ISSN: 18158129 E-ISSN: 18151027
Volume 18, Issue 07, July, 2022

DESIGN PANEL OF HEXAGONAL NANOWIRE-BASED BLUE LEDS FOR INACTIVATION BACTERIA IN FOOD SAFETY

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ABSTRACT— Thanks to the development of theoretical foundations and technical methods in manufacturing Light Emitting Diodes (LED), many innovative design ideas and applications have been developed and recorded in many fields. Previously, blue light (400-470 nm) has successfully shown the ability to inactivate many strains of harmful bacteria. In this context, we fabricated a 405 nm LED panel with the full width at half maximum (FWHM) of ~10 nm to illuminate common harmful bacteria strains, including *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*). A LED panel consists of 6 LEDs with nanowire structure arranged in a uniform hexagon. The LED panel is composed of functional components for easy replacement and improvement which provides to the safety and convenience of use. We checked the photoelectric parameters to prove the ability of the LED panel to work continuously in high power mode with a proper temperature for practical use. We observe that the panel under specific experimental conditions shows the bacterial inactivation rates of up to 90% for *S. aureus* at 10^{-6} CFU/ml. According to the design calculations and practical measurements related to the LED system, a series of reliable parameters has been collected, showing the suitability to become a device used in bacterial inactivation experiments.

KEYWORDS: Light Emitting Diode, Antimicrobial Blue Light (aBL), Bacterial Inactivation, Photodynamic Therapy (PDT), Food Safety

1. INTRODUCTION

Light Emitting Diode (LED) contributes to the rapid development of applications. One of which is considered to be an ideal light sources which meet practical requirements. LED light sources have promising properties such as versatility, suitability, and ease of use element due to many reasons. Firstly, the small size and light weight make it easy to integrate and replace. Secondly, the lifespan of LED chips can reach tens of thousands of hours, which is suitable in system installations requiring long-term stability. Thirdly, working with LED-based devices does not require special training for the user compared to Laser Diode light source. The last but not least, LEDs have a significant efficiency (about 10% much larger than other conventional sources and LASER, except LASER Diodes); the output power of LED arrays, when combined, can be enormous, much more than laser diode [1]. Lighting systems based on LEDs have recently been built and expanded in continuous applications from display technology, optical sensors, therapy, and healthcare [2- 4].

The field of bacterial inactivation poses a real challenge with rapid change, evolution, and the emergence of numerous new forms of drug resistance. Overcoming these antibacterial changing requires constantly changing and complementary methods to achieve the best performance under different conditions. Over the past decade, many studies have reported using blue light in the inactivation of bacterial strains - antimicrobial blue light (aBL) as a branch of interest in photodynamic therapy (PDT). A series of publications aims to update findings from new studies, including the effectiveness of aBL inactivation on different bacterial strains, its mechanism of action, the support of aBL along with other antimicrobial agents, or their effects on host cells and tissues [5- 7].

Applying aBL as a method for the inactivation of bacteria requires research and development of a suitable lighting system. In many previous experiments, many light sources have been used in bacterial inactivation, such as lamps combined with filters (tungsten filament lamps, tungsten-halogen lamps, gaseous-discharge lamps, Xeon lamps, metal halide lamps, …), LASER and LED [8- 12].

Table 1: Characteristics and results when using different types of light sources in bacterial inactivation

Light sources	Parameters	Photosensitizer	Results	Reference
Metal halide Lamp	$\lambda \in$ (600- 700) nm P: 400W	Exogenous Phthalocyamine	*E. coli* - 2 $\log_{10}$ log reduction	[8]
Tungsten Lamp	$\lambda \in$ (546–600) nm P: 0.3- 0.7 mW/ cm^2	Exogenous Fenothiazine	*S. aureus* 4-5 $\log_{10}$ log reduction	[9]
LASER	$\lambda = 660 \pm 2$ nm P = 100mW S = 0.4 cm^2	Exogenous Methylene blue	*A. actinomycetemcomitans* declined 99.85% after 5 minutes	[10]
LASER diode	$\lambda = 405.5 \pm 0.2$ nm P = 49.5 mW S= 0.39 cm^2	Endogenous Porphyrin	*S. mutans* declined 61.9% with the energy 20 J/cm^2	[11]
LED	$\lambda \sim$ (460–470) nm P= 286.8 J/ cm^2	Endogenous Porphyrin	*P. fluorescens* 1.3 $\log_{10}$ log reduction	[12]

For the bacterial inactivation, LED lighting systems have proved to satisfy the requirements for size, field width, wavelength, and full width at half maximum (FWHM). The use of LED with blue light does not require to incorporate a photosensitizer [7]. Thus, LED light source has provided the great potential for further use, integrated into realistic cases.

In this study, we designed and fabricated an LED panel using a nanowire-based Blue LED chip with a wavelength of 405 nm with the FWHM of 10 nm to inactivate bacteria under a laboratory environment. The honeycomb design of the LED panel would be optimal for inactivation due to homogeneous light distribution. A symmetrical design creates balanced geometry and spatial layout, expanding each LED's projection angle and contributing to light spectrum distribution. Secondly, this layout does not follow a specific row or column to facilitate heat dissipation and can easily integrate to expand the projection space if necessary. The device, after fabrication, had precise photo-electrical results after a series of tests. The above results are consistent with the original design concept and existing manufacturing capabilities. Using LED panel, we recorded the inactivation of *S. aureus* and *E. coli* at a dose of 46.02 J/cm^2 after 5 minutes of irradiation at a distance of 5 cm.

2. LED PANEL DESIGN

Figure 1 shows the design of the LED panel used to inactivate bacteria. The LED panel contains six nanowire-based Blue LEDs of 405 nm in wavelength arranged in a hexagonal shape at a distance of 22.5 mm from the center with an 1 Ohm resistor to stabilize the current. The supply power is A DC voltage of 12 V with a

maximum power of 60 W. An Arduino Uno R3 circuit is used as the control circuit, and a power circuit is designed with resistors and transistors. To ensure no thermal effect on the sample, the LED panel is mounted on a heat sink. The LED system combines a set of brackets and a measure to adjust the distance from the light source to the sample.

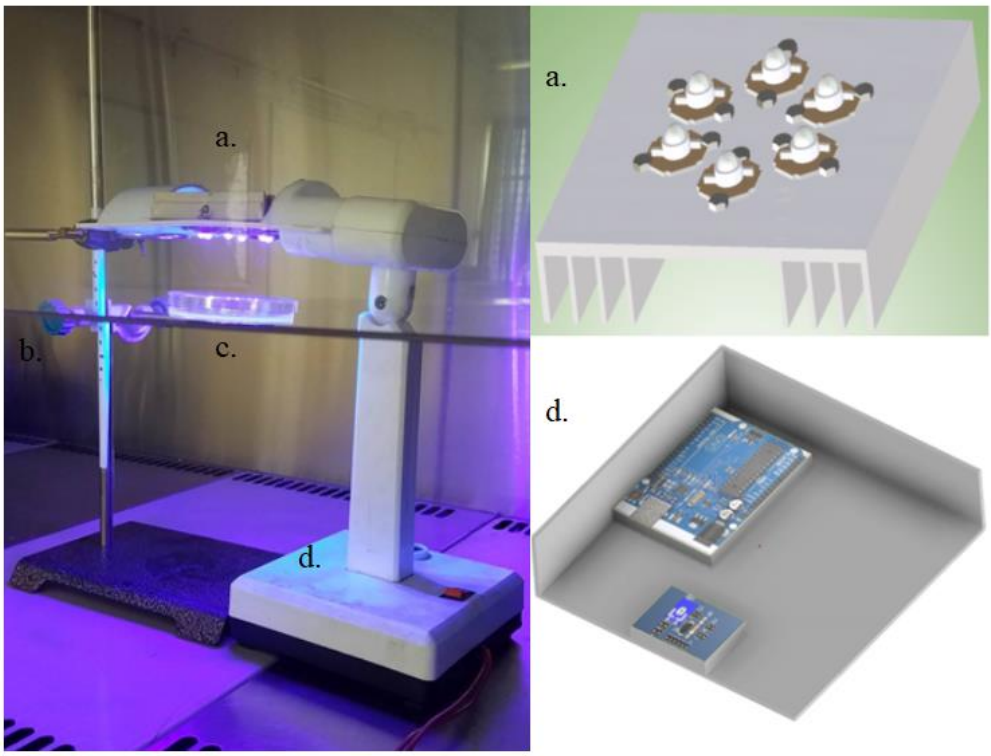

Figure 1: Actual operation of the experimental model LED systems; a. LED panel; b. height adjustable ruler; c. Petri 90 mm diameter with medium for bacterial growth; d. Electrical circuits and controls

Measurements were carried out at Testing Laboratory of Lighting Equipment (VILAS 317) - Dien Quang Lamp Joint Stock Company, including Lamp Photometric test report, Avg.L LED report, Spectral test report, etc.

Table 2: Photoelectric specifications of the LED system in continuous mode (U= 12.026 VDC, T= 25.3°C)

Item	Result	Unit
Input current (I_{in})	0.9902	Amps
Power (P)	11.908	Watts
Peak wavelength (λ p)	404 (±7)	nanometers
Luminos flux (Φ)	3.3574	Lumens
Luminaire efficiency (Eff)	0.28	Lumen/Watt
Maximum luminous intensity (I-max)	1.212	Candela
Angle (α) (d_1=9 m, d_2= 2983.27 cm, E_{avg}=0.0039 lx)*	117.79	Deg

*The parameter picked at d1 is the distance, d_2 is the diameter of the projection area, E_{avg} is the average brightness with a luminous flux of 2,780 (lumens)

Data shows the parameters E_{ff} = 0.28 lm/W with the angle C = 0° and γ = 0° corresponding to I = 1.07 (cd). Combining with the condition of the angle in space, we get:

$$P = \frac{1.074}{0.28l^2}(W/m^2)$$

Table 3: Energy parameter with time and distance - E (J/cm^2)

Time (minute) / Distance (centimeter)	5	10	15	30	60
5 (P = 0.1534 W/cm^2)	46.02	92.04	138.06	276.12	552.24
10 (P = 0.0384 W/cm^2)	11.52	23.04	34.56	69.12	138.24
15 (P = 0.017 W/cm^2)	5.1	10.2	15.3	30.6	61.2

The obtained results through a series of photovoltaic parameters has clearly been shown consistent with the design's theoretical calculation. In addition, the measurement is accurate and can give more parameters that cannot be calculated theoretically, such as the flatness or symmetry of the spectrum, etc. From the above points, the LED system satisfies the conditions to perform experiments involving illumination to use 405 nm in general and specific bacterial inactivation experiments.

3. RESULTS AND DISCUSSION

3.1 Spectrum – Wavelength Test

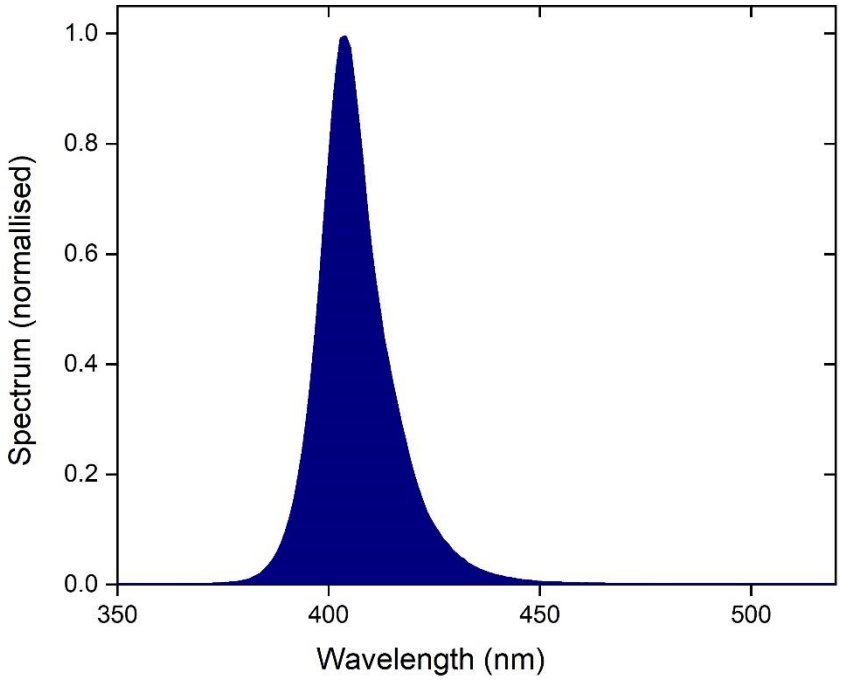

Figure 2: Spectrum of LED system (Testing Laboratory of Lighting Equipment (VILAS 317) - Dien Quang Lamp Joint Stock Company)

Figure 2 shows the electroluminescence spectroscopy with a quite narrow spectrum and covers the region of light from purple (about 380 nm) to blue (about 470 nm). The emission band is at 404.2 nm. The FWHM is about 14 nm, which is defined as the light's bandwidth at half-peak maximum. This is a significant advance compared to the commercial LEDs which often have the FWHM of several tens of nanometers.

This significant narrowing of the spectral bandwidth is an advantage of nanowire-based LEDs over thin film-based LEDs. The light-emitting mechanism of nanowire-based LEDs is similar to thin film-based LEDs in which a diode consists of essentially a p-n junction. When current flows through the junction and emits light

intermittently. Most commercial LEDs are made using a layer of n-type (negative charge carrier) semiconductors combined with a highly doped p-type (positive charge carrier) semiconductor layer. In nanowire-based LEDs, nanowire semiconductors are grown on the Si substrate and are a light emitter individually [13]. With the diameter of several tens nanometers, there are numerous nanowire being integrated on an area of square centimeter. On each nanowire, the element doping concentration can be varied and thus will help to change the emission wavelength. Due to the small diameter of the nanowire, the new generation LED will help overcome the limitations of thin-film LEDs, such as lattice mismatch, material structure failure, and polarization.

3.2 Luminous Intensity Distribution Test

The luminous intensity distribution diagram is a collection of curves representing a measurement of the luminous intensity of a lamp. It represents the light distribution as the luminaire emits light, extending from the light source in all directions. Where the shear plane in the horizontal direction is represented by (C0-C180), the shear plane in the longitudinal direction is (C90-C270), and the numbers in the shear plane indicate the angle at which the plane lies when looking at the curve light distribution from above (Figure 3).

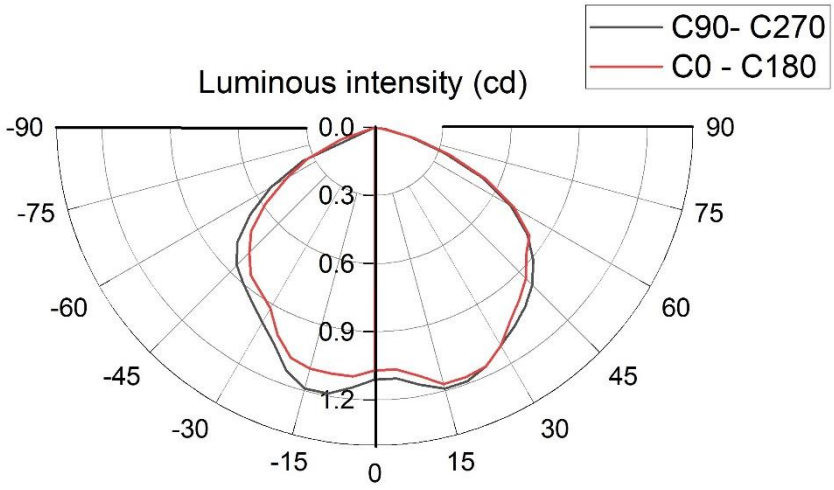

Figure 3: Luminous intensity distribution diagram (Testing Laboratory of Lighting Equipment (VILAS 317) - Dien Quang Lamp Joint Stock Company)

Based on the light intensity distribution curves, the luminaire system is evaluated at the appropriate level for showing symmetry and spreading in the space of the luminaire with the intended purpose when used in the field microbiological environment with the use of a distance of no more than 0.15 m. In addition, the obtained luminous intensity distribution data table is also one factor in calculating the LED system's projection energy (Table 3).

3.3 Temperature Experiment

The LEDs undergo testing when operating at maximum current in a continuous design for about 180 minutes in the incubator (where microbiological experiments are performed), which is satisfactory for the microbiological experiment setup when the time is up 60 min irradiation time. At the same time, the LED panel temperature test, when irradiated continuously for 80 minutes, also produced a standard temperature that did not exceed 42^{o}C.

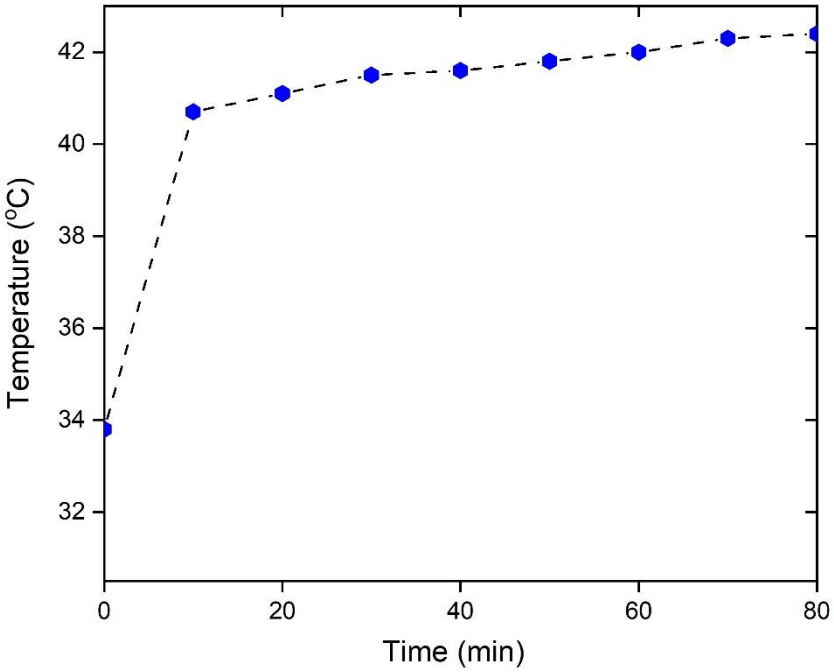

Figure 4: LED panel temperature measured at the center of the LED panel (top side) with the condition temperature in the biological cabinet with an initial temperature at 33.7oC

LEDs usually operate ambient at room temperature (20°C to 25°C) with the current recommended by the manufacturer. In many cases, chip LEDs can have much higher junction temperatures, up to 80°C. Prolonged high temperatures on LEDs (more than 60°C) lead to higher junction temperatures, which can accelerate the degradation of LED junction elements and considerably shorten the useful life of the LED lighting system. The temperature components that affect the LED panel include the junction temperature of the LED chip, the ambient temperature, the steady current through the LED, and the heat dissipation material in and around the LED. The design produces a temperature difference from room temperature of around 8°C (from 34°C to 42°C) in 80 minutes (Figure 4). Therefore, the LED system has done an excellent job of controlling the temperature, which is one of the essential aspects of optimizing the performance of the LED system.

3.4 Bacterial Inactivation Experiment

Using the LED panel, we conducted an experiment to test out the ability of inactivity of *S. aureus* and *E. coli* - two of the important human pathogens, based on the aBL effect. In the laboratory condition, we cultured bacteria in Petri dishes. The pure strain was proliferated in NB solution, then diluted to a concentration of 10^{-5} - 10^{-6} CFU/ml with Phosphate-Buffered Saline (PBS), and then put 100 µl on a 90 mm diameter Petri dish.

E. coli- is a gram- negative bacteria, a member of the normal microflora of the gastrointestinal tract, accounting for the highest percentage of aerobic bacteria (about 80%). In addition, *E. coli* is also an essential pathogenic bacterium. It ranks first in the bacteria causing diarrhea, urinary tract infections, and cholangitis, leading in the causes of bacteremia [14]. *S. aureus*- is a gram- positive bacteria, the basis of which forms many different antibiotic-resistant strains. One of the most popular strains is *Methicillin-resistant Staphylococcus aureus* (*MRSA*).

With the blue light source provided by the built-in lamp system, we tested the feasibility of the LED system in the experimental environment at the laboratory through several experiments. Three different exposure times were applied to the sample 5 min, 15 min, and 25 min, respectively. While the projection time varies, the

sample distance is kept constant: 5 cm to ensure the coverage of LED light from the system onto the Petri dish. The effect of irradiation time was carried out to evaluate the effect of light exposure time from the designed LED system on the effectiveness of bacteria inactivation at the stable growth stage. Each experiment for each exposure time was repeated at least three times.

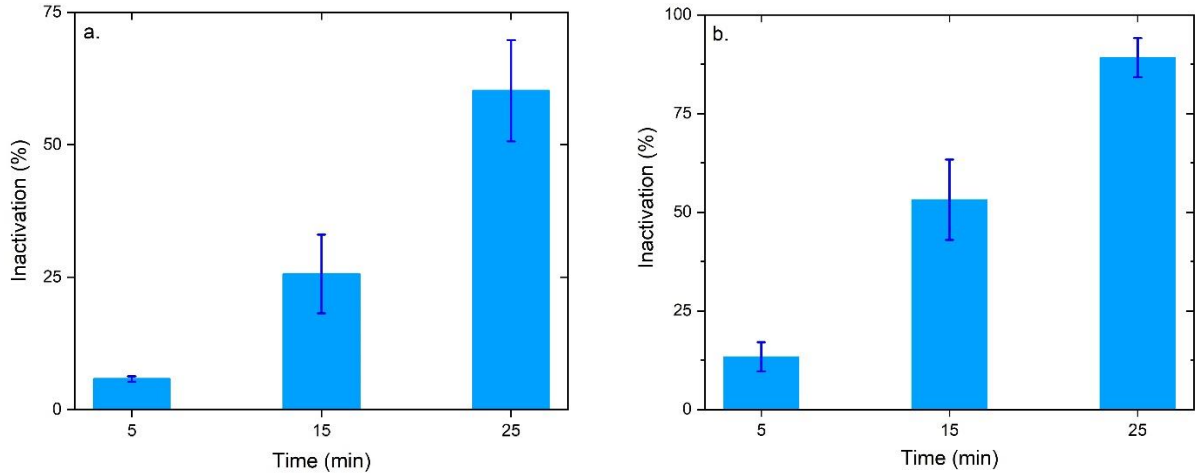

Figure 5: Efficacy in inactivation of E. coli (a) and S. aureus (b) at a distance of 5 cm for 5 min, 15 min, and 25 min, respectively

Figure 5 showed that only 46.02 (J/cm^2) dose corresponding to the shortest irradiation time of 5 minutes had the effect of inactivating *S. aureus* and *E. coli* bacteria. When exposed to LED light for 15 min, *E. coli* and *S. aureus* were inactivated to more than 50% and 25% on nutrient agar, respectively. Moreover, can see a significant reduction of bacteria *S. aureus* and *E. coli* at the dose of 230.10 (J/cm^2), corresponding to 25 minutes when the inactivation rate is up to 90% and 60%, respectively. The results showed that the method of treating bacterial samples exposed to light sources from LED systems with increasing time intervals caused changes proportional to the inactivation of *S. aureus* and *E. coli*.

These results could be explained by the reaction to produce reactive oxygen species (ROS). ROS is formed as a natural product of oxygen metabolism that plays a vital role in cell signaling and homeostasis. The increase of ROS will cause significant damage to the cell structure, and the LED system with 405 nm wavelength has partly activated the factor causing this increase [7], [15].

4. CONCLUSION

The LED panel was made using 6 LEDs based on Blue LED nanowires with a wavelength of ~405 nm and a full width at half maximum around 10 nm. The LED panel lights are designed in a hexagonal arrangement with the appropriate distances between the LEDs to arrange the light and temperature, which are used in microbiological experiments and to project harmful bacteria, including *S. aureus* and *E. coli*. The results from the theoretical calculations and the actual measurements show power supply, consumption components energy, luminous intensity distribution diagram, and a complete spectrum of blue light. When the LED system is applied, it operates stably continuously and contributes to reliable results. With a distance of 5 cm corresponding to energy 46.02 (J/cm^2) LED system has to write get results any active, result in any activity matches with the projection time and inactivation rate 90% for *S. aureus* and 60% for *E. coli* at 25 minutes with the energy of 230.10 (J/cm^2). The system design with each block (LED panel, control part, power) makes it easy for the improvement process after it can be replaced, repaired, or upgraded accordingly.

Acknowledgments

This work is supported by Vietnam National University Ho Chi Minh City under grant number VL2020-20-03. We acknowledge the support of times and facilities from Ho Chi Minh City University of Technology (HCMUT).

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