in the internal spaces for its weak thermal conductivity. Accordingly, there was a high demand to start focusing on cleaner energy and recycled materials for more sustainability in balancing the resources [3, 4]. One of the cleaner alternative resources that the paper is focusing on is organic and ecological grown material such

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as algae. The integration of algae in architecture opens new research explores to merge the renewable and waste materials in construction for its dual ability in producing oxygen and reducing carbon emissions both from the air and industrial materials [5, 6]. Freshwater, saltwater, wastewater, and rainwater are the sources of algae, which play an important dual role in oxygenation, filtration, wastewater purification, and water quality monitoring [7–11]. Algae usage can be seen in assessing ecological variations and addressing global environmental concerns, which include degradation and energy demands [12–14]. In addition, their role in enhancing the mechanical, thermal, and acoustic behavior and fire resistance of the composite [15] can also be observed. Another application of a similar type of marine phanerogam is *Posidonia oceanica* that grows in Mediterranean coasts. The fibers of these plants are used in enhancing building materials such as composite and concrete, which increase both reinforcement and workability of the mechanical behavior instead of using cement. In addition, its vital role in reducing waste by recycling it [16] should also be noted.

One of the algae applications in buildings is photobioreactors, which are known as 'PBR'. These nature-based reactors are an alternative element of glass facades that became part of the building components of large glass surfaces [17]. The flat panels of PBR act as a passive cooling system and solar thermal, which can provide shade and efficiently absorb the ultraviolet light and other thermal light rays besides its ability to improve the indoor AC. For biomass production, PBR can produce an average of 1480 kg within 20 years [18].

Following PBR as a solution, with a focus on Cairo, one of the recently noticed problems in summer is the huge amount of outlet water that damages the building façade resulting from the air-conditioner (AC). In addition, the massive availability of algae in the Nile can be used as a renewable resource, which is considered 'biological waste' that is expensive to be used in construction applications. Accordingly, this as a case study focused on an administrative building in Cairo to test the 3D-printed algae façade to assess the solar radiation before and after the algae and act as an aesthetic element getting the benefits of algae. As a continuation of our previous research to reuse this outlet wastewater through 3D printed – a sustainable product solution for automated watering using algae [19], this paper presents the concept of the new double-skin façade element made of algae that has a dual function, firstly, at reducing the solar radiation on the building, which decrease the temperature of the space. Secondly, that acts as an irrigation system, which produces O_2, absorbs CO_2, and collects and cools the outlet water temperature from AC through an internal engraved spiral tube to ensure a smooth flow to be suitable for plantation.

This paper aims to evaluate by simulation the solar radiation reduced from using an algae façade on an administrative building façade in Cairo. The objective of the research is to focus on improving the double-skin façade by reusing the algae as a 3D-printing material reaching more sustainable facades that reduce solar radiation. The thermal conductivity of the algae façade will be addressed and calculated mathematically. Using recycled materials can help in reducing the use of plastic products that depend on fossil fuels as a sustainable feature. The façade acts as a green wall that has a dual function in reducing solar radiation and irrigation/filtration system of air with an aesthetic element.

2 APPLICATIONS OF ALGAE IN ARCHITECTURE

As a way of tackling the environmental problems in our cities, researchers focused on integrating biohybrid structures into building facades as living green architecture [20]. This type of structure opens the doors for more innovative green facades and roofs, which is considered an alternative energy resource [21].

The plant waste extract natural fibers that are being reused and recycled to enhance the structural, mechanical, and thermal behavior of the composite and polymer of the materials. Their sustainability can be seen in their usage as an alternative to cement and glass fibers, which become more lightweight by turning those fibers into wooden boards [16]. Many studies tackled the importance of integrating the natural fibers in the supplementary cementing materials in replacing cement in concrete, which enhances the workability and strength. For instance, Solask *et al.* [15] studied the impact of the silica fume, fly ash, and *P. oceanica* ash on the concrete properties. The study recorded a good impact on enhancing the lightweight aggregate concrete.

Algae is considered one of the biomaterials represented as naturally derived biopolymers from marine biomass. The applications of algae in architecture can be seen in building facades, which are used as an insulation and purification material to reduce environmental pollution and carbon emission besides producing oxygen through the photosynthesis process [5, 11, 19]. In 2013, the BIQ (Bio Intelligent Quotient) house in Hamburg fabricated hybrid structures on the façade that includes 'PBR' [20]. The PBR is used as an adaptive shading screen, thermal insulation, and it decreases carbon emissions by transforming them into biomass and oxygen [11, 21]. The algae in this façade were responsible for providing solar thermal heat, which in parallel provides biofuel and bioenergy as renewable energy resources [6].

Since then, bio-reactive walls including PBR became a potential alternative for green walls [20]. Hence, with the great shift in technology, the fabrication and manufacturing process of these types of facades developed to include 3D bioprinting for large scale [20, 22, 23]. For instance, one of these processes that have been used in architecture is additive manufacturing and rapid prototyping for their ability to reach the homogenous hybrid structure and complex form using several materials that are printed layer-by-layer with no waste [20, 24, 25]. As a way of using waste materials in 3D printing, the Emergent Object group led by Rael and Fratello [26] has been using nonconventional materials such as sawdust, rubber, salt, and bioplastic as 3D printing materials as replacement for non-eco-friendly materials. 'H.O.R.T.U.S. XL Astaxanthing' is another project that used 3D-printed algae as a living sculpture. The structure contains 3D-printed units that were injected by microorganisms to absorb the CO_2 resulting from human breathing transforming it into oxygen and biomass [27]. Another application for a 3D-printed large-scale wall is 'BANYAN', which combines both irrigation and drainage system. The wall has an embedded controlled internal system that spans through the whole structure to feed the plant without the need for human assistance [28, 29]. The complexity of the wall would not be reachable without the AM techniques. The project can be scaled up for green vertical gardens in facades and other forms of urban farming. For PBR mechanical properties, based on Mohler, the PBR tubes yielded a range of heat transfer coefficients of 19–64 $\mathrm{Wm^{-2}\ K^{-1}}$ at wind speeds of 1–10 $\mathrm{m\ s^{-1}}$. He generated also another model that was based on data collected from the PBR and gave an overall heat transfer coefficient of 24.8 $\mathrm{Wm^{-2}\ K^{-1}}$ [30].

With all the previous applications above that highlighted the important role of algae, architecture applications need to be studied deeply to allow more evaluation and assessment in the long term of using algae in facades. By focusing on the PBR façade systems, some factors need to be taken into consideration such as the maintenance of the inner part of the façade that includes living organisms, the different extraction ways of biomass that it generates, and the fire safety [5]. As in architecture, many software started to focus on the simulation and assessment of materials based on the optimized design such as grasshopper, which is a plugin inside Rhino software that allows visualizing the data easily for verification and optimization.

As known, the extraction of algae can be too expensive if not following a specific technique. For instance, in Egypt, although, the massive availability of algae in the Nile can be used as a renewable resource, yet, they are considered ‘biological waste’ that is expensive to be used in construction applications [19]. However, as new applications started to appear, PBR can offer a new perspective for regenerative building construction to be integrated with the environment. Hence, unlike the previous algae applications, our research provides an evaluation of using wastewater from AC to ensure solar radiation reduction, enhance thermal performance, and decrease the water temperature based on algae.

3 MATERIALS AND METHODS

This paper presents the assessments and evaluation of a modelled PBR façade made of algae on a real building facade. The method followed four phases as shown in Fig. 1: design, simulation, evaluation, and prototyping/fabrication. The design of the façade was tested on a southern–western façade in a building that is in Cairo. Several form generations were tested by using Rhino digital modeling simulation software controlling the parameters of the form and the pores. For the simulation phase, the Ladybug plug-in in Grasshopper software was used to measure the solar radiation, which helps us locate the panel and measure the water temperature in the PBR façade. A water calculation was done to optimize the length and width of the algae tube to ensure the reduction of water temperature to reach the end of the pot and to be suitable for the plantation. An evaluation assessment was tackled to compare the amount of radiation that has been reduced from using the algae compared to a traditional glass façade without any louvers or treatment. A solar radiation test was run on the prototype by attaching it to a building façade to act as a double skin to run radiation analysis, thermal assessment, and shadow analysis to assess the design as a façade element. A prototype of the façade was fabricated on a small scale using the 3D-printing technique.

3.1 Materials

The main material used in the PBR façade is algae filament that uses a bio-printing technique based on our previous research and the main material [19]. This filament is a ready-made algae filament that was developed by Luma [31], confidential information under the umbrella of Algae lab a bio-laboratory in collaboration with Studio Klarenbeek & Dros. The façade

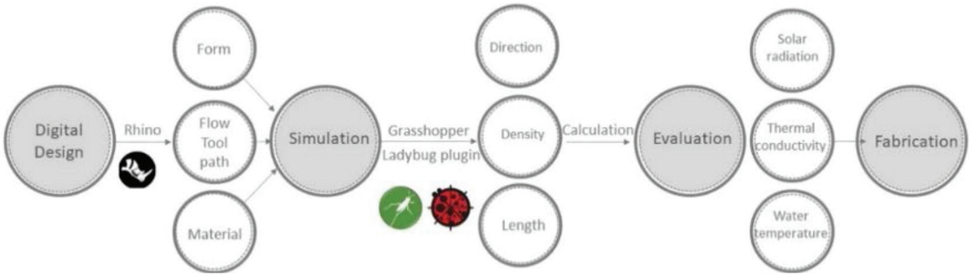

Figure 1: The three phases of the method.

consists of a printed tube that is made of algae with diameter dimensions of 22 and 26 cm for inner and outer tubes, respectively. The length and the form of the tube facade were calculated and designed based on the water temperature and heat loss.

3.2 Study area and climate zone

The site selection of the administrative building is located in the Gate complex project in the business park district at one of the newest and most recent projects ‘the new administrative capital’ in Cairo. The assessment was done on a modelled façade on Rhinoceros, focusing on the southern–western façade that is the longest hours facing the sun during the day. From the data extracted from the EnergyPlus database for Cairo city, and with the use of the Ladybug plug-in, Fig. 2 shows the temperature through the year where it is noticed that the months with the highest temperature are June and September. Accordingly, the simulation time selected the months with the highest temperature from 7 am to 6 pm where the average temperature is between 38 and 48°C during the day.

3.3 Tools

The simulation of the solar radiation run through using Ladybug tool grasshopper plug-in in Rhino software to assess the radiation on each façade, which helps us in selecting the highest

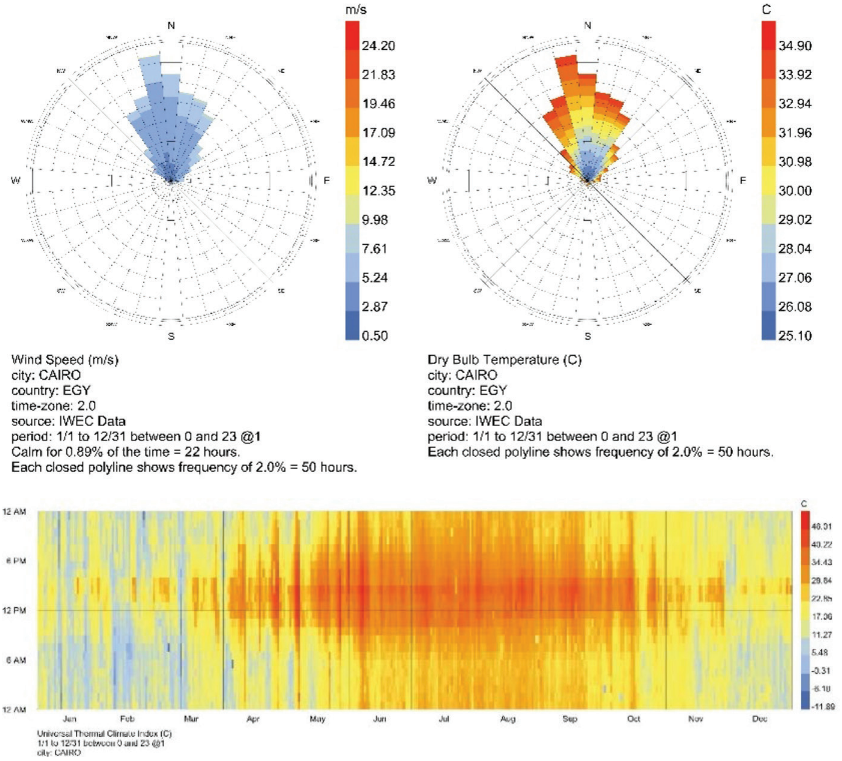

Figure 2: The thermal climate of Cairo shows the temperature during different months.

thermal solar radiation to locate the PBR panel. This tool provides a direct calculation for the percentage of daylight exposure on a building façade throughout the year without any further calculations [32]. Direct sun exposure is considered the main factor to complete the close cycle of the PBR through photosynthesis.

4 RESULTS

4.1 Design process and form generation

Based on the solar radiation results from the Ladybug, Figs. 3 and 4 show the high solar radiation in the southern and the western façade, which is between 263 and 301 KWh/m^2. Yet, the research is focusing on the highest one which in this case the western façade to reduce the solar radiation after adding the PBR double skin. The shadow diagram helps in determining the best façade to locate the PBR algae based on the number of hours exposed to the sunlight and the surrounding neighboring. The design direction of the louvers was selected based on the results from the solar radiation test. As shown that the western façade has the highest solar radiation, where the louvers should be vertical to prevent the low angle of the sun to enter

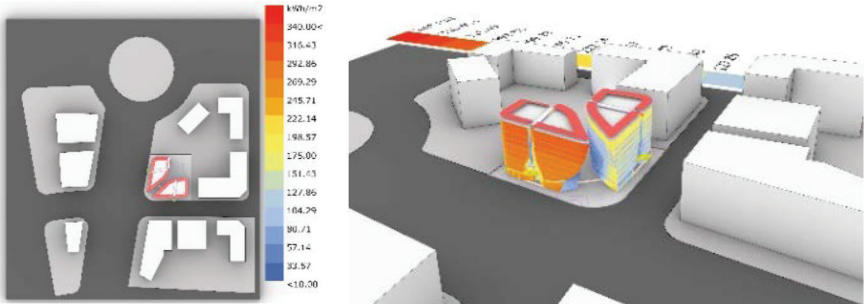

Figure 3: The current solar radiation on the building within the surroundings.

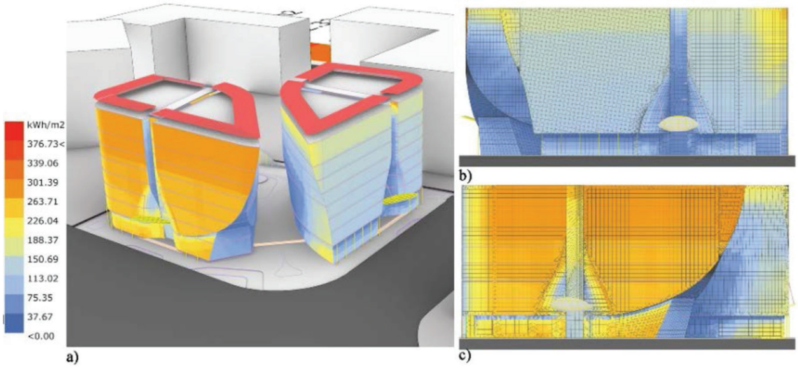

Figure 4: a) The current solar radiation of the building, b) the Southern façade, c) the Western façade.

space. The louvers consist of spiral tubes with internal engraved to ensure more water fluidity till reaching the base. The spiral engraves sloped with a degree of 30° act as an inner tube to provide a longer path to increase the water travel time. This in parallel will allow cooling of the outlet water from AC by decreasing its temperature to be suitable for plantation. The end of this tube is located inside plant pots.

4.2 Tube length effects on heat loss and water temperature

The length of the spiral tube affects the water temperature, where the density of the spiral was used as an equivalent solution. The calculation was done on a designed strip on the building that is 10 m in width and five floors in height with an average of 10 AC. To be able to decrease the water temperature from the AC outlet, which is between 30 and 35°C, to reach 15°C, which is suitable for plantation, heat loss was accumulated to optimize the length of the tube. Thus, we needed to determine the required tube length to allow losing energy through friction with the tube material's inner surface. The calculation was done based on the following formula:

$$\frac{Ts - T\infty in}{Ts - T\infty out} = e\frac{h\pi dL}{miCp} \tag{1}$$

Where the T_{out} is the tube temperature outlet, which is 15°C (suitable planting water temperature), T_s is the temperature of the algae surface surrounding thin air film exposed to the sun with a value of 50°C based on Cairo climate in June at noon, while T_{in} is the temperature (from AC outlet/tube inlet), which is 35°C. The *mi* is the flow rate, which is estimated and calculated to be 30 kg/s based on five floors and 10 AC. The *Cp* is the water heat capacity, which is 4186.1 J/kg K, *h* is the heat transfer coefficient of water, which is 11789.2 w/m^{2}K, and the *L* is the length of pipe over which the fluid will be transported a tube diameter of 0.05 m.

$$Ln\ 0.482 = -0.729 = \frac{11789.2 * \pi * 0.05 * L}{30 * 4178.1}$$

The result of the length is 49.34 m, which means 10 m length in each floor with a total of five floors, which can be distributed based on the solar radiation assessment through increasing the density of the loop, which will be described in the coming section. Based on the tube length, the design of the form was done based on the optimized results along the elevation side. This calculation was done mathematically, yet computational fluid dynamic test is suggested for further study for more accurate water temperature.

4.3 Tube distribution through visual analysis based on the solar radiation assessment

Through tracing the different thermal zones on the façade, the facade was divided into four labeled zones starting from 0 to 4, where 0 is the lowest part that does not need any treatment and 4 is the higher part that needs treatment as shown in Fig. 5a. The curvature of this projection mapping on the elevation allowed us to have a dynamic design based on solar radiation. Accordingly, different tube lengths are distributed based on the results of each part. Orange color tubes in Fig. 5b refer to a less dense spiral loop that has high solar radiation with a wider surface, while the tube gets denser at the bottom to allow cooling of the water in a short time

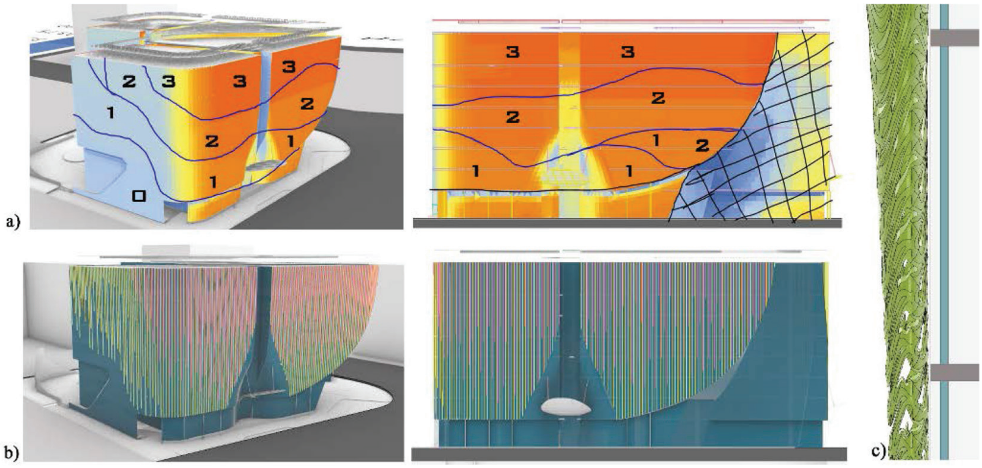

Figure 5: a) Labelled Western façade, b) the louver tubes distribution, c) the spiral loop tubes.

Table 1: Thermal transmittance of the algae façade.

	Solar radiation KWh/m^2	
	Before PBR	After PBR
Southern façade	263	-
Western façade	301	75–113
Optimum thermal radiation	80–100	

on the lower floors as shown in Fig. 5c. The spiral slopes in the tubes allow more water fluidity where the density of the spiral increases in the parts with high solar radiation and decrease in the lowest part. The tubes end with a plant pot with different heights based on the radiation, which gives a more dynamic green fence form to the façade.

4.4 Solar radiation assessment

Based on the solar radiation of the western façade, Fig. 6 shows the difference between the facades before and after adding the PBR louvers, taking into consideration that the optimum thermal radiation is between 80 and 100 kWh/m^2. It is noticed that the solar radiation shows a dramatic decrease of four times the current radiation after adding the algae panel with a value from 301 to 75–113 kWh/m^2 as shown in Table 1. This reduction will decrease the heat transfer from outside to inside the space, while the consistent water flow inside the louvers' tubes will provide more cooling to the space. This in parallel will decrease the usage of the AC resulting decrease in heat loss.

4.5 Path planning strategy in fabrication

For the fabrication process of the tube in the louvers, it was suggested either to 3D print the tubes into parts and then assemble them or mold them through a 3D-printed mold, which will be faster to assemble. The second suggestion of the mold was left for further testing. While for the 3D-printed tubes, part of the form was tested to ensure the path planning strategy for minimal structure supports for reducing the material waste and the fabrication time. Based on the tested printing process of the position in our previous study Fig. 7a [19], Fig. 7b shows the different layers during the printing and how the 3D printer can bridge any gap even if the layers are not connected or closed. A simulation of the slicing process of each layer is done through 3D slicer software to ensure that the layers do not need any support. Accordingly,

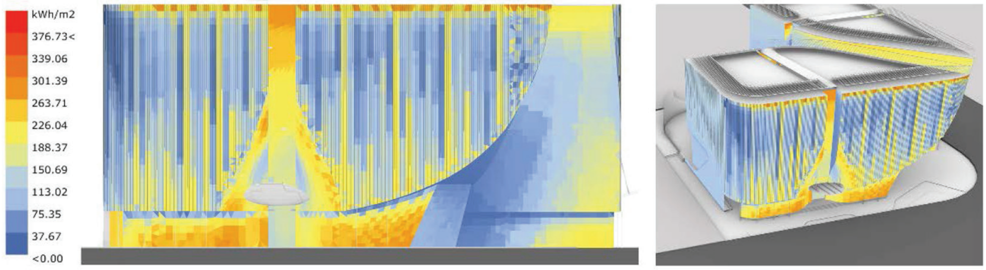

Figure 6: The solar radiation analysis of the building after adding the PBR.

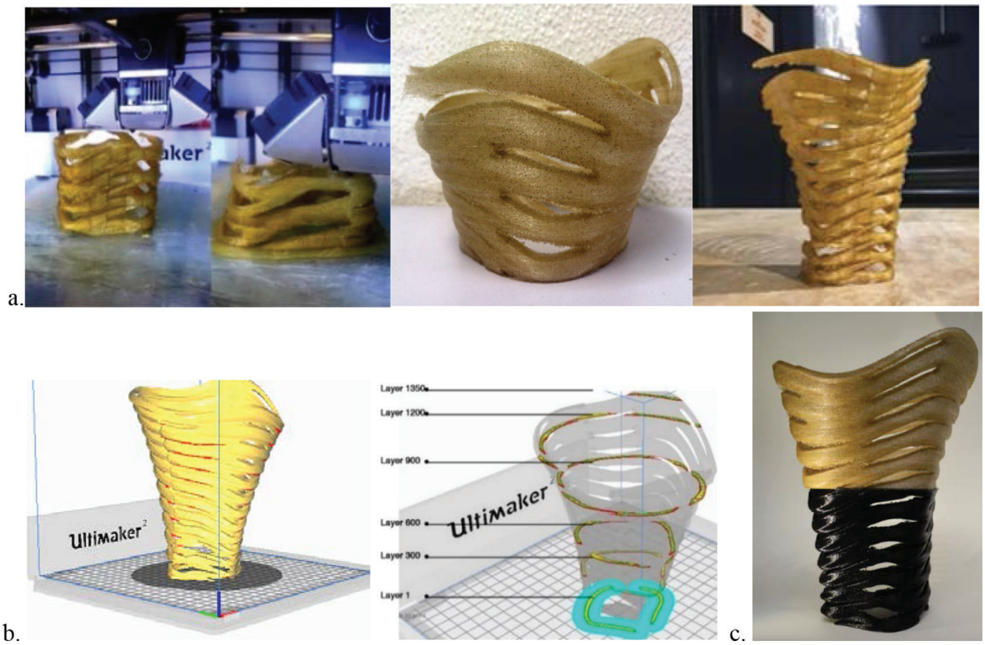

Figure 7: a) The spiral path, b) a simulation of the different printed layers, c) final prototype.

the first part was printed flipped where the top was printed first to provide support during the printing of the above layers.

5 DISCUSSION

5.1 Thermal conductivity of the algae facade

To develop a testing process and assess the PBR façade, the U-value of the wall shows the material's effectiveness as an insulator where the higher the resistance, the lower the U-value, and the better the material is as a thermal insulator [34]. To calculate the thermal resistance of a wall (R), R_{in} and R_{out} of the building should be added to the following formula, where L is the wall thickness and λ is the thermal conductivity of the wall.

$$(R = L/\lambda, \text{where } R_{total} = R_{in} + R_{layers} + R_{out}) \tag{2}$$

Figure 8 shows the different layer thicknesses of each material added to the wall. Based on the Egyptian Code for Improving the Efficiency of Energy Use in Buildings [35], R_{in} and R_{out} are considered constant 0.123 and 0.080 m^2K/W, respectively. Table 2 shows the calculation of the total wall resistance after adding the PBR double facade, showing the thermal resistance and layer thickness. As a result, the thermal transmittance of 0.36 W/m^2K compared to most industrial materials was used in construction, which are fired brick concrete walls that are 2.45 and 1.9 W/m^2K respectively [34, 36]. While its U-value was less than materials that have good thermal performance for instance rammed earth, which has a value between 1.25 and 1.4 W/m^2K [37, 38] that is better as well.

Table 3 shows the U-value of the algae façade in comparison to the most used building material, especially in the arid region. It is reported that the best thermal performance after is the algae façade (0.36 W/m^2K) with a wall thickness of 8 cm. Also, the algae façade showed five times better performance compared to both fire brick and concrete with a wall thickness of 25 cm.

5.2 Recyclability, durability, and transparency

For recyclability, the algae panel plays a vital role in recycling the water to act as greywater besides its ability for both air and water filtration. The maintenance of the algae facades needs to be done on an annual basis to clean the parts that might block the water fluidity. This needs to be studied by the chemical engineering department to find a liquid that can melt any

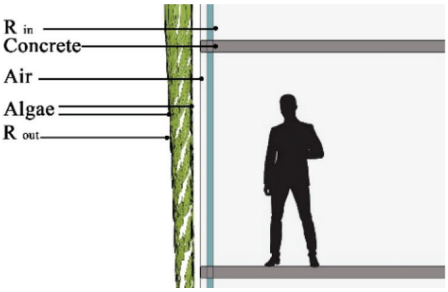

Figure 8: Wall section showing the different layer thickness.

Table 2: Thermal transmittance of the algae façade.

Material layers	Thermal conductivity	Material thickness	Thermal resistance	U = 1/R
	Λ = W/mK	m	R = m^{2}K/W	W/m^{2}K
In (internal)			0.123	
Fired brick [34]	2.45	0.12	0.05	
Algae [39]	0.04	0.04	1 * 2 layers	
Water	0.598	0.22	0.36	
Air gap			0.153	
Out (external)			0.080	
	R Total=		2.766	U = 0.36

Table 3: Thermal performance of the algae façade in comparison to commonly used building material.

Façade material	Thickness	Thermal performance U-value	Embodied energy consumption
	Cm	W/m^{2}K	MJ/kg
Algae façade	8	0.36	-
Rammed earth [36, 40]	30	1.25–1.4	0.7
Concrete/cement block [36]	25	1.7–2	5.6
Fire brick [34]	25	1.7	6.4

plankton. By this time, the algae tube is changing its color based on the filtration process that occurs in this part. This change might block part of the tube transparency. Thus, it is important to select the location of the tubes that might be added in places that do not need any visual access to the outside such as toilets. For the aesthetic functionality, the tubes fixed on the double facades play also a functional role to hide any AC units besides acting as a green wall, which is considered passive cooling. The distribution of the solid and opaque parts can also be in places that do not need direct visual access to outside, while the more transparent parts can be in spaces that need direct sunlight. However, this study left for further investigation where some loggers can be added to measure the percentage of algae growth inside the tubes. Another further study is to test the mechanical behavior and compressive strength of the bio-algae composite.

5.3 Sustainability of the 3D-printed algae panel

The use of waste algae as a 3D-printed filament allows for generating complex forms fast and without any waste. In addition, printing can reduce carbon emission and energy consumption compared to other traditional techniques. The assessment of the solar radiation followed after evaluating the form generated helped in reaching the most optimized form with fewer materials. For the sustainability of the algae filament, it can be reused after the end of the building life cycle. It is essential to implement the 3D-printed algae on a large scale and test the measurements in real.

6 CONCLUSION

This paper highlights the importance of algae as a bio-based material reflected in many architectural applications, especially facades. The projects presented show the benefits of the algae in producing biomass as a clean source of generating energy and oxygen and absorbing CO_2. The PBR double-skin façade shows dual advantages in cooling the water that reduces both the heat transmitted and the solar radiation on the building. This in parallel will allow decreasing the internal temperature and the thermal performance of the space.

This paper evaluated a modelled PBR facade in the new administrative capital by using the Ladybug plug-in to simulate the solar radiation and assess it. The PBR tube on the façade showed a reduction in the solar radiation of 75 kW h/m^2 with recording a good thermal performance of 0.36 W/m^{2}K. The thermal performance of the façade was calculated showing a reduction of five times the fire brick and concrete wall with a thickness of 8 cm. The form generation of the spiral tube and the density of the spiral loop allow cooling of the water with reaching an aesthetic design that is based on an environmental function. One of the disadvantage about the algae façade is that they need annual maintenance to clean the blocked parts that might be caused by water fluidity in addition to keeping their transparency to ensure their efficiency. This paper presented the advantages of 3D printing with algae as a grown material that can be scaled up on a larger scale. Using algae, waste – which is massively available – can be used as a renewable resource, which is considered ‘biological waste’ that is expensive to be used in construction applications.

On an urban scale, PBR can influence the facades to be smarter and sustainable by inserting them directly even on an existing building, performing the dual function of absorbing CO_2, and producing oxygen and biomass where needed most. However, the research is considered a first step to integrating 3D-printed algae skin on facades. Given the alarming increase in the current substitution of traditional materials with new industrial materials, the application in this research will open new doors for more innovative PBR facades. Further research is also needed to measure the flow of the water using computational fluid dynamic CFD analysis software. Further life cycle assessment and light testing are needed to assess the efficiency of the algae transparency after a long time. The CO_2 efficiency needs to be measured in future studies with a cost analysis to highlight the tangible and intangible benefits of the PBR system.

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