IJHSR
ijhighschoolresearch.org
RESEARCH ARTICLE

Development and Evaluation of a Novel Automated Spirulina Cultivation System for Sustainable Food Production: A Sustainable Solution

Mohamed Abdelghani, Saif Eldin Hatem, Omar Khaled, Mohamed Hashim

STEM High School for Boys - 6th of October, Hadayek October, Giza, 6th of October, 12578, Egypt; mohamedi.mashhour1@gmail.com
Mentor: Mohamed Bekheet

ABSTRACT: This research paper presents an innovative automated system to cultivate spirulina, a microalga with significant potential as a sustainable food source. Spirulina is a nutrient-rich microalga that can address malnutrition and food insecurity globally. However, large-scale cultivation requires an automated system. This study aimed to develop and evaluate an automated photobioreactor system to cultivate spirulina. A prototype system was constructed with integrated pH and temperature control mechanisms. Structured experiments assessed the maintenance of optimal pH 9-10 and temperature 30-35°C. The system effectively sustained desired growth conditions despite perturbations. Continuous sensor measurements evidenced rapid feedback correction. The automated system demonstrates immense promise for sustainable, large-scale spirulina production. Additionally, further optimization can enhance productivity. This novel technology can improve food security, nutrition, and health, particularly in regions with high malnutrition rates.

KEYWORDS: Biomedical and Health Sciences; Nutrition and Natural Products; Spirulina; Automated Cultivation System; pH & Temperature Regulation.

Introduction

According to the Food and Agriculture Organization (FAO), between 691 and 783 million people faced hunger in 2022.[1] It has been estimated that the hunger crisis is pushing "one child into severe malnutrition every minute in 15 crisis-hit countries." UNICEF estimates that among these 15 countries, a minimum of 40 million children are severely malnourished, lacking access to the essential and varied diet.[2] This alarming scenario underscores the urgent need to address the global food crisis.[3-8] According to this, the urgent search for viable and sustainable food sources has become imperative.

Among the various possibilities, spirulina, scientifically named *Arthrospira platensis*, is a microscopic blue-green alga that has emerged as a promising candidate, i.e., a promising solution for the global crisis. This alga is distinguished by its extensive nutritional profile, encompassing vitamins, minerals, and proteins. Having the ability to grow in various environments, spirulina is known for its adaptability and resource efficiency. Further, spirulina's capacity to function as a sustainable and nutrient-rich food source has attracted significant scholarly interest. Thus, this underscores its potential to address issues related to malnutrition and food insecurity on a global scale. In addition to this, spirulina also holds great potential in various other sectors, including pharmaceuticals and cosmetics, owing to its potential therapeutic properties and natural pigments. Additionally, it is used in wastewater treatment due to its ability to remove contaminants.[9-15]

Numerous scholarly studies have corroborated that the optimal conditions conducive to Spirulina growth are a temperature range of 30°C to 35°C and a pH range of 9 to 10. For instance, research published in the Journal of Applied Phycology demonstrated that Spirulina exhibits its most efficient growth under these specific temperature and pH conditions. This finding is further substantiated by another study from MDPI, which emphasized that Spirulina thrives best in highly alkaline environments and can flourish across a wide variety of pH values. Similarly, research published in Springer confirmed that Spirulina's growth and pigment production were most efficient under the same conditions of temperature and pH. Moreover, a study conducted by Maejo University, Thailand, concluded that the highest growth yield of Spirulina resulted from pH levels between 8.5 and 10.5 and temperature ranges of 25 to 30°C.[16-19]

This research paper aims to present an innovative automated system designed to cultivate spirulina, eliminating the necessity for manual labor or human intervention. The automated system seamlessly integrates with the photobioreactor, adeptly regulating pH within the optimal range of 9-10, sustaining a temperature between 30-35°C, and achieving waste-free operation.

This research paper is organized into key sections. Firstly, the paper emphasizes the importance of spirulina cultivation and its necessity as a food source. Then, the paper will delve into the methodology employed to develop the automated spirulina cultivation system. Following that, the results of rigorous testing to evaluate the system's performance will be discussed. The paper will conclude with a comprehensive discussion and analysis of the findings and implications for future research in this domain.

DOI: 10.36838/v6i6.5

Methods

The medium for growing the spirulina was prepared by dissolving and mixing chemicals in distilled water (Table 1).

Table 1: This table shows the chemicals used to make the medium.

Media for Spirulina	
$NaHCO_3$	16.8 g/l
NaCl	1 g/l
Urea	0.9 g/l
K_2HPO_4	0.5 g/l
K_2SO_4	1 g/l
$MgSO_4$	0.2 g/l
$CaCl_2$	0.04 g/l
$FeSO_4$	0.01 g/l
Na. EDTA	0.08 g/l
Boric Acid	2.86 g/l
Copper Sulphate	0.07 g/l
Manganese Sulphate	1.81 g/l
Zinc Sulphate	0.222 g/l

The construction of the algae growth environment prototype involved several key steps. Firstly, an acrylic tank was custom-fabricated, featuring dimensions measuring 14 cm in length, 14 cm in width, and 24 cm in height. Four identical rectangular acrylic boxes were also crafted, each measuring 2.4 cm by 2.4 cm by 24 cm. This collective assembly serves as the fundamental structural framework for our prototype (Figure 1). Subsequently, these four rectangular acrylic boxes were securely affixed within the acrylic tank, thus forming individual compartments designed to house LED modules (Figure 2). LED light strips were positioned within each rectangular box to facilitate controlled lighting conditions within the prototype, comprising the illumination system.

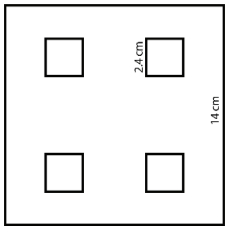


Figure 1: Identical rectangular acrylic boxes, each measuring 2.4 cm x 2.4 cm x 24 cm.

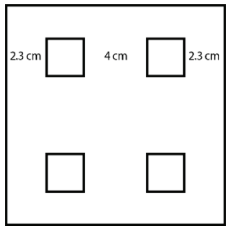


Figure 2: Integration of rectangular acrylic boxes into the acrylic tank, creating LED lighting compartments.

Image 1 shows the complete prototype.

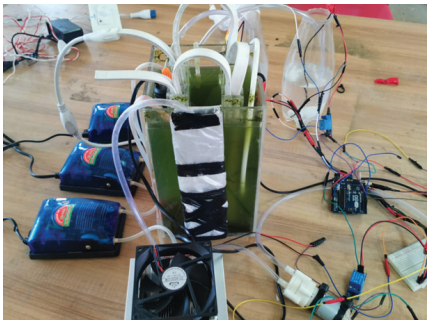


Image 1: A complete view of the prototype.

In our research, precise pH measurements were crucial, necessitating a rigorous calibration process to ensure the accuracy and reliability of our pH sensor. This process began with selecting calibration standards to serve as reference points for our measurements. Our initial choice for calibration was distilled water, known for its pH value of 7 at 25°C, offering a stable foundation for our calibration. The calibration procedure involved several steps. Firstly, a calibration solution was prepared using distilled water, with strict attention to maintaining a consistent temperature matching our experimental conditions. Subsequently, the pH sensor was immersed in the solution to ensure precision, allowing adequate time for the sensor to stabilize and reach thermal equilibrium with its environment. The pH sensor's readings were recorded once stabilization was achieved, and this process was independently repeated ten times to establish data consistency and precision.

Our calibration process included refinement through adjustments to the potentiometers within the sensor module, guaranteeing optimal sensitivity and linearity in pH measurements. Immediate adjustments were made when deviations exceeded our predefined error tolerance, maintaining the sensor's accuracy throughout the research. Following calibration with distilled water, a critical verification step involved measuring the pH of acetic acid (CH3COOH), known to have a pH value of approximately 2.4 in a 0.4 M solution at 25°C. This served as a reliable reference standard. Each measurement with acetic acid was conducted independently, consistently yielding a modest error of approximately 0.2 pH units. This minimal error was duly acknowledged and integrated into subsequent pH measurements during our experiments, emphasizing our commitment to precision.

The prototype incorporates essential feedback systems to regulate pH and temperature, ensuring optimal conditions for algae growth. We initiated the process in the pH feedback system by preparing 500 ml of 0.4 M acetic acid and 500 ml of 0.2 M sodium hydroxide solutions. Two 1-liter plastic bottles were designated as containers for these solutions. The pH sensor was meticulously integrated into the acrylic tank to monitor pH levels within the growth medium. The components of the pH feedback system were interconnected to facilitate real-time pH monitoring and adjustment (Figure 3).

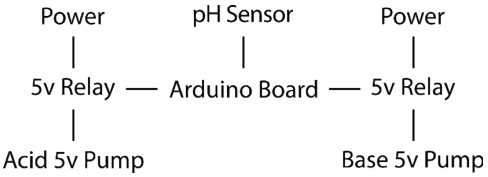


Figure 3: Interconnected components of the pH feedback system for real-time pH monitoring and adjustment.

In tandem, the prototype features a temperature feedback system to maintain the desired temperature range conducive to algae growth. This system encompasses a heating coil affixed to the tank's wall for controlled heating and aluminum sheets on the interior and exterior tank walls to facilitate efficient temperature regulation. Working with a Peltier Refrigeration

cooling system, this setup ensures precise temperature control (Figure 4).

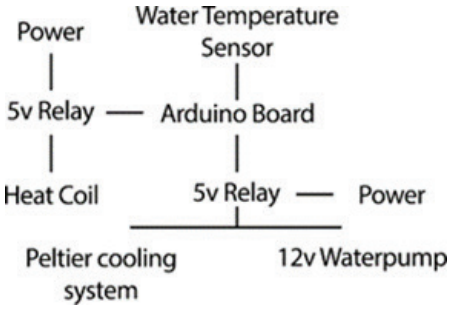


Figure 4: Interconnected components of the temperature feedback system for real-time temperature monitoring and adjustment.

Additionally, we implemented a bubbling system to promote effective aeration within the algae growth medium and prevent the formation of biofilms. An aerator was thoughtfully connected to an aquarium bubbler submerged within the tank, enhancing the system's overall efficiency.

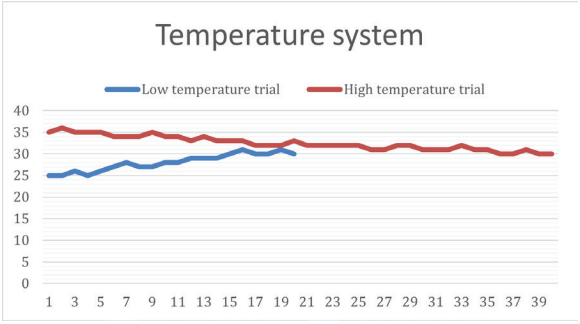
A test plan was implemented to rigorously assess the prototype's ability to uphold optimal algae cultivation conditions. This plan encompassed a series of structured experiments designed to evaluate the system's performance. In the initial phase, 50 ml of 0.8 M acetic acid was introduced into the algae growth medium. Employing a pH sensor, continuous monitoring of pH levels within the growth medium commenced. The process entailed thorough documentation of pH sensor readings, focusing on the system's ability to achieve and maintain the desired pH conditions. After this, 10 ml of 1 M sodium hydroxide (NaOH) was introduced into the growth medium, and pH tracking with the sensor was initiated again. The objective was to continuously record pH readings and observe the system's proficiency in adjusting pH conditions in acidic and alkaline directions.

Subsequently, controlled heating was applied to exceed the optimal temperature range using the heating coil. At the same time, a cooling experiment was executed to lower the temperature below the optimal threshold through the water-cooling system. Throughout these heating and cooling trials, temperature sensor readings were recorded and plotted to assess the control system's effectiveness in maintaining the desired temperature range conducive to optimal algae growth.

■ Result and Discussion

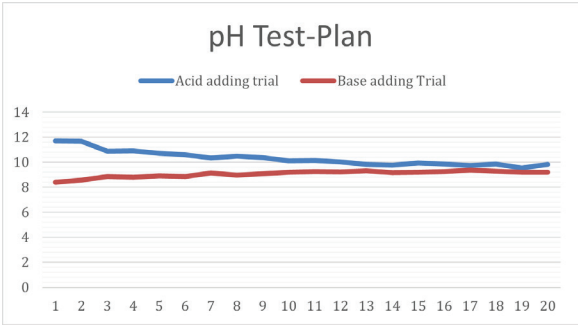
Results:

The prototype has demonstrated a performance consistent with the established design criteria, affirming its efficacy. The design specifications principally revolved around two key parameters: temperature and pH regulation within the photobioreactor. Despite external variables inherently influencing temperature, the implemented feedback control system effectively maintained an optimal temperature range of 30-35°C (Graph 1).



Graph 1: Maintenance of the optimal temperature range (30-35°C) by the implemented feedback control system.

Similarly, the pH control system exhibited comparable performance. Even when subjected to the introduction of acids or bases intended to perturb the pH levels, the feedback control mechanism adeptly sustained the desired pH range of 9-10 (Graph 1). Furthermore, a comprehensive assessment of the photobioreactor was conducted to assess the potential generation of waste byproducts. Remarkably, the reactor demonstrated a complete absence of waste production, thus unequivocally meeting the stipulated criteria.



Graph 2: The implemented feedback control system maintains the optimal pH range (9-10).

The tables provided contain the data utilized to generate the corresponding graphs. Tables "a" represent the pH sensor readings obtained during two distinct experiments, introducing acidic substances and basic substances. Table "b" contains temperature readings recorded during two separate experiments, one involving heating and the other involving cooling. These tables are the foundation for this research's graphical representations and analysis.

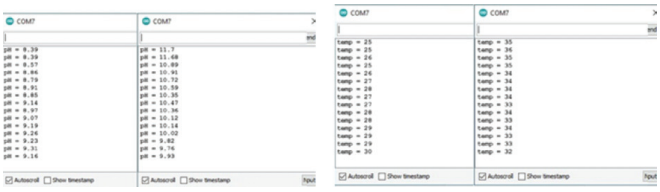


Table 2: Tables a represent pH sensor readings (acidic and basic experiments); tables b represent temperature readings (heating and cooling experiments).

Discussion:

-Temperature feedback system:

The temperature feedback system effectively maintained the prescribed temperature range of 30-35°C and pH levels

DOI: 10.36838/v6i6.5

between 9-10, fostering the optimal growth conditions for spirulina. Observable evidence of spirulina growth, signified by an increased greenish coloration, substantiated its efficacy, consistent with findings from previous research papers.

The efficiency of the temperature feedback system in transferring heat to and from the reactor was critical to its performance. This efficiency was underpinned by applying Fourier's Law of Heat Conduction. According to this law, the heat transfer rate is directly proportional to the material's temperature gradient and thermal conductivity. In our context, the selection of the conductive material between the water-cooling system and the photobioreactor was based on this fundamental principle. Aluminum plates were chosen after a calculation of their heat transfer rate using the formula:

$$Q = \frac{kA\Delta T}{d}$$

Where:

- Q represents the heat transfer rate,
- k is the thermal conductivity of the material,
- A signifies the surface area,
- ΔT denotes the temperature difference between the two surfaces and
- d represents the thickness of the material.

$$Q = \frac{205\ W/mk \times 0.07\ m \times 0.21\ m \times (35°C - 25°C)}{0.0015\ m} = 20090\ W$$

The calculation yielded a heat transfer rate of 20090 W, underscoring the significant efficacy of aluminum in facilitating rapid heat transfer. Water, acting as a coolant, complemented the aluminum plates within the temperature feedback system. Its high thermal conductivity (0.6 W/mK) and specific heat capacity (4.18 J/gK) enabled it to absorb substantial heat energy and efficiently convey it to the cooling system. Moreover, water's ready availability and cost-effectiveness rendered it a practical choice for the water-cooling system.

Fourier's equation was applied to further illustrate the effectiveness of water as a conductive medium between the water-cooling system and the aluminum plates. Assuming a liquid temperature of 30˚C and an aluminum plate temperature of 35˚C, the calculated heat transfer rate through the aluminum plate amounted to 10045 W, as shown in the following calculation.

$$Q = \frac{205\ W/mk \times 0.07\ m \times 0.21\ m \times (35°C - 30°C)}{0.0015\ m} = 10045\ W$$

This outcome reaffirmed the efficiency of water as a conduit for heat transfer between the water-cooling system and the aluminum plates, thus contributing to the overall effectiveness of the temperature feedback system.

-Light Source:

The choice of wavelength for the light source was determined based on its known effect on the growth of spirulina, as supported by previous research findings. An earlier trial revealed inefficient distribution of light intensity within the photobioreactor, resulting in areas with both excessively high and low light intensity. This imbalance adversely affected algae growth, leading to its deterioration. To rectify this issue, the positioning of LED lights was adjusted using principles derived from the Beer-Lambert law, which elucidates the attenuation of light as it traverses a medium, such as a liquid culture.

According to this law, light intensity at a specific depth is directly proportional to the initial light intensity and the attenuation coefficient, quantifying the extent to which light is absorbed or scattered per unit length of the medium. In our photobioreactor scenario, the attenuation coefficient measured 0.0164 cm^-1. With a photobioreactor height of 24 cm, the resulting light intensity at the reactor's top was attenuated by a factor of e^(0.0164 cm^-1 * 24 cm) as it traversed the culture, yielding a value of 53.86 µmol photons/m^2/s under ideal conditions, assuming no losses from reflections or other factors.

This calculated value served as the basis for determining the minimum light intensity required at the bottom of the reactor to ensure every point in the culture received sufficient light for effective photosynthesis. LED strips were employed to meet this minimum requirement, providing a minimum intensity of 5.39 µmol photons/m^2/s at the reactor's bottom. This calculation presupposes uniform light distribution within the rectangular reactor and the necessity for every point in the culture to receive at least 10% of the intensity at the reactor's top for efficient photosynthesis to occur.

-Aeration System:

In a previous experimental trial, an issue emerged when the aerator was connected to the photobioreactor through a single opening, leading to an uneven distribution of gasses within the photobioreactor. This uneven distribution resulted in biofilms, thin layers of various microorganisms, including bacteria, fungi, and algae. Upon observation, it was evident that biofilms had a detrimental impact on spirulina growth. They competed with spirulina for essential nutrients and light, obstructed the flow of gases and fluids, and impeded spirulina development. Additionally, biofilms could lead to fouling, diminishing the system's efficiency and necessitating increased maintenance efforts. To address this issue, a modification was introduced involving using five aquarium bubblers to uniformly distribute air throughout the photobioreactor, thus preventing biofilms' formation. This adjustment mitigated biofilm formation and ensured adequate oxygenation of the culture medium. Introducing air into the aquarium bubblers through pipes facilitated the even dispersion of air bubbles throughout the medium, addressing the initial problem.

■ Conclusion

This research study presents the development and evaluation of an automated system for cultivating spirulina. The system integrates pH and temperature control mechanisms to maintain optimal growth conditions within a photobioreactor. Structured experiments confirm the system's ability to sustain the desired pH range of 9-10 and temperature range of 30-35˚C despite perturbations—the feedback systems rapidly correct deviations, as evidenced by continuous sensor measurements. No waste byproducts were generated, satisfying a key design criterion. The system's efficacy is further substantiated

by observable Spirulina growth and proliferation within the photobioreactor. Quantitative analysis of growth rates and biomass yields would provide additional validation and could be pursued in future work.

Acknowledgments

We extend our genuine gratitude to Dr. Mohamed Bekheet for his invaluable mentorship. His guidance and support have been instrumental in making this research paper possible.

References

1. *Hunger.* Food and Agriculture Organization of the United Nations. https://www.fao.org/hunger/en/.
2. *Global hunger crisis pushing one child into severe malnutrition every minute in 15 crisis-hit countries.* https://www.unicef.org/press-releases/global-hunger-crisis-pushing-one-child-severe-malnutrition-every-minute-15-crisis.
3. Swaminathan, M. S. Achieving Food Security in Times of Crisis. *New Biotechnology* **2010**, *27* (5), 453–460. https://doi.org/10.1016/j.nbt.2010.08.002.
4. Weinberger, K.; Easdown, W.; Yang, R.-Y.; Keatinge, J. D. H. Food Crisis in the Asia-Pacific Region. *PubMed* **2009**, *18* (4), 507–515.
5. Sánchez, P. A.; Buol, S. W. Soils of the Tropics and the World Food Crisis. *Science* **1975**, *188* (4188), 598–603. https://doi.org/10.1126/science.188.4188.598.
6. Caplan, P. Struggling for Food in a Time of Crisis: Responsibility and Paradox. *Anthropology Today* **2020**, *36* (3), 8–10. https://doi.org/10.1111/1467-8322.12573.
7. Hashim, H. T.; Miranda, A. V.; Babar, M. S.; Essar, M. Y.; Hussain, H.; Ahmad, S.; Tazyeen, S.; Abujledan, H. M.; ALsanabani, N. T.; Khan, H.; Ramadhan, M. A.; Tuama, Y. D.; Isa, M. A.; Ahmadi, A.; Lucero-Prisno, D. E.; Islam, S. M. S.; Basalilah, A. F. M. Yemen's Triple Emergency: Food Crisis amid a Civil War and COVID-19 Pandemic. *Public Health in Practice* **2021**, *2*, 100082. https://doi.org/10.1016/j.puhip.2021.100082.
8. Liao, I.-C.; Chao, N. Aquaculture and Food Crisis: Opportunities and Constraints. *PubMed* **2009**, *18* (4), 564–569.
9. Khan, Z.; Bhadouria, P.; Bisen, P. S. Nutritional and Therapeutic Potential of Spirulina. *Current Pharmaceutical Biotechnology* **2005**, *6* (5), 373–379. https://doi.org/10.2174/138920105774370607.
10. Mishra, P.; Singh, V. P.; Prasad, S. M. Spirulina and Its Nutritional Importance: A Possible Approach for Development of Functional Food. *Biochemistry & Pharmacology* **2014**, *03* (06). https://doi.org/10.4172/2167-0501.1000e171.
11. Holman, B. W. B.; Malau-Aduli, A. E. O. Spirulinaas a Livestock Supplement and Animal Feed. *Journal of Animal Physiology and Animal Nutrition* **2012**, *97* (4), 615–623. https://doi.org/10.1111/j.1439-0396.2012.01328.x.
12. Sánchez, M. P. R.; Bernal-Castillo, J.; Rozo, C.; Rodríguez, I. Spirulina (Arthrospira): An Edible Microorganism: A Review. *Universitas Scientiarum* **2003**, *8* (1), 7–24.
13. Koru, E. Earth Food Spirulina (Arthrospira): Production and Quality Standarts. In *InTech eBooks*; **2012**. https://doi.org/10.5772/31848.
14. Usharani, G.; Saranraj, P.; Kanchana, D.; Nagar, A. Spirulina Cultivation: A Review. *International Journal of Pharmaceutical & Biological Archive* **2012**, *3* (6).
15. Soni, R. A.; Sudhakar, K.; Rana, R. S. Spirulina – From Growth to Nutritional Product: A Review. *Trends in Food Science and Technology* **2017**, *69*, 157–171. https://doi.org/10.1016/j.tifs.2017.09.010.
16. Bhat, O. A.; Unpaprom, Y.; Ramaraj, R. Spirulina Cultivation Under Different light-emitting Diodes for Boosting Biomass and Protein Production. *Molecular Biotechnology* **2023**, https://doi.org/10.1007/s12033-023-00842-8
17. Doan, T. T. Y.; Ho, M.; Nguyen, H.; Han, H. Optimization of Spirulina sp. cultivation using reinforcement learning with state prediction based on LSTM neural network. *Journal of Applied Phycology* **2021**, *33* (5), 2733–2744. https://doi.org/10.1007/s10811-021-02488-y
18. AlFadhly, N. K. Z.; Alhelfi, N.; Altemimi, A. B.; Verma, D. K.; Cacciola, F. Tendencies Affecting the growth and cultivation of genus spirulina: An investigative review on current trends. *Plants* **2022**, *11* (22), 3063. https://doi.org/10.3390/plants11223063
19. Kumar, D.; Kumar, N.; Pabbi, S.; Walia, S.; Dhar, D. W. Protocol optimization for enhanced production of pigments in Spirulina. *Indian Journal of Plant Physiology* **2013**, *18* (3), 308–312. https://doi.org/10.1007/s40502-013-0045-8

Authors

Mohamed Abdelghani is a rising senior at STEM High School for Boys - 6th of October, Egypt. Mohamed's passions lie in neuroscience, psychology, and environmental science. Mohamed is eager to pursue a double major in neuroscience and psychology for his undergraduate studies at his dream school, Harvard.

Omar Khaled is a rising senior at STEM High School for Boys - 6th of October, Egypt. Omar's passions lie in molecular biology and physics. Omar is eager to pursue a major in molecular biology for his undergraduate studies.

Seif Eldin Hatem is a rising senior at STEM High School for Boys - 6th of October, Egypt. Seif's passions lie in chemistry and computer science. Seif is eager to pursue a double major in chemistry and computer science for his undergraduate studies.

Mohamed Hashim is a rising senior at STEM High School for Boys - 6th of October, Egypt. Mohamed's passions lie in biology and neuroscience. Mohamed is eager to pursue a medical major, with a particular interest in surgical specialties, for his undergraduate studies.

DOI: 10.36838/v6i6.5