WASTEWATER MATTER: FROM ALGAE TO BIO-ALGAE PLASTIC 3D PRINTED FAÇADE ELEMENT

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ABSTRACT

In Egypt during the extreme heat in summer, numerous amounts of air conditioners – that provide a cooler environment – are producing a huge amount of outlet wastewater. The continuous flow of this water causing great damage to buildings' façades. Therefore, the paper presents an innovative product solution made from algae that aim to reuse this wastewater as a self-watering landscape façade element that acts as an irrigation system. The prototype is designed from concept to manufacturing to implementation based on 3D printing with a bio-algae filament. With the dual algae ability in producing O_2 and absorbing CO_2, the fabrication follows a spiral engrave path to collect and cool the water droplet and ensure a smooth flow to be suitable for plantation. A path strategy is used during the printing for minimal structure supports aimed at saving unnecessary material waste and fabrication time. Solar radiation and water simulation are tested to measure the effect of the algae and to ensure the water fluidity from the AC tube till reaching the soil. The solar radiation results record a solar reduction from 316.43 to 80.71 kWh/m^2 after adding the algae panel to a building façade with a decrease of 6°C in the water temperature. The design demonstrates highly significant materials and resource savings, where no supports are needed during printing. The finding addresses the manufacturing of a low-cost algae product using cleaner technology as additive manufacturing. Given the alarming increase in the new industrial materials, algae will allow designers to explore their benefits regarding their O_2 production and CO_2 absorption, which will influence the façades to be smarter and sustainable using large-scale of PBR – photobioreactors – applications as a nature-based alternative to large glass surfaces with the potentials of additive manufacturing. This can reduce plastic production using fossil fuels to be eco-friendly.

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

1 INTRODUCTION

Since the last three decades, the extreme fluctuations in climate change have been rising the energy consumption rates globally at an escalating pace. The shortage in the resources caused by the rapid population growth also is increasing the demand for the use of industrial construction materials such as concrete and fired bricks causing non-comfort in the internal spaces. Since then, many countries have started to use recycled materials, cleaner resources energy, and sustainable process during manufacturing to ensure fulfilling the sustainable development goals for reaching sustainable cities. As a way to find new cleaner alternative and sustainable materials in construction, several studies integrated algae in architecture as a bioprinting material that can reduce carbon emissions and provide oxygen [1], [2]. For instance, with the importance of water management, many projects started to invest in providing more water to solve the shortage in some places. Thus, a new exploration of renewable and clean sources of water and energy started to gain prime importance. Consequently, a new concept of the regenerative city that depends on water, land, and energy in the respect of the environment grows widely, contributing to the resilience of the entire system [3]. The new agenda of Habitat III is to targeting cities to be

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highly energy efficient with low CO_2 emissions by increasing the relay on renewable energy sources through reusing and recycling the waste [4].

Climate change not only encompasses raising the average temperature, but it has a potential impact on many sectors in construction and water resources management [5]. Thus, the high changes in temperature did not affect only the indoor environment which increased the HVAC systems usage but the growth of the aquatic plants causing water pollution [6]. Therefore, the integration of green architecture became a good example to reduce carbon emissions and find renewable resources of energy to support the global climate action change summit. One of these green applications is biomaterials and algae which started to spread with the aid of technology [7]. Algae are one of the main components of aquatic organisms and plants that serve as the base of the food chain [8]. Both algae and microalgae can either live in colonies or grow with different patterns in freshwater, saltwater, wastewater, and rainwater [3], yet their nutrients are provided from the wastewater. Scientists and researchers have been widely studied and integrated algae in several fields up to now for plant physiology investigations because of their important role in oxygenation, filtration, and wastewater purification [5], [9]. In some countries, algae play a big role in the economy by the useful substances extracting from them. Microalgae also act as a useful biological indicator of environmental change and water quality monitoring [10], [11]. They also can be used in assessing ecological variations [12], addressing global environmental concerns including environmental degradation, energy demands [13], and producing light energy [1], [14].

In Egypt, one of the main noticed problems during summer is the numerous amounts of air conditioners (AC systems) that are working over the day producing a huge amount of outlet wastewater. The continuous water flow is causing great damage to the building façades besides the AC tubes that spoil the façade as shown in Fig. 1. As a way to prevent the damage of the façade caused by the water-waster, the paper presents an innovative sustainable product solution that aims to reuse the wastewater of the air conditioner as an automated watering platform for plants as a landscape element. The concept of the new device element stands for reusing algae as a local biopolymer material that is environmentally friendly and non-toxic with a low cost that adds more value to the design. Besides its availability in the Nile and its environmental benefits.

Figure 1: The damage of the wastewater from the AC tubes on the building façade in Egypt.

The paper documents the fabrication process of the 3D printing plant pot using bio-algae through our participation in (Algae lab workshop) that was held in Cairo under the supervision of Atelier Luma. The paper provides a method of using algae as a double skin in building façades for CO_2 filtration from the atmosphere. This element acts as an irrigation system that collects and cools the dropped water through an internal engraved spiral tube allowing water to flow around the outer skin till reaching the roots. The resulted prototype was tested on a building façade to measure its effect on solar radiation. A water simulation was done to verify the decrease in the water temperature from the air-conditioner tube until reaching the bottom of the pot. The reason for choosing the algae arises from two main factors which are; the high cost of the filament polymers and plastics that are neither locally produced nor widely available in the Middle East, and the non-sustainable filament that is hard to be scaled up. Using organic materials in 3D printing can change the production of plastic made from fossil fuels to be more environmentally friendly.

2 ALGAE AS A GROWN MATERIAL IN ARCHITECTURE

In Egypt, the River Nile, which is considered one of the main sources of water for irrigation, industrial and drinking purposes, contains different types of unused algae. Due to climate change and external pollution in this water, algae and biological life are affected [15]. Yet, the abounded availability of the organisms and macroalgal biomass in the marine ecosystem are considered as producers of clean source energy, oxygen, heat, and biological compounds biomass such as nutraceuticals, food, and fertilizers [7], [16], [17]. The global attention towards microalgae as a source of biofuel is mainly due to their ability to be converted into electricity and heat through the higher efficiency in the photosynthesis process [1]. This production process is activated by using sunlight and CO_2 to absorb carbon dioxide from the atmosphere transforming it into biomass and oxygen with the use of nutrients [2], [3].

With focusing on organic and ecological "grown material" studies and particularly on "algae-based" studies, the integration of algae in architecture has been performed at building and urban scale raising the threshold of resilience and built environment [3]. This integration opens new research dimensions to explore and reuse the renewable and waste materials that are merged in construction as a way to reduce the carbon emissions produced by the industrial materials. The application of living species as a construction material translated into algae-powered buildings is quite new in the world of architecture. Thus, this could serve as a multifunctional key to integrate smart cities with new eco-friendly technologies and concepts such as renewable energy production, waste valorization, circular economy, zero discharge, etc. Another usage of algal cells that they are being integrated into the design of solar thermal collectors because of their ability to improve indoor air conditioning systems, lighting systems, shading, etc. As an application, algae photobioreactors known as "PBR" became part of the building components that have been considered as a nature-based alternative to large glass surfaces [7]. One of the PBR benefits that they can provide shade during sunny days by cooling the building beside their long lifetime of 20 years, with an average of 1,480 kg of biomass production during this period [18]. The utilization of flat PBR panels on building façades can mimic the solar thermal unit in generating heat and efficiently absorb the UV light and other thermal light rays. Employing the production of bioenergy, preventing energy loss, recycling wastewater, and purifying air are among the major benefits.

Many applications of building façades used algae as an insulation and purification material to reduce environmental pollution, carbon emission, and produce oxygen.

Research into living architecture started to implement the biohybrid structure on the building façades [19] which is an integration of biological elements within structures to tackle the extreme environmental problems of our cities. The growing movement towards biohybrid structures potentially increases vegetation and green cover on building façades and rooftops. A bioprinting microalgae technique. Biomaterials as algae are represented as another group of naturally-derived biopolymers from marine biomass for 3D bioprinting for large-scale is developed for potential applications within architecture [19]–[21]. Thus, the appearance of additive manufacturing (AM) also known as 3D printing and rapid prototyping [22], [23] coupled with an interest in crafting traditions to develop biomaterials for architectural construction. One of the main AM advantages is the ability to reach homogenous hybrid structure components from mixed materials layer-by-layer [19] with no material waste. For instance, Ronald Rael with his group Emergent Object used non-conventional materials as sawdust, rubber, salt, and bioplastic as a 3D printing material [24].

From this perspective, the architects' role increased to bridge the gap between engineering and biotechnologist to develop new innovative products as a sustainable treatment. Eric Klarenbeek and Maartje Dros are Dutch designers who have developed a bioplastic made from algae as a solution to replace synthetic plastics over time. They cultivate algae then dry it to turn it into a filament material that can be used for 3D printers. After then the designers were invited to establish an open research and algae production lab at the Atelier Luma in Arles [25]. This lab developed an algae filament that can be used in 3D printers instead of PLA, which is used in our research.

Several applications of building façades and product design coupled algae with vegetation. In 2013, the BIQ (Bio Intelligent Quotient) house in Hamburg deployed Biohybrid large-scale structures on the façade including "PBR" Photobioreactors [19], which is considered the first bio-reactive green building façade known as solar-leaf. The PBR façades system is used as an adaptive shading screen and thermal insulation which in parallel utilizes the environmental advantages of algae to decrease carbon emissions. It also is regarded as a practicable solution to reduce the costs of this system [1], [3], [26] and to act as an acoustical element, economic, and aesthetics features. Through the treatment of wastewater, this façade used algal biomass and solar thermal heat to generate heat, biomass, biofuel, and bioenergy as renewable energy [2]. Bio reactive walls and PBR became a potential strategy for a ready scale-up of green walls [19] to transform CO_2 into biomass and oxygen through the photosynthesis process through sunlight and CO_2 [1], [3].

Another application that uses algae in 2019 is "H.O.R.T.U.S. XL Astaxanthing" which is considered the first 3D printed bio digital living sculpture and a new generation of biophilic architectural skin accessible on an urban scale. The project was a collaboration of many entities, where it was designed by ecologic-studio and fabricated by both CREATE group from the University of Southern Denmark and WASP Hub Denmark and developed by the Synthetic Landscape Lab at Innsbruck University. Inspired by coral morphology, a digital simulation was done to simulate the substratum growth. Based on large-scale 3D printers, the structure was made of triangular 3D printed units that were assembled to form hexagonal blocks. Cyanobacteria and micro-organisms were then injected into the printed units to absorb the carbon dioxide resulted from human breathing transforming it into oxygen and biomass through photosynthesis [27].

BANYAN eco wall project is one of the fully 3D printed green walls that comes with an embedded irrigation and drainage system designed by NOWLAB. The feature of this wall that it has rooted channels and a micro shower system that allows the feed of the plants with the precise amount of water and hydrates plants that live in and on the structure. The sophisticated drainage system of the prototype spans the whole structure [28]. The form of the wall was inspired by the organic components found in the plants such as roots, stems, and leaves. Without the AM technique, the complexity of the prototype form would be hardly achieved, injected the irrigation system inside, and controlled the size of the internal channels. The irrigation systems are fully controlled which ensures the amount of needed water in plants without human intervention need [29]. The project could be an inspiration for interior design or as a green vertical garden in façades and other forms of urban farming.

Apart from all the above-mentioned advantages of algae which need to be studied more deeply in practice, some challenges can be regarded applying PBR façade systems in buildings, which include a lack of sufficient regulation for construction, fire safety, and maintenance. Besides, the large-scale PBR needs complicated technology for biomass production, where regular maintenance is needed to ensure the cleanness of the living organism in the panel [1].

In Egypt, the massive availability of algae in the Nile and beaches is annoying, yet they are considered "biological waste" that is expensive to be disposed of. Tracing the gap where Egypt does not have any construction applications that use "algae" yet which is an abundant and renewable source, extracting "algae-based grown materials" can offer a new perspective for regenerative building construction to be integrated with the environment. Hence, the state of the art of our research is in using the wastewater from air conditioners in façades, unlike the previous algae applications. This is to highlight the importance of using this wastewater through a small-scale algal prototype which can be scaled up to be a façade element that functions for watering, filtration, purification, and aesthetic design as well.

3 MATERIAL AND METHOD

The paper highlights the importance of using the wastewater from air-conditioning for plantation which in parallel will reduce the carbon dioxide and act as an aesthetic element for more green façades. The methodology focuses on generating a prototype that is designed algorithmically using algae as filament material. The fabrication process of the prototype used a bioprinting technique that can change the plastic production in the world to be cleaner and environmentally friendly and provide more renewable resources. Fig. 2 shows the workflow of the fabrication that followed during the workshop which was two weeks long. The workflow started by sketching the prototype followed by a digital computational model on Rhino software for parameter controlling to prepare the model for printing. The digital model was converted to g-code layers to be ready for printing.

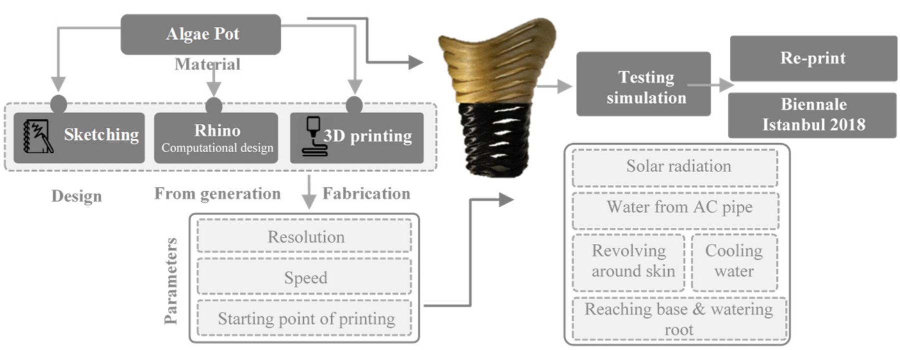

Figure 2: Method workflow process.

Different trials were done to adjust the speed of the nozzle and the temperature of the printer. The pot was then displayed at the design Biennial of Istanbul 2018, Arles 2018, Milano 2018, and Belgium 2019.

3.1 Material

The main material used is a ready-made algae filament -a bio-polymer mixture- whose ingredients were developed by Luma [30], confidential information under the umbrella of Algae lab a bio-laboratory in collaboration with Studio Klarenbeek and Dros. The production of this filament started in 2017 to explore the potential of growing both micro- and macro-algae by *Algae Lab*. The algae are mixed with biopolymers to produce a fully bio-sourced material that can replace non-biodegradable fossil oil-based plastics for a new circular production model through bio-fabrication as 3D printing [30]. The process of algae manufacturing was presented at the design Biennial of Istanbul as shown in Fig. 3.

Figure 3: The filament algae process by Algae Lab during design Biennial of Istanbul 2018.

3.2 Design process and form generation

The pot has dimensions of 40 × 20 cm that its main function is to provide an automated process for watering the plants by collecting the wastewater and transfer it back to roots. The novelty of the spiral form followed several iterations on Rhino software to design a multifunctional piece that includes pours patterns and engraves from inside to ensure smooth water fluidity from the air conditioner tube until reaching the base. The spiral engraves act as an inner tube inside the pot which decreasing the outlet water temperature from the air-conditioner to be suitable for plantations While the patterns allow the airflow to pass to cool the water and act as an aesthetic form. The top of the pot is designed to be connected with the AC outlet pipe to guarantee to collect the water directly from the source as shown in Fig. 4. The pot diameter is larger in the top for providing a longer path to increase the water flow time and to ensure cooling the warm water from the tube before reaching the bottom.

3.3 Fabrication and machine

For the fabrication process, two models of 3D printers were used (Ultimaker 2) and (Monoprice MP Select Mini 3D Printer V2). The digital model of the prototype was divided into slices to be printed layer-by-layer each has its designed pattern through 3D slicer software – open-source – to be ready for printing. With a layer thickness of 0.1 mm,

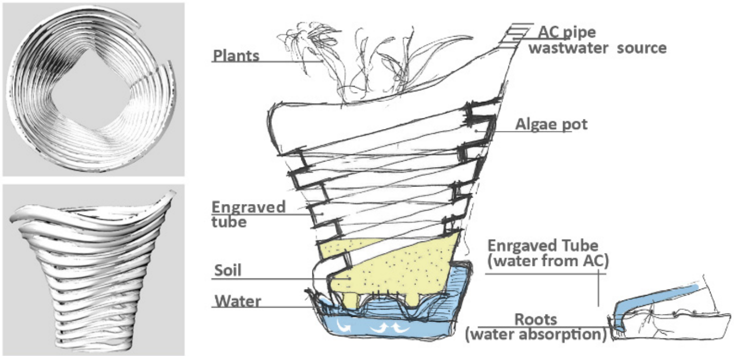

Figure 4: The form of the pot shows the mechanism of the water flows till reaches the base.

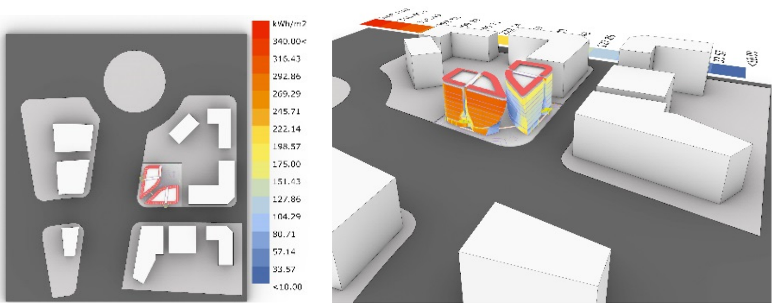

Figure 5: Radiation analysis of the building at the new administrative Capital in Cairo.

each layer was characterized by specific coordination (x, y, and z). Utilizing these data, the 3D printer traced each layer with a speed of 100 mm/s and a temperature of 220°C. The algae filament was not tested before in Egypt, which forces us to test the form first with its real scale using PLA filament to set any modification needed in the design before adding algae filament to the printer. A small-scale mock-up was first tested by using algae filament to examine the engraving in the form, temperature, speed, and accuracy. Several iterations were experienced to reduce the printing time and provide the material waste to print the pot with no support.

3.4 Mechanism and solar radiation test

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. The test was done by using the ladybug tool in the Grasshopper plug-in in Rhino. This tool provides a direct calculation for the percentage of daylight exposure on a building façade through the year without any further calculations [31]. With a site selection at the New administrative capital in Cairo during July which is one of the highest degree summer months during the year, the shadow diagram helps in determining the best façade to place the PBR algae growing systems based on the number of hours exposed to the sunlight and the surrounding neighbouring which is our case western façade where the angle of the sun is lower than the southern façade as shown in Fig. 5. The direct sun exposure which is the main factor is to complete the close cycle of the PBR through photosynthesis. A water simulation was run to show the reduction of its temperature till reaching the end of the pot showing the circulation of the warm water cycle.

4 RESULTS AND DISCUSSIONS

4.1 Fabrication and printing mechanism

During the several iterations of setting up for parameters, speed, resolution, and direction of the printing, Fig. 6(a) shows the stability of the printing process using algae on the small-scale, where it started from the small diameter base till reaching upward the pot. It was observed that during the scaling up, some failures accrued because of the layers' weight where the materials needed more structural support. Accordingly, the pot was flipped upside down as shown in Fig. 6(b) to print the wide diameter of the top to ensure holding the weight without any extra structure support, which decreased the material waste. During the fabrication printing process, the form was tested with PLA before using the algae filament to ensure the consistency and smoothness of the water flow in the internal engraves. The complexity of the engraved form causes some errors during setting the speed.

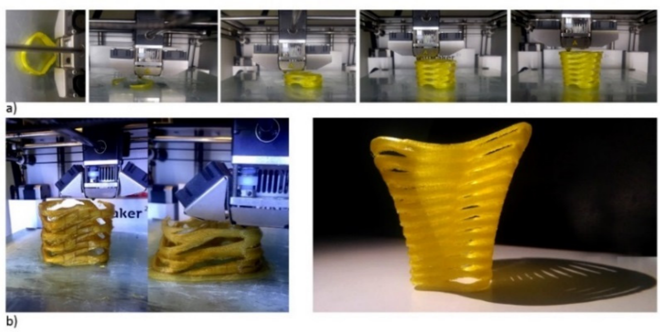

Figure 6: (a) The printing process of the small-scale; and (b) The two printing iterations of flipping the pot.

4.2 Path planning strategy for minimal support

Path planning strategy was followed to achieve successful fabrication without any structure supports for saving unnecessary material waste and fabrication time. Thus, different iterations were tested for managing the minimal way of positioning the pot for printing as shown in Fig. 7(a). The printing started with the base as a starting point in the first iteration till reaching the top. It was observed that the deformation that occurred was a result of the form inclination where the radius of the base is smaller than the top. Hence, the layer was not hard enough to support and hold the additional weight of the materials upon each layer, which caused a pressure below causing collapse as shown in Fig. 7(b).

Consequently, in the second iteration, the direction of the pot printing was flipped where the top was printed first. This flip allowed the wider radius to act as a support during the printing to hold the weight of the above layers. This mechanism decreased the filament waste in the supports as shown in Fig. 7(c). For time reduction in the total nozzle movement length, a continuous path planning strategy was followed to decrease the distance traveled between subsequent space-filling for both the cantilever layer and the curves providing more time.

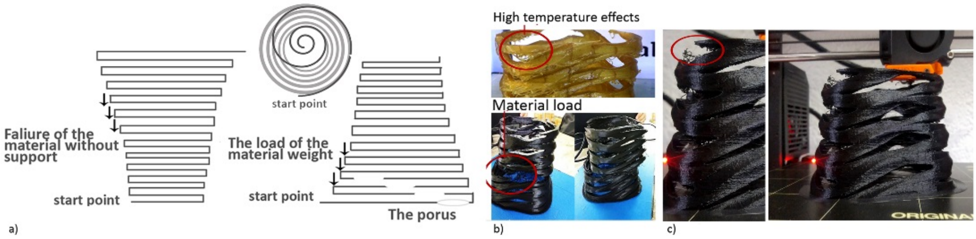

Figure 7: (a) The spiral path; (b) The errors during printing; and (c) Minimum waste with no support.

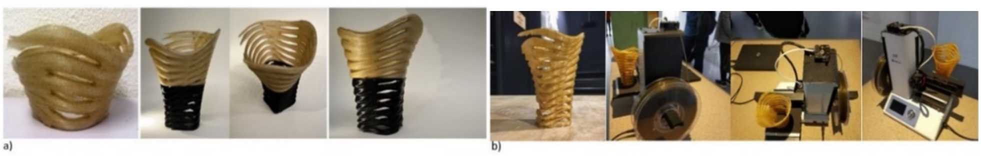

Figure 8: (a) The algae printed pot; and (b) Printing process during the Biennale exhibition, 2018.

4.3 Time reduction

Concerning the nozzle speed, resolution, and temperature, some failures occurred in the middle of the model while printing, where the speed started with 50 mm/s and an extrusion temperature of 280°C. It was observed that the higher temperature was, the higher the gaps in the materials that occurred. Therefore, the speed was increased to be 100 mm/s with a temperature of 220°C. Time reduction was one of the main targets to achieve the completed printing pot successfully with good quality. Yet, as known that 3D printing is a trial-and-error process where it needs more trials to get the final results. The estimation of the time was calculated before printing with a total of 18 hours when the speed was 50 mm/s. The prototype was first printed as a whole unit which was time-consuming because of the corruption that occurred during the printing. Therefore, the prototype was cut into two parts to be printed separately to decrease the failure, with a reduction in the resolution and increase in the speed which then decreases half of the time to be 9 hours in total for both parts. Fig. 8 shows the final assembly of the pot exhibited at the design Biennale in Istanbul in 2018, where the printer was set to print on-site to allow user interaction showing the whole printing process.

4.4 Solar radiation assessment and water temperature

Fig. 9 shows the comparison of the sun radiation before and after installing the algae PBR panel on the western building façade. The first model (a) shows a maximum radiation scale of 316.43 kWh/m^2. Taking into consideration that the optimum thermal radiation is between 80 to 100 kWh/m^2, the radiation in the model (b) after adding the algae panel was decreased to reach lower radiation that varies between 80.71 and 104.29 kWh/m^2. This will allow using less AC which in parallel will decrease the energy cost and the consumes excess energy.

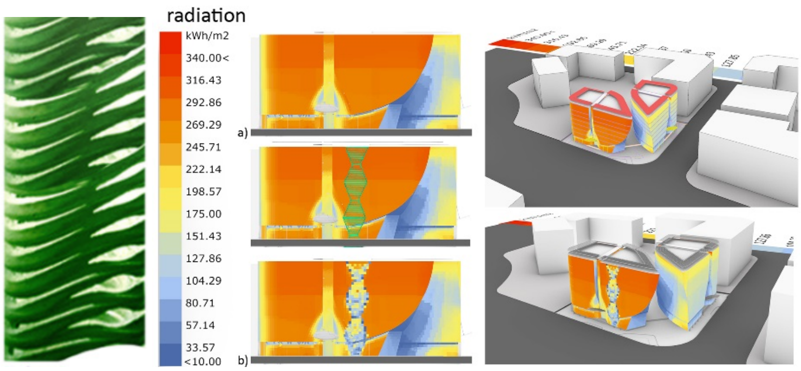

Figure 9: The sun radiation on the western façade before and after adding the algae panel.

Fig. 10 shows the fluidity of the water through the spiral engraves that allow water to flow around the skin and cool the water droplets till reaching the roots. The length of the spiral path (60 cm) with the wide diameter at the top allowed more travel time to the water which decreased its temperature around 5–6°C from 42°C to be 36°C which means (1 degree each 10 cm. The small opening patterns in both the model and the panel prevent the solar radiation to pass inside, yet it still completes the cycle of photosynthesis to filter the carbon dioxide.

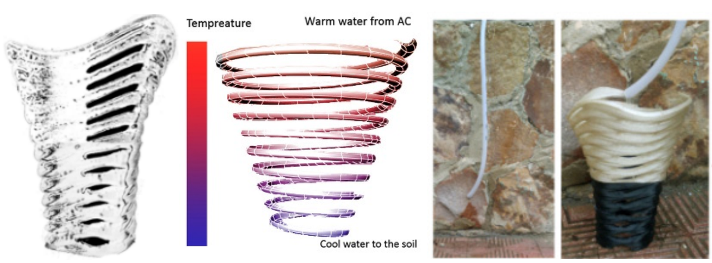

Figure 10: The decrease in the water temperature through the engraved spiral inner tube.

5 CONCLUSION

The paper highlights the importance of algae as a grown material showing several architectural applications integrated into building façades. The benefits of algae can be seen as producers of clean source energy, oxygen, heat, and biomass and also for CO_2 absorption through the photosynthesis process. Potentially, the paper demonstrated the possibility of a 3D printing algae device for using wastewater and attempted to generate an automated watering system on a small-scale pot that can then be applied up-scaled as bio-reactive green façades for self-controlled growth on buildings and urban scale.

The solution in this paper mainly targets rich places with algae to reuse this biomaterial in 3D printed construction elements. The added value of the new prototype lies in its automation system, affordability, property, flexibility, and sustainability. The spiral design played the main role in cooling the wastewater from the AC tube till reaching the soil. The fabrication process elaborated the direction of the printing which used a minimal amount of material without any structural support which provided unnecessary waste materials. The paper reached a process that could be followed regarding our different usage of algae. Given the alarming increase in the current substitution of traditional materials with new industrial materials, we believe that the findings will impact the construction building façades and will open new doors for more innovative large-scale PBR applications. This research is considered a first step to integrating algae in architecture where further research will be followed to study the LCA and thermal tests. Further research is also needed to monitor the effects of PBR-based microalgae façade design on its performance. On an urban scale, PBR can be inserted directly into the existing buildings, performing the dual function of absorbing CO_2 and producing biomass where needed most. Therefore, we assumed that in the future, these self-watering biohybrid systems could be custom fabricated with large scales using AM techniques from biomaterials. Further environmental and life cycle assessment of the algae is needed for future research. The CO_2 efficiency needs to be measured in future studies. A cost and benefit analysis to compare the tangible and intangible benefits of PBR system is needed. Finally, the future of 3D bioprinting towards bio digital materials will allow anyone to customize and 3D print any element using any type of materials as simple as baking bread.

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