

**Development of a Sunlight Adjustable Parabolic Trough Reactor for 24-hour
Efficient Photocatalytic Wastewater Treatment**

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Abstract:

Solar energy is the ideal energy source for activating photocatalysis. However, due to the solar motion, achieving 24-hour solar-powered efficient photocatalytic reactions remains a challenge. In this study, a Sunlight Adjustable Parabolic Trough Reactor (SA-PTR) integrated with flexible parabolic mirror and solar panel was developed. During the daytime, flexible parabolic mirror could be rolled up under sunny condition or expanded under cloudy condition, thus providing optimal light irradiance ($1500 \text{ W} \cdot \text{m}^{-2}$) and temperature (rises yet below 55°C) for photocatalysis. Additionally, the solar panel behind the flexible parabolic mirror could generate solar-electricity. At night, the stored solar-electricity could meet 100% power demands of UV lamp, enabling a 24-hour solar-powered photocatalytic process. Compared with traditional parabolic trough reactor and inclined plate collector, SA-PTR exhibited higher treatment efficiency against carcinogenic organic dyes (Rhodamine B, Methylene Blue, Methyl Orange), antibiotic (Tetracycline) and pathogenic bacteria (*Escherichia coli*) during day and night. Moreover, SA-PTR exhibited superior global deployability, economic advantage, safety and lifetime. Therefore, SA-PTR, as a novel solar controllable 24-hour operational photoreactor, is promising to be employed in real wastewater treatment plant.

Keywords:

Sunlight adjustable parabolic trough reactor (SA-PTR); flexible parabolic mirror; photocatalytic wastewater treatment; 24-hour continuous operation; whole-year evaluation

1. Introduction

As human society progresses, a large amount of industrial, medical and domestic wastewater has been discharged into water bodies [1–3]. Due to the presence of carcinogenic organic dyes, antibiotics and pathogenic bacteria in wastewater, water quality is deteriorating around the world [4]. Amid this water crisis, the UN strives to achieve SDG 6 (Clean Water and Sanitation) [5], encouraging researchers to innovate sustainable and efficient wastewater treatment systems.

In past decades, photocatalysis, a cost-effective wastewater treatment method without secondary pollution, has been extensively studied [6–8]. Under the light irradiation, photocatalyst could produce free electrons and holes with strong oxidation and reduction [9], so as to decompose the organic pollutants. Solar energy, as an eternal, eco-friendly and abundant energy [9], encompasses ultraviolet (UV) light, visible light and infrared light [10]. Technically, high-energy UV and short-wave visible light activate photocatalyst [8], while long-wave visible light and infrared light with strong thermal effect could increase the temperature to promote the photocatalytic reaction rate [11]. Therefore, the broad spectrum of sunlight makes it ideal for driving and accelerating photocatalytic process [11].

In the early explorations, Inclined Plate Collectors (IPC) were employed to provide solar energy to photocatalysis [11,12]. IPC utilizes an inclined flat mirror to passively capture sunlight, enabling photocatalytic reactions to occur within the reaction tubes mounted on this mirror. However, since IPC could only passively receive sunlight, its photocatalytic efficiency is generally limited by the inefficient acceptance

of solar energy [11]. It has been reported that sufficient light irradiance and favorable temperature are prerequisites for promoting photocatalytic efficiency [13]. For example, Reuterġardh et al. demonstrated that $1000 \text{ W}\cdot\text{m}^{-2}$ light irradiance and temperatures between $30\text{-}60^{\circ}\text{C}$ were conducive to efficient photocatalysis [14]. Zhang et al. also reported that the light irradiance above $1000 \text{ W}\cdot\text{m}^{-2}$ and raised temperature ($< 65^{\circ}\text{C}$) were beneficial for the effective photocatalysis [11]. Nevertheless, the environmental average light irradiance level is only around $500 \text{ W}\cdot\text{m}^{-2}$ [15], and the typical environmental average temperature on earth is only 12°C [16]. Therefore, solar energy needs to be concentrated to achieve the optimal light irradiance and temperature required for efficient photocatalytic reactions.

Parabolic Trough Reflector (PTR), as a typical light concentrator in solar thermal projects [17], is not surprisingly employed to provide concentrated sunlight for photocatalysis [18]. PTR used a parabolic mirror to focus incident sunlight onto the reaction tube, which was located at its focal point. Its parabolic mirror size determines the amount of concentrated solar energy. The larger the mirror, the more solar energy could be concentrated [18]. Since PTR passively concentrates solar energy, it usually concentrates over 30-70 times the amount of sunlight onto the reaction tube, which provides ultra-high light irradiance [17,19]. However, violent recombination of electrons and holes may occur under ultra-high illumination, which may limit the photocatalytic efficiency [11,14,19]. Furthermore, the massive amount of concentrated solar energy in PTR could lead to ultra-high temperatures of up to $400\text{-}500^{\circ}\text{C}$ [20], potentially damaging the photocatalytic system and causing wastewater evaporation

[11]. Therefore, appropriate adjustment of concentrated solar energy is necessary to achieve efficient photocatalytic reactions while mitigating issues caused by excessive light irradiance and temperature. Recently, flexible mirrors with excellent bendability have been developed for deployable space telescopes [21], as they could be shaped into different forms as well as rolled up or expanded. Compared with glass mirrors, flexible mirrors offer superior deployability while maintaining high reflectiveness [21]. If a flexible parabolic mirror is used to replace the glass parabolic mirror which is currently used in PTR, it could have the potential to change the mirror size by rolling or expanding, thus adjusting the concentrated solar energy. In addition, it also has the potential to reduce the cost and weight of photoreactor, which benefits the large-scale deployment. To the best of our knowledge, a PTR utilizing flexible parabolic mirrors to adjust concentrated solar energy for efficient photocatalytic reactions has not been proposed yet.

Despite the potential of using a flexible parabolic mirror to adjust natural solar energy during the daytime, achieving photocatalysis during nighttime remains a tricky challenge. At present, photoreactors solely powered by solar energy for 24-hour continuous photocatalytic reactions are still waiting to be explored [13]. The breakthrough in this technology may be a boon for photocatalytic application in industrial fields with high robustness requirements (such as wastewater treatment plant). Notably, solar panel, as a device which converts solar energy into electrical power, might be a solution to above issue. If a solar panel is integrated behind the flexible parabolic mirror, during the daytime, the photoreactor could not only provide optimized

solar energy for photocatalysis, but also generate electrical power. During nighttime, the solar-electricity could drive a lamp for activating photocatalyst, thus achieving 24-hour solar powered continuous photocatalytic reaction.

Therefore, in this study, a Sunlight Adjustable Parabolic Trough Reactor (SA-PTR) for 24-hour photocatalytic operation was developed for the first time. The SA-PTR features a flexible parabolic mirror that could change its size based on actual solar conditions to adjust the concentrated sunlight. Additionally, a solar panel was highly integrated with the mirror to power a UV lamp at night. The wastewater treatment capability of SA-PTR was investigated through the removal of carcinogenic organic dyes (Rhodamine B (Rh B), Methylene Blue (MB), Methyl Orange (MO)), antibiotics (Tetracycline (TC)) and pathogenic bacteria (*Escherichia coli* (*E. coli*)) during daytime and nighttime. Furthermore, the economic efficiency, long-term availability, wide applicability and safety of the SA-PTR were also evaluated.

2. Materials and methods

2.1. Identification of the optimal solar energy for efficient photocatalysis

To achieve high photocatalytic efficiency, the optimal solar energy that needs to be concentrated by SA-PTR was first identified. In this step, Rh B solution (500 mL, 2 mg·L⁻¹) was treated by photocatalyst in a batch reactor (Fig. S1a) under different solar energy conditions. The TiO₂-coated silica gel beads (HQC-21, Sinto V Ceracs) were adopted as photocatalyst. The different solar energy conditions were provided by a simulated solar lamp (XC-100, SERIC., Ltd) or the concentrated real sunlight. The simulated solar lamp provided the light irradiance ranging from 0 to 2100 W·m⁻², while

the concentrated real sunlight provided the light irradiance of 3000 and 4000 W·m⁻². The simulated solar lamp and the concentrated real sunlight have similar light spectrum (Fig. S1b). During experiments, light irradiance was measured by pyranometer (LI-200R, LICOR) and temperature was measured by thermocouple (TR-71wf, TANDD). The surrounding temperature was kept at 25°C.

2.2. Calculation of the mirror size in SA-PTR for providing the optimal solar energy

To ensure the optimal light irradiance and reaction temperature, SA-PTR employed a flexible parabolic mirror to adjust the concentrated solar energy. Technically, when natural sunlight is intensive, the flexible mirror would be rolled up, while during the period of weaker sunlight, the mirror would be expanded. The mirror size of SA-PTR was calculated according to natural solar energy throughout the year in Tsukuba area (36.1°N, Japan). The yearly natural solar energy I was calculated by Eq. (1) [22].

$$I = S \times 0.7^{AM^{0.678}} \quad (1)$$

where S represents the solar constant (= 1356 W·m⁻²). AM represents the air mass, which could be calculated by Eq. (2) [23].

$$AM = 1 / (\sin\alpha + 0.50572 \times (\alpha + 6.07995)^{-1.6364}) \quad (2)$$

where α represents the solar elevation, which could be calculated by Eq. (3) [23].

$$\sin\alpha = \sin\varphi \times \sin\delta + \cos\varphi \times \cos\delta \times \cos ha \quad (3)$$

where φ represents the latitude of Tsukuba area (= 36.1°N). ha represents the solar hour angle, which is the number of degrees that the earth must rotate until the sun is directly

above the local meridian. δ represents the solar declination and could be calculated by Eq. (4) [23].

$$\delta = 23.45^\circ \times \pi / 180^\circ \times \sin(2\pi \times (284 + n) / 365) \quad (4)$$

The mirror size MS of SA-PTR was calculated by Eq. (5) according to the natural solar energy.

$$MS = \text{Optimal solar energy} / I \times WRT \quad (5)$$

where WRT represents the width of reaction tube (= 20 mm) equipped in SA-PTR.

2.3. Manufacturing of SA-PTR for daytime operation

As the first step in the development of SA-PTR, it was manufactured for the lab-scaled wastewater treatment experiments during the daytime. A flexible parabolic mirror described by Eq. (6) was equipped in SA-PTR for adjusting and concentrating solar energy.

$$y^2 = 2 \times p \times x \quad (6)$$

where y and x are cartesian coordinate system parameters, and p (= 170 mm) is the distance from the focal point to the corresponding directrix of the parabola.

Then, the arc length AL of the parabolic mirror of SA-PTR was calculated by Eq. (7).

$$AL = p / 2 \times (\sqrt{2 \times x / p \times (1 + 2 \times x / p)} + \ln(\sqrt{2 \times x / p} + \sqrt{1 + 2 \times x / p})) \quad (7)$$

For the SA-PTR manufacturing, all of its parts were purchased online or from local hardware stores and manufactured according to the design blueprint. At the same time, traditional PTR and IPC were also manufactured, serving as control reactors. The equation of the parabolic mirror of PTR was consistent with that of SA-PTR. The mirror

size of PTR was the maximum mirror size of SA-PTR. All three reactors were operated simultaneously under their optimum working conditions on a south-facing rooftop located in Tsukuba area (= 36.1°N). The detailed information of PTR and IPC employed in this study could be found in supplementary materials Text S1.

2.4. Verification of the sunlight adjustment capability of SA-PTR

After SA-PTR manufacturing, its ability to adjust the solar energy under real sunlight was verified. The experiment was carried out on 2022-12-23 (winter solstice) characterized by the lowest solar altitude angle, which presents the worst solar condition during the year [11]. If SA-PTR could provide optimal solar energy on this day, it could provide optimal solar energy during the yeartime. During the experiment, 1 L water was circulated inside the photoreactors. The solar energy and water temperature in photoreactors were measured and recorded at 5-minute intervals.

2.5. Photocatalytic wastewater treatment experiments during daytime

In this study, carcinogenic organic dyes (Rh B, MB, MO), antibiotics (TC) and pathogenic bacteria (*E. coli*) were targeted to evaluate the wastewater treatment performance of photoreactors. Rh B, MB and MO were purchased from Wako Pure Chemical Industries, Ltd. (Osaka, Japan). TC was purchased from Sigma–Aldrich Co., Ltd. (Louisiana, USA). The *E. coli* was isolated from Matsumi Lake in Tsukuba, and the preparation of *E. coli* solution could refer to previous study [15].

Firstly, the degradation experiments of Rh B (1 L, 2 mg·L⁻¹) were conducted under sunny, cloudy and heavy snow conditions, respectively. Then, MB (1 L, 5 mg·L⁻¹), MO (1 L, 5 mg·L⁻¹) and TC (1 L, 10 mg·L⁻¹) were degraded under sunny days and cloudy

days, respectively. The concentrations of Rh B, MB, MO and TC were measured by a spectrophotometer (UV-1600, Shimadzu, Japan) at their maximum absorption wavelength of 554, 664, 465 and 267 nm, respectively. The Total Organic Carbon (TOC) results were measured by a total organic carbon analyzer (TOC-L, Shimadzu, Japan). The disinfection experiment for *E. coli* (0.3 L, 1.2×10^5 cfu·mL⁻¹) was carried out under typical sunny-cloudy condition. The concentration of *E. coli* was calculated by the standard plate count method. The reaction rate k of degradation and disinfection experiments were calculated according to the first-order reaction model Eq. (8).

$$-\ln \frac{C_t}{C_0} = kt \quad (8)$$

2.6. Evaluation of the whole-year daytime performance of photoreactors

The applicability of SA-PTR, PTR and IPC throughout the year during the daytime was evaluated based on the natural meteorological data in Tsukuba area (= 36.1°N) in 2022. To calculate the light irradiance and reaction temperature provided by photoreactors during the yeartime, solar energy conversion process in photoreactors needs to be clarified. This analysis was based on the solar conditions on the vernal equinox, a typical day when the length of daytime equals the length of the night [9], which could represent the average solar conditions during the year. Firstly, the accurate optical models of SA-PTR, PTR and IPC were created by a 3D modeling software *Solidworks* [24]. Then, the optical simulations were performed by *Tracepro* software to quantify the amount of solar energy harnessed by photoreactors [25]. When solar energy is provided onto reaction tubes, a portion of solar energy would be converted into internal energy for increasing temperature. The conversion ratio of solar energy

into internal energy could be calculated by Eq. (9).

$$\text{Solar-internal conversion ratio} = \text{Internal energy} / \text{Solar energy} \times 100\% \quad (9)$$

As the solar energy was provided to reaction tubes, some energy was also lost to the environment in the form of heat. The computational fluid dynamics analysis was carried out by *Fluent* software for analyzing the boundary heat flux distribution [26], which refers to the heat loss in photoreactors. Accordingly, the solar energy loss ratio of photoreactors could be calculated by Eq. (10).

$$\text{Solar energy loss ratio} = \overline{\text{Boundary heat flux}} / \text{Solar energy} \times 100\% \quad (10)$$

Ultimately, the whole-year solar energy harnessed and the reaction temperatures within the photoreactors were calculated utilizing meteorological data sourced from the Japan Meteorological Agency [27].

2.7. Wastewater treatment experiments during nighttime

After studying the daytime performance of SA-PTR, the wastewater treatment experiments were further conducted at night. First, solar panels (maximum electrical power generation = 50 W under 1.5 air mass) were integrated behind the flexible mirror. The size of solar panel was similar with that of flexible mirror in SA-PTR, thus no extra installation space was required. The solar panel was connected to a battery for energy storage and subsequently supplied power to a UV lamp (FL10BLBX1, Tokyo Metal Industry) mounted above the reaction tubes. During the nighttime experiments (2023-10-02 to 2023-11-03), Rh B, MB, MO, TC, *E. coli* were degraded or disinfected in SA-PTR. At the same time, in order to simulate the photocatalytic performance of PTR and IPC (no solar-electricity generation capability) during the nighttime, dark condition

experiments were comparatively conducted. Other experiment conditions remained the same as daytime experiments (as described in section 2.5).

3. Results and discussion

3.1. Optimal solar energy for efficient photocatalytic reaction

To identify the optimal solar energy for the efficient photocatalytic reaction, the Rh B degradation experiments were carried out at the solar energy of 0-4000 W·m⁻². Figure 1a showed the change of reaction temperature under different solar energy conditions. When the solar energy increased from 300 to 4000 W·m⁻², the reaction temperatures also increased. This might be due to the fact that the solar spectrum includes long-wavelength visible light and infrared light, which possess significant thermal effects [23]. The stronger the solar energy, the greater the increase in reaction temperature.

To identify the optimal solar energy, the relationship between solar energy and photocatalytic Rh B degradation reaction rate was studied and shown in Fig. 1b. As the solar energy increased from 300 to 1500 W·m⁻², the reaction rate increased rapidly (from 0.0189 to 0.0374 min⁻¹). Therefore, to achieve an efficient photocatalytic reaction, it is reasonable to increase the solar energy from 300 to 1500 W·m⁻². However, no obvious increase in the degradation rate was found when the solar energy exceeded 1500 W·m⁻². Many studies have reported that excessive light energy may increase the recombination rate of electrons and holes generated by photocatalyst, thus limiting the photocatalytic efficiency [14,19]. In addition, excessive solar energy may lead to elevated reaction temperature (such as 77°C at 4000 W·m⁻², shown in Fig. 1a). At this

temperature, due to the vaporization of water, many photocatalysts could not contact with pollutants (Fig. S2), which may limit the photocatalytic activity. Based on the above results, SA-PTR was designed to provide the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ solar energy to achieve efficient photocatalytic reaction.

3.2. Design and manufacturing of SA-PTR for providing optimal solar energy

Due to the movement of the sun, the amount of natural solar energy reaching the earth is constantly changing [11]. To provide the optimal solar energy ($1500 \text{ W}\cdot\text{m}^{-2}$), a flexible parabolic mirror was employed in SA-PTR, and the mirror size determining the concentrated solar energy amount could be changed.

Figure 2a showed the variation of natural solar light irradiance in Tsukuba area throughout the year. During the morning and afternoon, the natural sunlight is weaker, while it is stronger in the noon. In addition, in winter, the natural sunlight irradiance is lower, while in summer it is higher. As shown in Fig. 2b, the photocatalytic reaction tubes were located at the focal point of the parabolic mirror. In order to achieve the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ solar energy in reaction tubes, the mirror size of SA-PTR was changed according to real solar conditions. Figure 2c showed the variation of the parabolic mirror size of SA-PTR throughout the year. In the morning and afternoon, the size of flexible parabolic mirror needs to be increased, while at noon it needs to be decreased. In addition, the mirror size needs to be larger in winter and smaller in summer. Furthermore, the maximum and minimum mirror size were also calculated. Since the natural sunlight is weakest at sunrise (or sunset) on the winter solstice (December 23rd) during the year (Fig. 2a), the flexible parabolic mirror in SA-PTR

needs to be expanded to the maximum size (396 mm) to provide the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ of solar energy. At noon on the summer solstice (June 21st), since natural solar energy is strongest during the year (Fig. 2a), the mirror size needs to be rolled up to the minimum size (54 mm). This adjustment ensured that SA-PTR could provide the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ solar energy for the photocatalytic reaction tubes during the year.

After determining the maximum and minimum parabolic mirror size, the structure of SA-PTR for daytime operation was designed and shown in Fig. 3a. The SA-PTR featured a flexible mirror attached to a parabolic arch supporting structure. The flexible mirror could be magnetically attracted to the mirror supporting structure, forming a paraboloid shape. The photocatalytic reaction tubes were installed at the focal point of the parabolic mirror and filled with photocatalyst. The inlet and outlet of photocatalytic reaction tubes connected with a pipeline, which was in turn connected to a water pump and a 1 L storage bottle containing organic wastewater. As shown in Fig. 3b, to control the concentrated solar energy at $1500 \text{ W}\cdot\text{m}^{-2}$ during the year, the flexible parabolic mirror could be rolled up or expanded by the reel to control the mirror size from minimum to maximum size (54-396 mm). The rotation of the reel could be controlled by a stepper motor (Bipolar Nema 17), which was mounted on a railcar. The railcar has wheels, which could move along the track installed on the mirror supporting structure. A light sensor (GY-30) was installed near the photocatalytic reaction tubes to receive the concentrated solar energy. The control system of the stepper motor in SA-PTR was based on the Arduino system (Arduino UNO REV3 mainboard) and shown in Fig. 3c. Arduino system is an open source compliant control system based on C language [28].

When the concentrated solar energy is higher than $1500 \text{ W}\cdot\text{m}^{-2}$, the light sensor would send the signal to the stepper motor for rolling up the flexible mirror, and the rail car would move to the center point of the mirror support. When the concentrated solar energy is lower than $1500 \text{ W}\cdot\text{m}^{-2}$, the flexible mirror would be expanded, and the rail car would go to the far edge of the mirror support. While on cloudy days, due to the low natural solar light irradiance at this time, the flexible parabolic mirror would be expanded to its maximum size (396 mm) to concentrate the solar energy as much as possible. The SA-PTR pictures of changed mirror size could be found in Fig. S3.

After the SA-PTR was designed and manufactured (Fig. S4a), the control reactors PTR (Fig. S4b) and IPC (Fig. S4c) were also manufactured. The reflectivity of PTR and IPC mirrors was similar to that of SA-PTR mirrors (shown in Fig. S5). Three reactors were equipped with temperature sensors (TANDD, TR-71wf) and light intensity sensors (UV-340 ultraviolet meter and LI-200R pyranometer). During the experiments, the three reactors were installed on rooftops with the same light conditions and were all oriented towards the incident direction of the solar rays.

3.3. Solar energy control capability of SA-PTR

The solar energy control capability of SA-PTR was verified on the winter solstice (December 23rd, 2022), which was the day with the worst solar conditions during the yeartime. The experiment lasted from 8:00 to 14:30, covering sunrise, morning, noon and afternoon periods. As shown in Fig. 4a, the natural solar energy only varied in the range of $26\text{-}549 \text{ W}\cdot\text{m}^{-2}$, which was insufficient to support the photocatalytic reactions effectively (Fig. 1b). For the IPC, which passively receives solar energy, provided the

slightly higher solar energy at 44-793 $\text{W}\cdot\text{m}^{-2}$, but still inadequate for efficient photocatalysis (Fig. 1b). Though PTR could provide the solar energy up to 4587 $\text{W}\cdot\text{m}^{-2}$, the excessive light irradiance may hinder photocatalytic activity by inducing high recombination rate of electrons and holes [14,19], which may inhibit the promotion of photocatalytic activity. In contrast, the SA-PTR could stabilize the solar energy at the optimal 1500 $\text{W}\cdot\text{m}^{-2}$ under various solar conditions by changing the parabolic mirror size. During the period of weak natural light irradiance (8:00-8:30, shortly after sunrise), the mirror size of SA-PTR was expanded to maximize the concentrated solar energy, rapidly increasing the concentrated solar energy from 204 to about 1500 $\text{W}\cdot\text{m}^{-2}$. In the following time with clear sky (8:30-10:15 and 10:40-14:30), by controlling the mirror size, the concentrated solar energy could be effectively stabilized at the optimal 1500 $\text{W}\cdot\text{m}^{-2}$. Even during the period that temporary clouds blocked sunlight (10:20-10:35), SA-PTR still provided 287-742 $\text{W}\cdot\text{m}^{-2}$ of solar energy, which was still more favorable for photocatalytic reactions than the natural condition (170-361 $\text{W}\cdot\text{m}^{-2}$). Therefore, the newly developed SA-PTR could effectively adjust the concentrated solar energy by changing the mirror size.

The temperature was also recorded and shown in Fig. 4b. The natural temperature was only 4.1-18.3°C, which was not effective for promoting the photocatalytic reaction rate [11]. For IPC, since the provided solar energy was only slightly increased compared to natural conditions, its temperature (5.2-22.3°C) was still unable to achieve efficient photocatalytic reactions. Although the PTR provided a high temperature (67.7°C) by concentrating a large amount of solar energy (up to 4587 $\text{W}\cdot\text{m}^{-2}$), excessive temperature

may cause wastewater evaporation and bubble generation (Fig. S2), which was unfavorable for system operation [11]. While for the SA-PTR, by adjusting the solar energy, not only provided the optimal and stable light irradiance of $1500 \text{ W}\cdot\text{m}^{-2}$, but also quickly raised the reaction temperature to a suitable range of $30\text{-}48^{\circ}\text{C}$, which was favorable for efficient photocatalytic reaction.

The above experiments confirmed that SA-PTR could provide the optimal solar energy and suitable reaction temperature by actively adjusting the mirror size even on the winter solstice with the worst solar condition through the year. This lays a foundation for SA-PTR to realize efficient photocatalytic wastewater treatment process under real weather conditions.

3.4. Degradation of organic dyes under real weather conditions

After verifying the ability of SA-PTR to control solar energy, its wastewater treatment performance was studied under different real solar conditions during the daytime. Rh B, MB and MO, as a typical carcinogenic organic dyes [29], were chosen as the wastewater models. Firstly, the Rh B experiments were conducted from 9:30 to 11:30 on several days with typical weather conditions, including sunny day (2023-01-08), temporarily cloudy day (2023-01-09) and heavy snowy day (2023-02-10), respectively.

Figure S6a showed the light irradiance during the experiments. Under sunny condition (2023-01-08), SA-PTR could effectively adjust the variable natural sunlight ($388\text{-}619 \text{ W}\cdot\text{m}^{-2}$) to the optimal solar energy $1500 \text{ W}\cdot\text{m}^{-2}$ by actively adjusting the mirror size. In addition, on temporarily cloudy day (2023-01-09), SA-PTR could

provide the optimal solar energy when the cloud does not obscure the sunlight. When clouds occasionally blocked solar rays, the SA-PTR mirror was expanded to the maximum size to maximize the light irradiance ($25\text{-}218\text{ W}\cdot\text{m}^{-2}$), which was much more favorable for photocatalytic reactions than natural sunlight ($12\text{-}89\text{ W}\cdot\text{m}^{-2}$). Furthermore, even on a heavy snowy day (2023-02-10) when the sun was completely blocked, the fully expanded mirror allowed SA-PTR to provide doubled solar light irradiance ($12\text{-}27\text{ W}\cdot\text{m}^{-2}$) for photocatalytic reactions, compared with natural sunlight ($6\text{-}14\text{ W}\cdot\text{m}^{-2}$). Therefore, SA-PTR could effectively control the concentrated solar energy under different weather conditions. Through the optimization of solar energy, the reaction temperature in SA-PTR could be rapidly increased while lower than 55°C under sunny or temporarily cloudy conditions (Fig. S6b), thus promoting the photocatalytic reaction and avoiding excessive temperature. Even on cold and snowy day, the temperature of SA-PTR could reach $4.4\text{-}5.9^{\circ}\text{C}$, which was still higher than natural temperature ($2.0\text{-}3.1^{\circ}\text{C}$). Therefore, SA-PTR could effectively adjust the sunlight under various typical weather conditions, thus providing the optimized reaction temperature. However, traditional PTR and IPC were unable to provide the optimal light irradiance and reaction temperature under real weather conditions (shown in Fig. S6). For PTR, since it could only concentrate the solar energy, it provided excessive light irradiance (up to $5324\text{ W}\cdot\text{m}^{-2}$) and reaction temperature (up to 70.7°C) on the sunny and temporarily cloudy days. While for IPC, its light irradiance ($6\text{-}705\text{ W}\cdot\text{m}^{-2}$) and reaction temperature ($4.5\text{-}21.9^{\circ}\text{C}$) were only slightly higher than the natural sunlight ($5\text{-}617\text{ W}\cdot\text{m}^{-2}$) and ambient temperature ($4.1\text{-}15.4^{\circ}\text{C}$), respectively.

The Rh B degradations were carried out under real weather conditions and the degradation processes were shown in Fig. 5a with the summarized reaction rate k (Table 1). Under sunny and temporarily cloudy conditions, the reaction rates of SA-PTR were 0.0338 and 0.0212 min^{-1} , which were slightly higher than that of PTR, and 1.75 and 1.64 folds of IPC, respectively. This might be due to that SA-PTR could provide the optimized solar energy (around $1500 \text{ W}\cdot\text{m}^{-2}$), thus effectively promoting the reaction process. In addition, on heavy snowy day, the reaction rates of SA-PTR and PTR were the same (0.0114 min^{-1}). This was due to that when the sunlight was completely blocked, the mirror of SA-PTR was fully expanded, making its light collection capacity equal to that of PTR, resulting in similar performance. Compared to IPC, the reaction rate of SA-PTR was doubled to that of IPC (0.0057 min^{-1}) during heavy snow, likely due to the more favorable light irradiance and reaction temperature provided by SA-PTR. Furthermore, SA-PTR exhibited the highest TOC removal capacity under sunny (81.7%), temporarily cloudy (56.9%) and snowy conditions (14.3%) (shown in Fig. S7), indicating its ability to efficiently mineralize the organic pollutants.

To further evaluate the capacity of SA-PTR to treat the wastewater containing different organic dyes, the degradation experiments of MB and MO under different actual weather conditions were carried out. Figure S8a-b and Fig. S9a-b exhibited that under sunny conditions (2023-02-16 and 2023-02-18), SA-PTR could always control the solar energy near the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ with suitable reaction temperature (around 40°C). Even under the rainy and cloudy conditions (2023-02-13 and 2023-02-17, shown in Fig. S8c-d and Fig. S9c-d), SA-PTR could still maintain the optimized

light irradiance and temperature. Under these superior reaction conditions, SA-PTR exhibited significantly improved MB and MO degradation efficiency (Fig. 5b-c). Under sunny condition (2023-02-16 and 2023-02-18), the degradation rate of MB in SA-PTR was 0.019 min^{-1} , which was 1.10 folds of PTR and 1.42 folds of IPC, respectively (Table 1). Besides, the degradation rate of MO in SA-PTR was 0.0094 min^{-1} , which was slightly higher than that of PTR and 2.94 folds of IPC, respectively (Table 1). While during the undesired weather (2023-02-13 and 2023-02-17), the degradation rate of MB in SA-PTR was 0.0099 min^{-1} , which was almost similar with PTR and 1.46 folds of IPC, respectively (Table 1). Additionally, the degradation rate of MO in SA-PTR was 0.050 min^{-1} , which was also similar with PTR and 2.42 folds of IPC, respectively (Table 1). Therefore, the above results demonstrated that SA-PTR not only avoided the negative effects of excessive light irradiance and temperature via sunlight adjustment, but also realized efficient photocatalytic degradation of different organic dyes. Moreover, considering the typical concentration of $5 \text{ mg} \cdot \text{L}^{-1}$ for MB or MO wastewater [30–32], which was consistent with this study, SA-PTR showed great potential for treating typical organic dye wastewater in practice.

3.5. Antibiotic treatment and pathogenic bacteria disinfection under actual sunlight

Antibiotics and pathogenic bacteria are also organic pollutants in wastewater, which cause serious problems on human health [33,34]. To further evaluate the capability of SA-PTR, the degradation and disinfection of typical antibiotic (TC) and pathogenic bacteria (*E. coli*) were carried out under real sunlight.

Firstly, TC was degraded on a typical sunny day (2023-02-22) and cloudy conditions (2023-02-23), respectively. Fig. S10a-b showed that SA-PTR provided the optimal solar energy (around $1500 \text{ W}\cdot\text{m}^{-2}$) and reaction temperature (around 38°C) for the photocatalytic degradation of TC by actively adjusting the mirror size under sunny conditions. In addition, SA-PTR also provided the optimized light irradiance and reaction temperature for TC degradation under cloudy weather (shown in Fig. S10c-d). Under such favorable photocatalytic reaction conditions, the TC degradation experiments were carried out (Fig. 6a). The TC reaction rate of SA-PTR on sunny day was 0.0201 min^{-1} , which was almost the same as that of PTR and 1.38 times that of IPC, respectively (Table 1). Additionally, the TC degradation rate of SA-PTR under cloudy condition reached 0.0182 min^{-1} , which was also almost the same with that of PTR, and 1.34 folds of IPC, respectively (Table 1). These results suggested that the strategy of providing optimal solar energy with SA-PTR could facilitate the photocatalytic degradation process of antibiotics. Moreover, in this study, the antibiotic solution with the concentration of $10 \text{ mg}\cdot\text{L}^{-1}$ was used, which was much higher than the TC concentration ($0.1 \text{ mg}\cdot\text{L}^{-1}$) in real hospital wastewater [35]. Therefore, the above results implied that SA-PTR has application value in the treatment of real antibiotic wastewater.

Then, the disinfection experiment for pathogenic bacteria *E. coli* was conducted under sunny-cloudy condition on a day (2023-03-01) near the vernal equinox. SA-PTR could provide optimal solar energy when the sun was not blocked, and could provide as much light energy as possible when the solar rays were weakened by clouds (Fig. S11a). In addition, the reaction temperature in SA-PTR was also increased to the

suitable range (around 32°C), which could effectively facilitate the reaction process (Fig. S11b). While for the PTR, on the one hand, it provided excessive light irradiance (up to 6500 W·m⁻²), which may lead to the fast recombination of electrons and holes in photocatalyst and could not increase photocatalytic efficiency. Therefore, as shown in Fig. 6b, SA-PTR still achieved the highest sterilization rate (0.0024 min⁻¹), which was 1.26 folds of PTR, and 2.67 folds of IPC (Table 1), respectively. In addition, the concentration of pathogenic bacteria in real waterbody was only around 1 × 10³ cfu·mL⁻¹ [36], which was much lower than the concentration used in this study (1.2 × 10⁵ cfu·mL⁻¹). Therefore, SA-PTR could also have applicability in eliminating the pathogenic bacteria in real waterbody.

The experimental results for the removal of organic dyes (Rh B, MB and MO), antibiotics (TC) and pathogenic bacteria (*E. coli*) during the daytime indicated that the newly developed SA-PTR could implement effective solar energy control under real weather conditions. With such solar energy adjustment strategy, SA-PTR could be expected to achieve efficient real wastewater treatment processes in future applications.

3.6. Assessment of whole-year daytime performance

The whole-year daytime performance of SA-PTR was evaluated at Tsukuba area (36.1°N, Japan) based on the open-available database of the Japan Meteorological Agency [27]. The solar energy conversion in photoreactors was calculated (as shown in supplementary materials Text S2), and Fig. 7a-b showed the whole-year natural sunlight irradiance and ambient temperature, respectively. Due to the solar movement and seasonal changes, the maximum natural light irradiance was only 889 W·m⁻², which

was much lower than the suitable $1500 \text{ W}\cdot\text{m}^{-2}$ (Fig. 1b). Due to the weak natural light power, the highest ambient temperature was only 33.4°C , which could not effectively promote the photocatalytic activity [11]. As for IPC, since it only passively receives solar energy using an inclined mirror, it could only provide the solar energy of $0\text{-}1013 \text{ W}\cdot\text{m}^{-2}$ (Fig. 7c) and temperature lower than 37.8°C (Fig. 7d), which were only slightly improved compared with the natural conditions and unfavorable for efficient photocatalytic process (Fig. 1b). Then, the PTR which passively concentrate solar light using the parabolic mirror provided the solar energy up to $7500 \text{ W}\cdot\text{m}^{-2}$ (Fig. 7e) and the excessive reaction temperature (near to 90°C) (Fig. 7f), which may cause the limitation of the photocatalytic reaction [11], damage of equipment, evaporation of wastewater [11] and the formation of undesired by-products [19]. Therefore, PTR may not be feasible for practical application in photocatalytic wastewater treatment.

To address the above issues, SA-PTR equipped with flexible parabolic mirror was proposed in this study. On the one hand, it could concentrate solar energy. On the other hand, it could adjust the concentrated solar energy amount by controlling the size of flexible parabolic mirror. As shown in Fig. 7g-h, SA-PTR could adjust the concentrated solar energy to the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ under actual weather conditions. In this way, the suitable reaction temperature could be achieved while avoiding the negative effects caused by excessively high temperature. In addition, further calculation showed that as long as the cloudage is less than 45%, the SA-PTR could provide the optimal $1500 \text{ W}\cdot\text{m}^{-2}$ solar energy to photocatalytic reaction (Table S1). Since such weather condition accounts for 73.4% of the yeartime in Tsukuba area (Fig. S14), SA-PTR could have

excellent weather adaptability.

Then, the global whole-year applicability of SA-PTR was also evaluated by assessing its performance at Ishigakijima (24.5°N) and Sapporo (43.1°N), which represent the southernmost and northernmost points of Japan. As depicted in Fig. S15, SA-PTR effectively controlled light irradiance and temperature within the optimal range throughout the year in Sapporo by adjusting solar energy. This indicated the potential of SA-PTR to achieve high-efficiency photocatalytic wastewater treatment in Sapporo. Additionally, SA-PTR simulation at Ishigakijima (Fig. S16) demonstrated the optimized solar energy by controlling the mirror size. Therefore, SA-PTR has the potential to effectively adjust concentrated solar energy across Japan. Furthermore, considering that the latitude of Japan encompasses the latitudes of the most densely populated areas in the world (Fig. S17), SA-PTR could effectively adjust solar energy and achieve efficient wastewater treatment at the global populated areas.

3.7. Nighttime operation of SA-PTR

The above results demonstrated that the developed SA-PTR could achieve effective control of natural solar energy under real solar conditions, enabling efficient photocatalytic treatment of different typical organic pollutants during the daytime. However, for modern industrial facilities with high robustness requirements (such as wastewater treatment plants), photocatalytic systems need to be operational not only during the daytime, but also at nighttime. Nowadays, for solar-powered photocatalytic systems, achieving 24-hour continuous operation remains a challenge.

It is worth noting that, since SA-PTR was designed to roll up the flexible mirror

(to provide optimal $1500 \text{ W}\cdot\text{m}^{-2}$) in sunny conditions, some spare spaces between flexible mirror and framework of reactor were displayed (shown in Fig. 8a), allowing sunlight to pass through. If a solar panel is integrated behind the flexible mirror, and a UV lamp is installed above the reaction tube, it is possible to achieve the 24-hour operation of SA-PTR. Figure 8b showed the working principle of SA-PTR during daytime and nighttime. Under sunny conditions during the daytime, when natural solar light irradiance is high, flexible mirror was rolled up to provide the optimal light irradiance and temperature, which allowed the solar panel behind the mirror to receive solar energy, thus generating and storing large amount of solar-electricity. Under cloudy conditions during the daytime, flexible mirror was expanded to provide the light irradiance and temperature as high as possible to maximize the photocatalytic efficiency. At this time, since the expanded flexible mirror blocked the sunlight, few electrical power was generated by solar panel. At night, the electrical power stored during the daytime would power the UV lamp mounted over the reaction tube, ensuing the continuous photocatalytic process

To verify whether the power generated by solar panel during the daytime could cover the power requirement of UV lamp during the nighttime, the power generation/consumption amount of SA-PTR for the whole-year time (2022) in Tsukuba area has been calculated. Figure 8c presented the daily power generation capability of SA-PTR. As can be seen, its power generation amount was greatly affected by the season and weather. In winter (January, November and December), the solar-electricity generation capability was weaker due to the short daytime hours and low solar altitude

angle. While in other seasons, more solar-electricity power could be generated owing to longer daytime hours and higher solar altitude angles. Then, compared with the power consumption of SA-PTR (Fig. 8d), its power generation amount (270,488 kJ) far exceeded the consumption amount (182,304 kJ) in spring, summer and autumn. Even in winter when solar radiation was the weakest, its power generation amount (58,393 kJ) still 100% satisfied the power consumption requirement (57,976 kJ). Therefore, the SA-PTR combined with solar panel and UV lamp could achieve solar-powered 24-hour continuous photocatalytic reactions during the whole-year time.

To investigate the 24-hour water purification performance of SA-PTR, photocatalytic degradation experiments of different organic pollutants were further carried out in SA-PTR during the nighttime. Figure 9a showed the Rh B degradation results in SA-PTR and in dark condition during the nighttime (2023-10-02). The solar-electricity-powered UV lamp in SA-PTR could effectively activate the photocatalytic reaction tube, so as to achieve Rh B degradation. While almost no Rh B was degraded under the dark condition, implying the weak photocatalytic capability of traditional PTR and IPC in the night. Similar results could be observed in Fig. 9b-e, which demonstrated that the solar-electrical powered UV lamp equipped in SA-PTR could achieve degradation of different organic pollutants (MB, MO, TC and *E. coli*) during the nighttime (from 2023-10-11 to 2023-11-03), while PTR and IPC exhibited negligible treatment efficiency toward organic pollutants. Interestingly, as shown in Fig. 9f, the degradation reaction rate of Rh B during the night operation of SA-PTR (0.0245 min^{-1}) was similar with that during the daytime ($0.0114\text{-}0.0338 \text{ min}^{-1}$), shown in Table

1). What's more, the degradation reaction rates of MB and TC in SA-PTR during nighttime (0.0498 min^{-1} and 0.0259 min^{-1} , respectively) were even much higher than those in sunny conditions during the daytime (0.0172 min^{-1} and 0.0201 min^{-1} , shown in Table 1). On the other hand, the treatment efficiency of SA-PTR for MO and *E. coli* at nighttime (0.00123 min^{-1} and 0.00024 min^{-1} , respectively) were lower than those during daytime ($0.0051\text{-}0.0094 \text{ min}^{-1}$ and 0.0024 min^{-1} , respectively, shown in Table 1). Kalaycıoğlu et al. also reported the similar phenomenon that the photocatalytic reaction rate varied under the different light sources (sunlight and UV light) [30]. However, the reason may need to be further studied in the future. The above results indicated that SA-PTR could provide superior light irradiance and reaction temperature for photocatalyst via solar energy controlling, thus realizing efficient photocatalytic water purification process during the daytime. At the same time, the power generated by SA-PTR under real sunlight during the daytime was sufficient to meet the power requirements of continuous 24-hour photocatalytic reaction. At night, SA-PTR could also achieve effective photocatalytic degradation of different organic pollutants.

In comparison to the photoreactors reported so far, SA-PTR potentially offered significant advantages in terms of light adjustability and all-weather operational capability. For instance, the maximum irradiance achieved by IPC was limited to $800 \text{ W}\cdot\text{m}^{-2}$ [11], while V-groove-based photoreactors struggled with inefficient sunlight harnessing, resulting in temperatures that rarely exceed 38°C [37]. This low solar energy capture capacity renders them inadequate for achieving efficient photocatalytic reactions. On the contrary, high-solar-concentrated photoreactors such as PTR,

Parabolic Dish Reflector (PDR), and Fresnel lens (FL) typically provided extreme light irradiances of up to $15,000 \text{ W}\cdot\text{m}^{-2}$ and temperatures of up to $200\text{-}250^\circ\text{C}$ [38,39]. However, numerous studies have highlighted the drawbacks of these systems [11,40,41]. Specifically, the rapid electron-hole recombination rate at high light irradiances fails to enhance photocatalytic efficiency. Additionally, excessive temperatures have detrimental effects on the reaction process. Despite Compound Parabolic Collectors (CPC) could provide a suitable light irradiance of $1018\text{-}2083 \text{ W}\cdot\text{m}^{-2}$ for photocatalysis [42,43], certain shortcomings specific to CPC are also noteworthy. One major drawback is the potential for localized excessive light irradiance and overheating within certain regions of reaction tube [44]. The intricate mirror of CPC may also lead to high manufacturing cost. Notably, the recently developed solar-energy-controllable Linear Fresnel Photoreactor (LFP) addressed above issues by tracking and controlling sunlight to achieve an optimized light irradiance of $1000 \text{ W}\cdot\text{m}^{-2}$ and a suitable temperature (increased while lower than 65°C), which were favorable for photocatalysis [11]. Nevertheless, its inability for night-time operation may limit its all-weather functionality. Although Portela et al. introduced a CPC that incorporated both solar and artificial lamp irradiation, allowing for daylight utilization and nighttime operation, the energy source for the artificial lamp still relied on municipal power [45].

Therefore, the developed SA-PTR could be a 24-hour solar-powered photocatalytic reactor that could be efficiently operated during the whole-year time, which laid the basis for its industrial large-scale application.

3.8. Economic analysis and application prospects of SA-PTR

One of the decisive factors determining whether a new technology could be popularized and applied on a large scale is its economic advantages. In order to explore the economic advantages of SA-PTR compared with traditional PTR and IPC, the economic analysis based on the actual situation was carried out. In this study, SA-PTR, PTR and IPC based photocatalytic systems located in Tsukuba area were proposed for daily 1000 m³ organic wastewater treatment, respectively. Assuming a citizen uses 100 L of water per day, and 70% of the used water becomes wastewater, each of these systems could provide water purification services for a community of 14,000 people. As shown in Fig. 10a, the insoluble and large particles in city-generated sewage would first be removed by a filtration/precipitation station for initial treatment. Then, the remaining waste liquid containing refractory soluble organic pollutants would be sent to the proposed SA-PTR, PTR and IPC based photocatalytic systems, respectively.

The estimated parameters of three photocatalytic systems for 1000 m³ wastewater purification were listed in Table S2. The total length of the SA-PTR system which was 24-hour operational was evaluated to be 216 m. Although the photocatalytic reaction efficiency of PTR was close to that of SA-PTR (Table 1), it could only work during the daytime (with an operational time of 12 h on average). Thus, in order to achieve the same daily wastewater treatment capacity (1000 m³), the total length of the PTR system needs to be doubled (432 m). Further, for IPC which could only work during the daytime with low photocatalytic efficiency, an even larger scale (840 m) was required. Notably, these differences in total length of the photocatalytic system would directly

638 impact the size of deployment area. For the SA-PTR system, its solar panel was highly
639 integrated behind the flexible mirror and did not require any extra installation space
640 outside the reactor body (Fig. 8a). Therefore, SA-PTR system only needs to occupy
641 about 1860 m², which was much smaller than the PTR (3360 m²) and IPC (5280 m²)
642 systems, thus making SA-PTR gains the advantages in reducing land costs (Fig. 10b)
643 and improving deployment flexibility (such as rooftop deployment). Besides, as shown
644 in Fig. 10b, the smaller size of the SA-PTR system also significantly reduced the cost
645 of reaction components (photocatalyst, reaction tubes, etc.), mirror components (mirror
646 pylon, mirror panel, etc.) and flow components (pipes and pumps). Despite additional
647 electronic devices (mirror controlling system, solar panel, rechargeable battery, UV
648 lamp, etc.) were required to be equipped in SA-PTR system for solar energy adjustment
649 and 24-hour continuous operation, they might not significantly increase the overall
650 construction cost budget of the SA-PTR system owing to their low market price and
651 limited equipment demand.

652 In addition to the construction budget, the operation cost could also be an
653 important aspect of the economic analysis, which was closely related to the system
654 power requirement. Figure 10c compared the daily power requirements for SA-PTR,
655 PTR and IPC based photocatalytic systems. Traditional PTR and IPC based
656 photocatalytic systems require pump operation, and PTR further requires a solar
657 tracking system to maintain the vertical incidence of sunlight. Since PTR and IPC
658 cannot be integrated with solar panel, their pump and solar tracking system could only
659 rely on external artificial power supply, which lead to extensive annual power cost

(16,530 kW·h for PTR, 30,306 kW·h for IPC). While for the SA-PTR system coupled with solar panel, despite additional electronic devices (for solar tracking/controlling and UV lighting) increased its total annual power demand (72,156 kW·h), it could generate 86,222 kW·h solar-electrical power during the year, thus no any external artificial power input was needed. Since all the energy for driving 24-hour continuous photocatalytic reactions in SA-PTR come from free and eternal solar energy, its sustainability and cost-effectiveness was highlighted. From the above results, it could be seen that the SA-PTR system requires low budget for construction and zero power cost for operation, thus enabling SA-PTR to have significant economic advantages over PTR and IPC.

Furthermore, the innovative design of SA-PTR may bring some additional benefits. For example, its flexible mirror could be rolled up to avoid structural damage during extreme weather such as typhoons and hail. Its lightweight flexible mirror could also lower the gravity center of system to avoid toppling during earthquakes. Moreover, excessive reaction temperature and light irradiance could be avoided by adjusting solar energy, thus reducing the aging and damage of system components (such as rubber connecting pipes and water pump blades). It is noteworthy that at the present stage, the photocatalyst used in SA-PTR is TiO_2 , which possesses low utilization ability of sunlight and poor adsorption for organic pollutants [46,47]. One of the future improvements may involve adopting solar-light-driven composite catalysts to enhance photocatalytic activity [15,47,48]. Adsorption technology, as an effective approach of contaminant removal [49,50], could also be leveraged to augment the performance of

SA-PTR. In particular, catalysts that possess excellent adsorption capabilities are promising candidates for this purpose [51–53]. Based on the above perspectives, SA-PTR could be a novel 24-hour operational photoreactor with excellent photocatalytic capability, industrial applicability, superior economic efficiency, high safety and long lifetime, which is promising to be applied in wastewater purification globally.

4. Conclusions

In this study, a 24-hour operational solar energy-controllable SA-PTR system was pioneeringly developed. This innovative system incorporated a flexible parabolic mirror, adaptively adjustable in size to harness optimal solar energy for photocatalytic reactions during daytime. Notably, the SA-PTR even retained operational capability during nighttime, independent of external power sources. Comparative assessments with traditional PTR and IPC reactors revealed that the SA-PTR outperformed in the removal of typical organic dyes, antibiotics and pathogenic bacteria, achieving superior treatment efficiency day and night. Additionally, its excellent economic feasibility and practical applicability make the SA-PTR a highly promising technology for widespread implementation in global real-world wastewater treatment.

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Table 1

Summary of experimental information and reaction rates in IPC, PTR and SA-PTR.

Weather condition	Treatment target	Reaction rate k (min ⁻¹)			Reaction rate comparison (folds)	
		IPC	PTR	SA-PTR	$k_{\text{SA-PTR}}/k_{\text{IPC}}$	$k_{\text{SA-PTR}}/k_{\text{PTR}}$
Sunny	Rh B	0.0193	0.0318	0.0338	1.75	1.06
Temporarily cloudy	Rh B	0.0127	0.0209	0.0212	1.64	1.01
Snowy	Rh B	0.0057	0.0114	0.0114	2.00	1.00
Sunny	MB	0.0134	0.0172	0.0190	1.42	1.10
Rainy	MB	0.0067	0.0100	0.0098	1.46	0.98
Sunny	MO	0.0032	0.0091	0.0094	2.94	1.03
Cloudy	MO	0.0021	0.0050	0.0051	2.42	1.04
Sunny	TC	0.0141	0.0195	0.0201	1.38	1.03
Cloudy	TC	0.0135	0.0184	0.0182	1.34	0.99
Cloudy-sunny	<i>E. coli</i>	0.0009	0.0019	0.0024	2.67	1.26

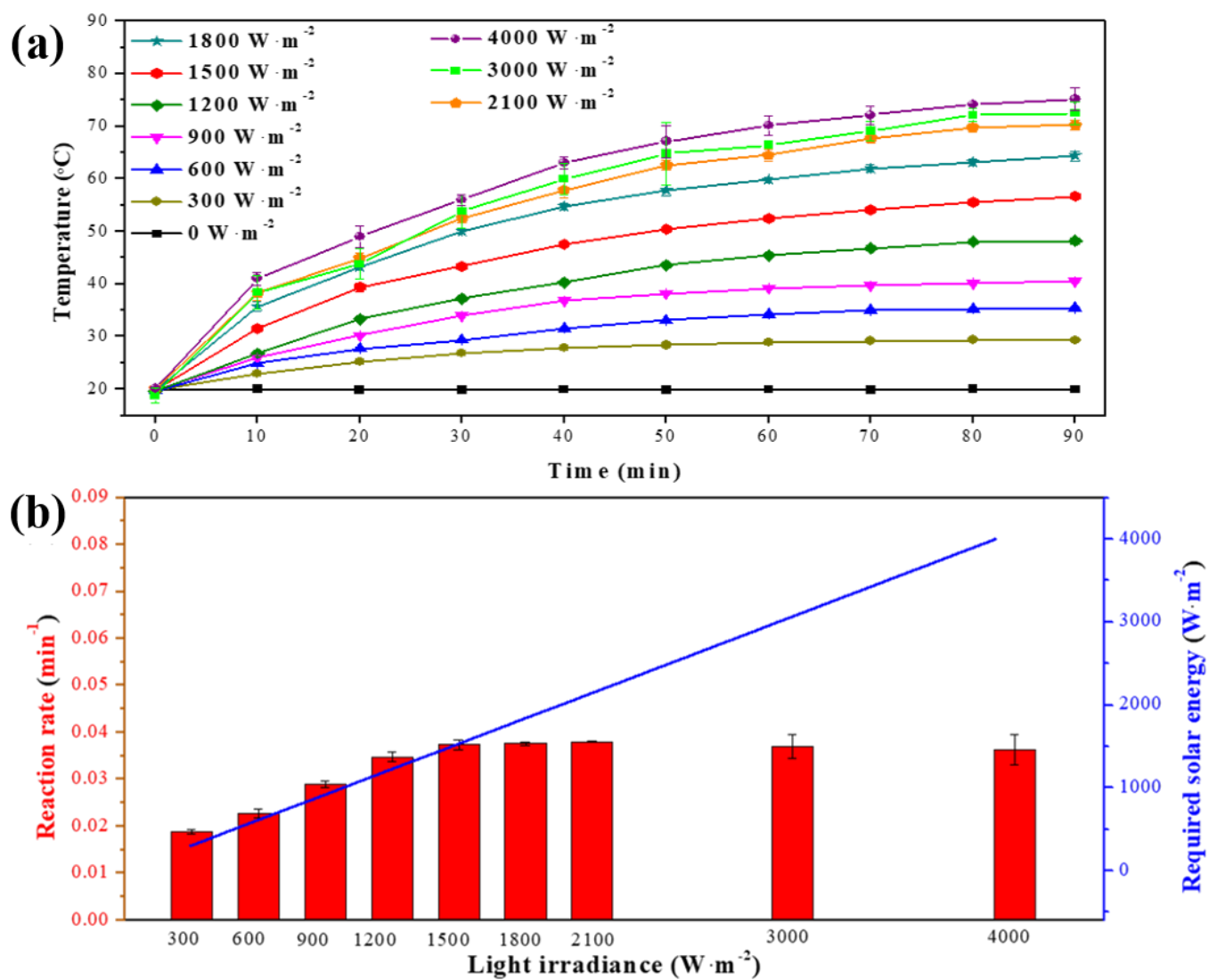


Fig. 1. (a) Variation of reaction temperature under different solar energy; (b) relationship between Rh B degradation reaction rate and solar energy.

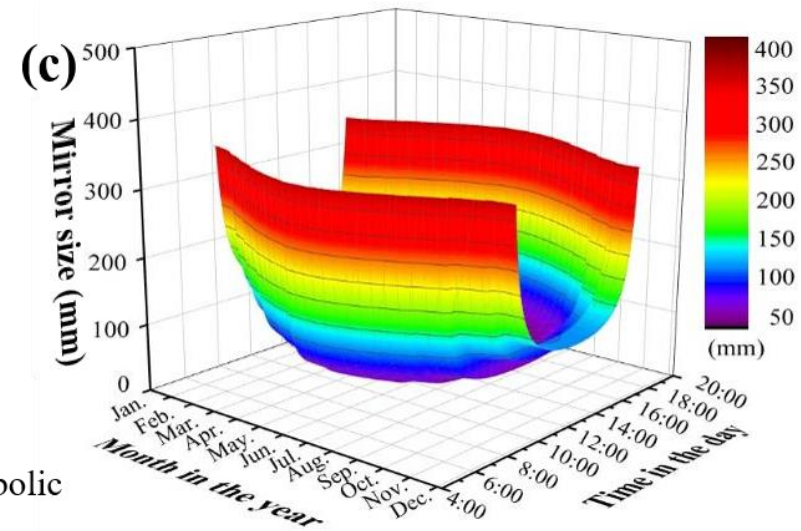
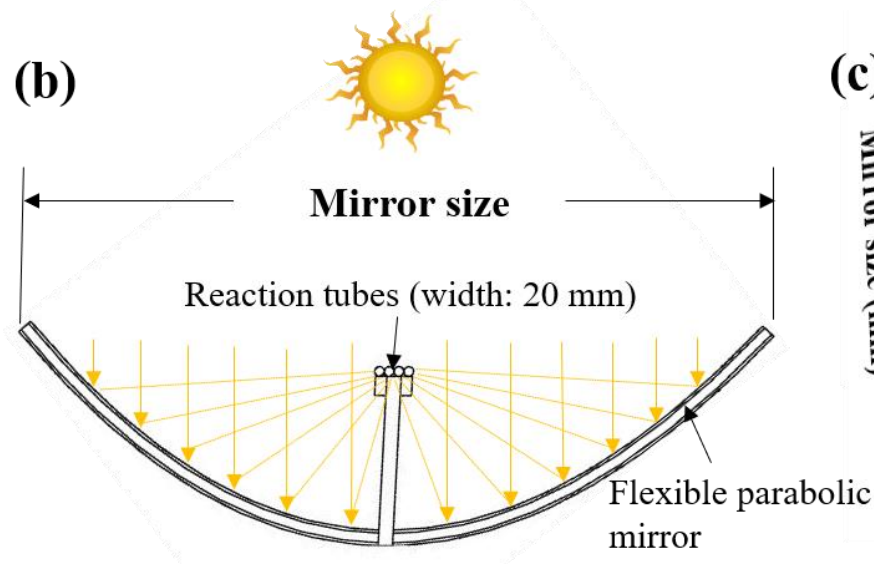
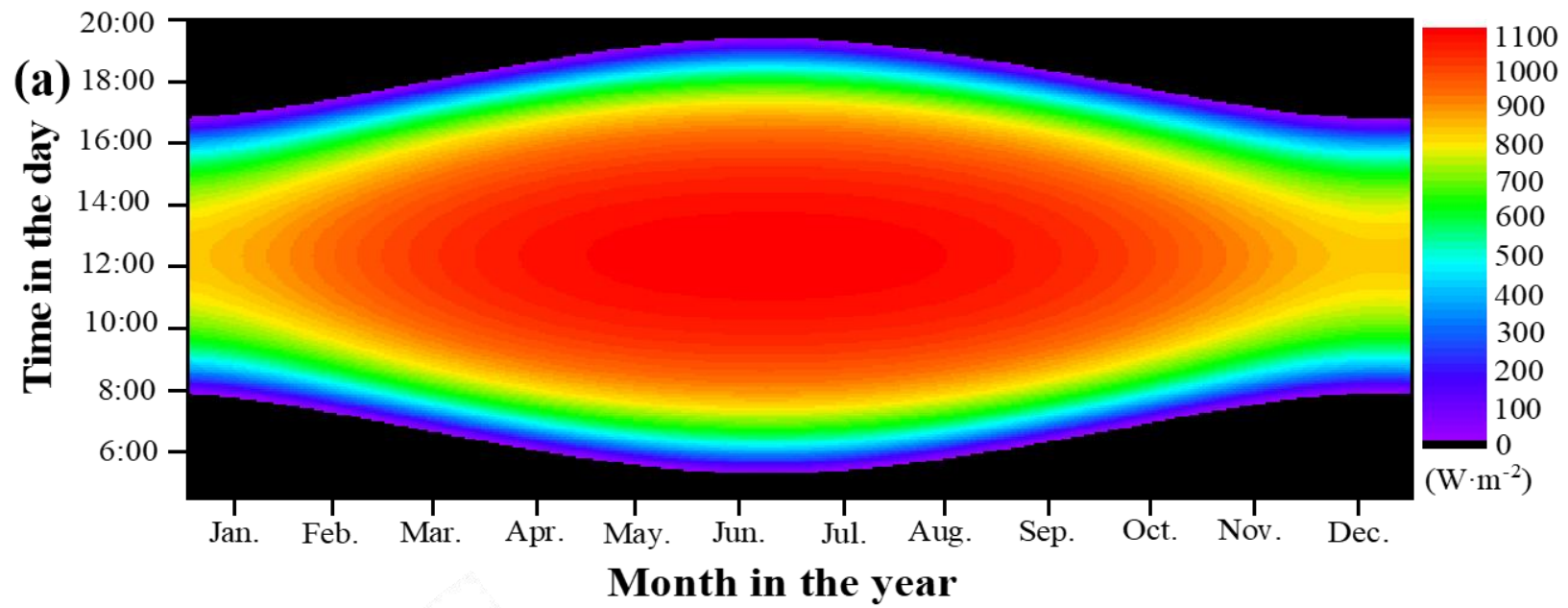


Fig. 2. (a) Whole-year natural solar energy at Tsukuba area (36.1°N , 140.1°N); (b) schematic diagram of mirror width in SA-PTR; (c) whole-year mirror size in SA-PTR for providing the optimal solar energy of $1500 \text{ W}\cdot\text{m}^{-2}$.

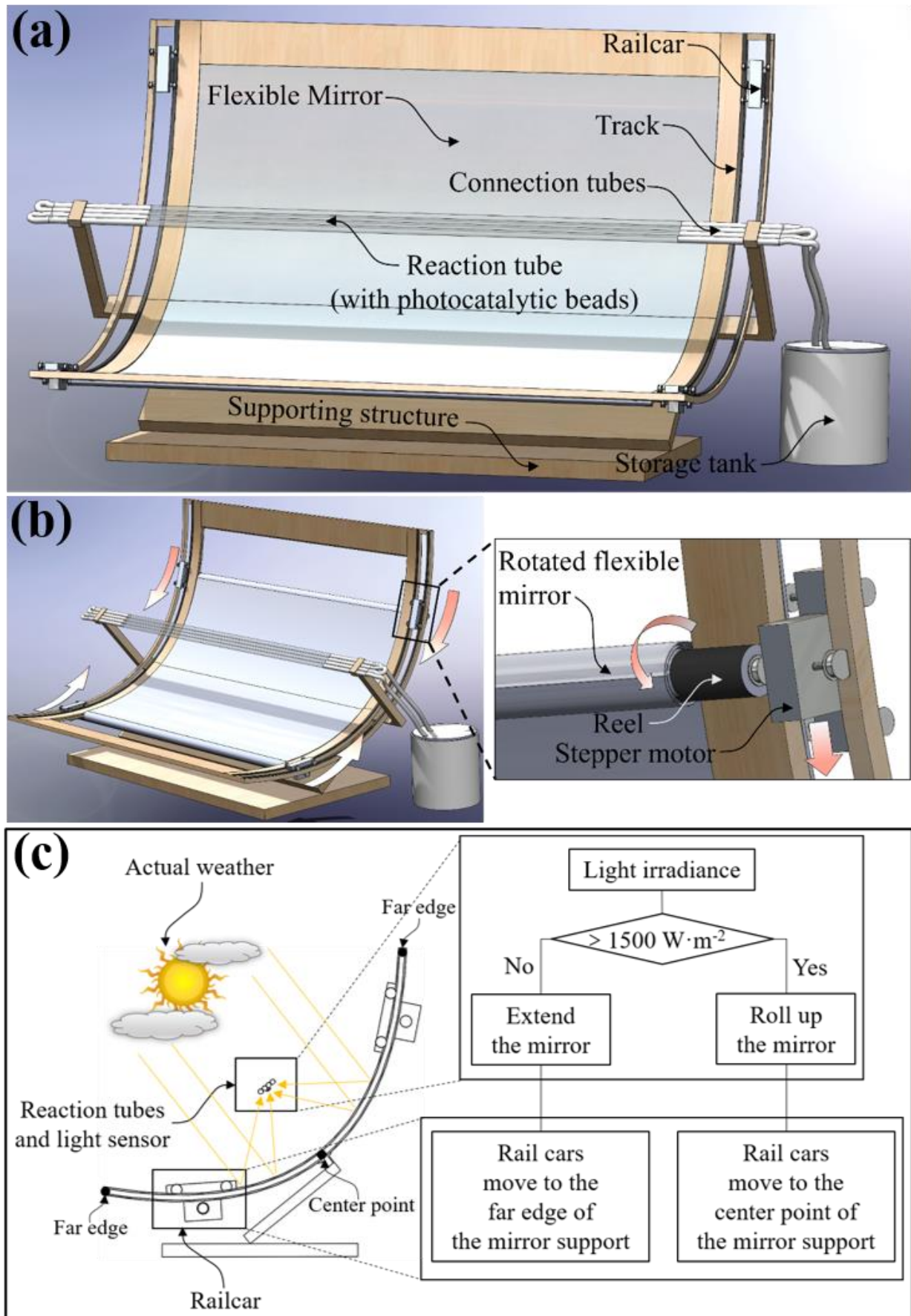


Fig. 3. Design of SA-PTR for solar energy controlling during the daytime. (a) Structure of SA-PTR; (b) control system of SA-PTR; (c) adjustment of mirror size in SA-PTR for providing the optimal $1500 \text{ W} \cdot \text{m}^{-2}$.

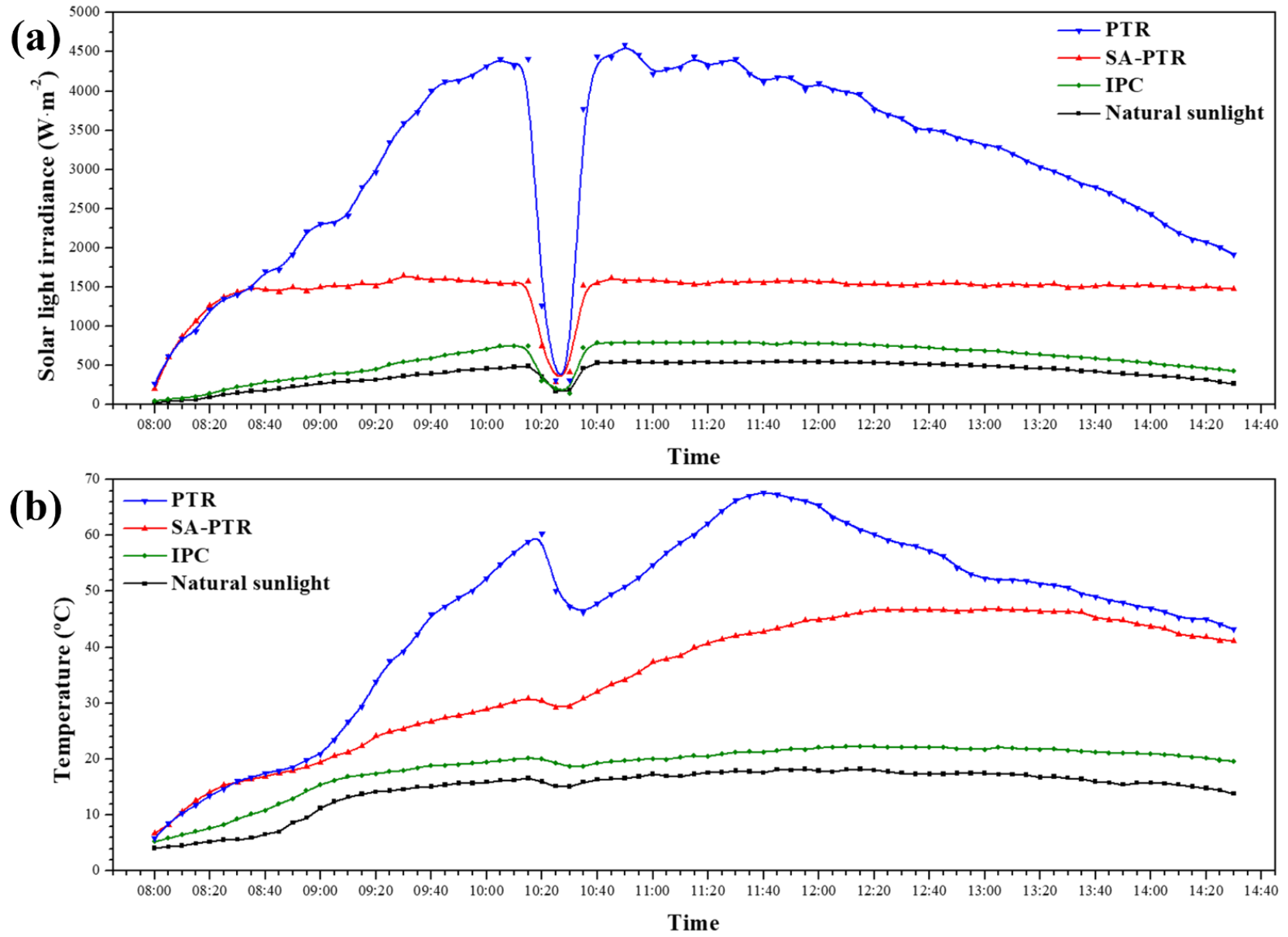


Fig. 4. Solar energy adjustment under typical sunny weather condition (2022-12-23, from 8:00 to 14:30). (a) Light irradiance; (b) temperature.

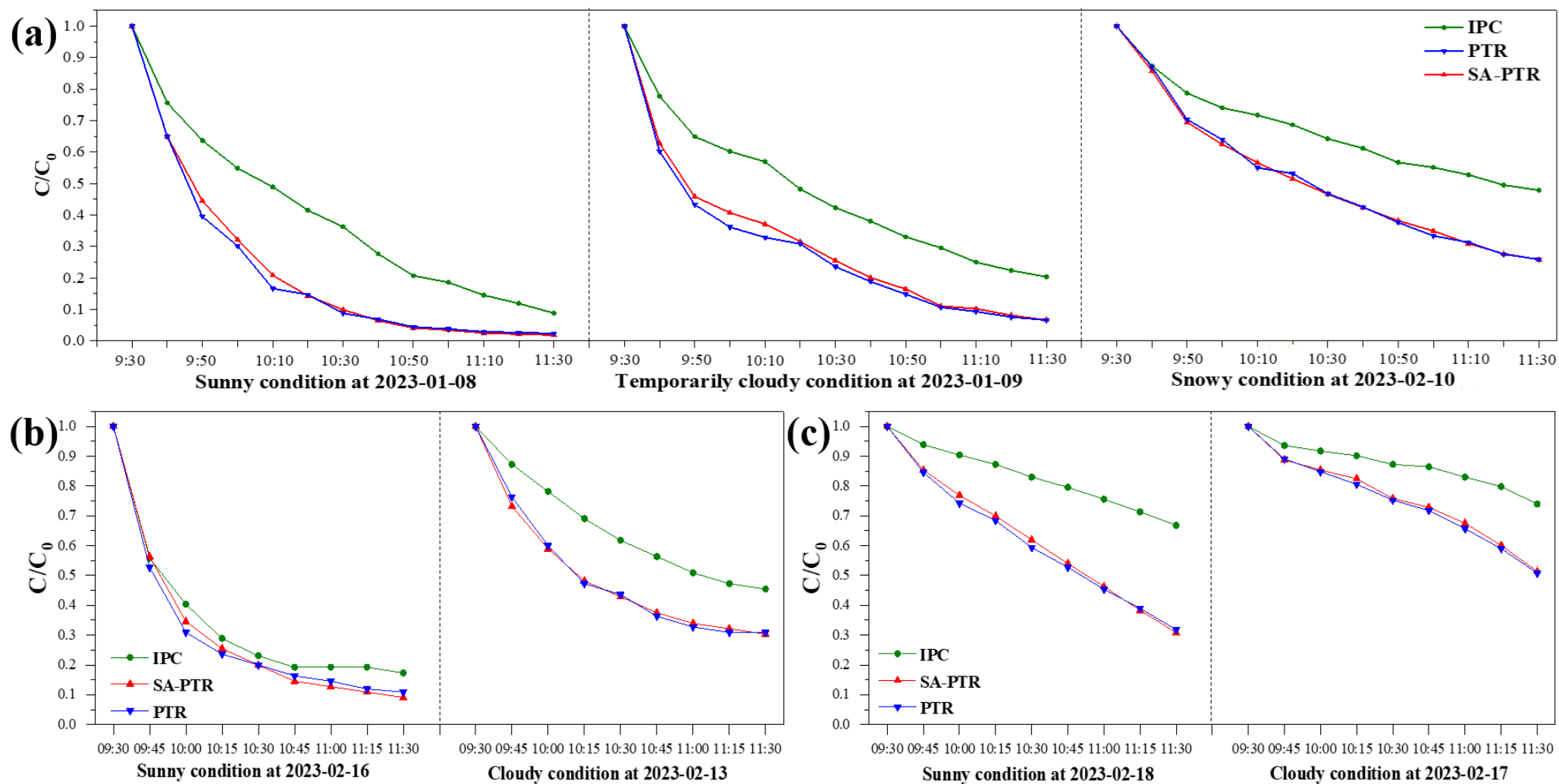


Fig. 5. Organic dye degradation experiments under different real weather conditions. (a) Rh B; (b) MB; (c) MO.

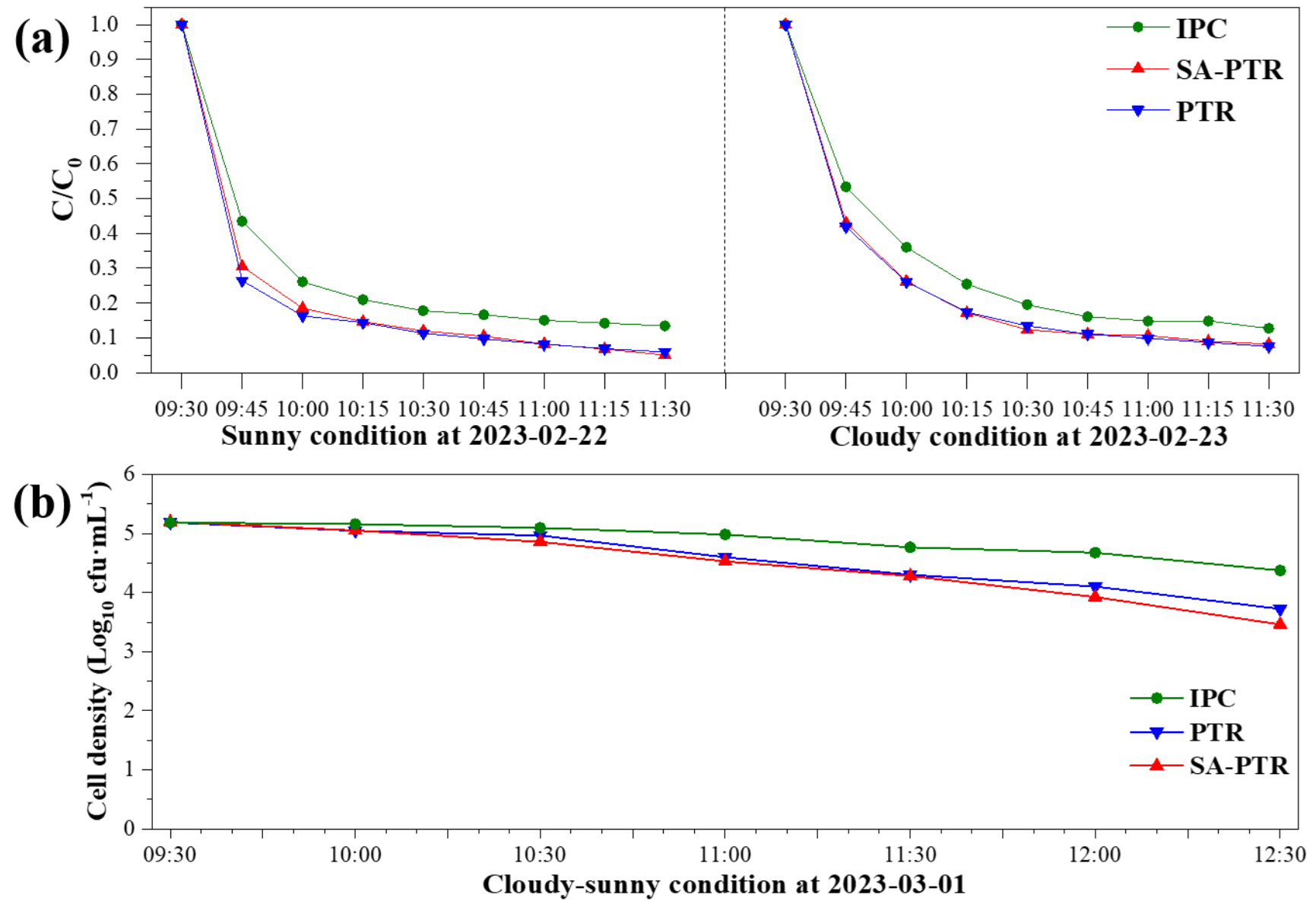


Fig. 6. (a) TC degradation and (b) *E.coli* disinfection experiments under real weather conditions.

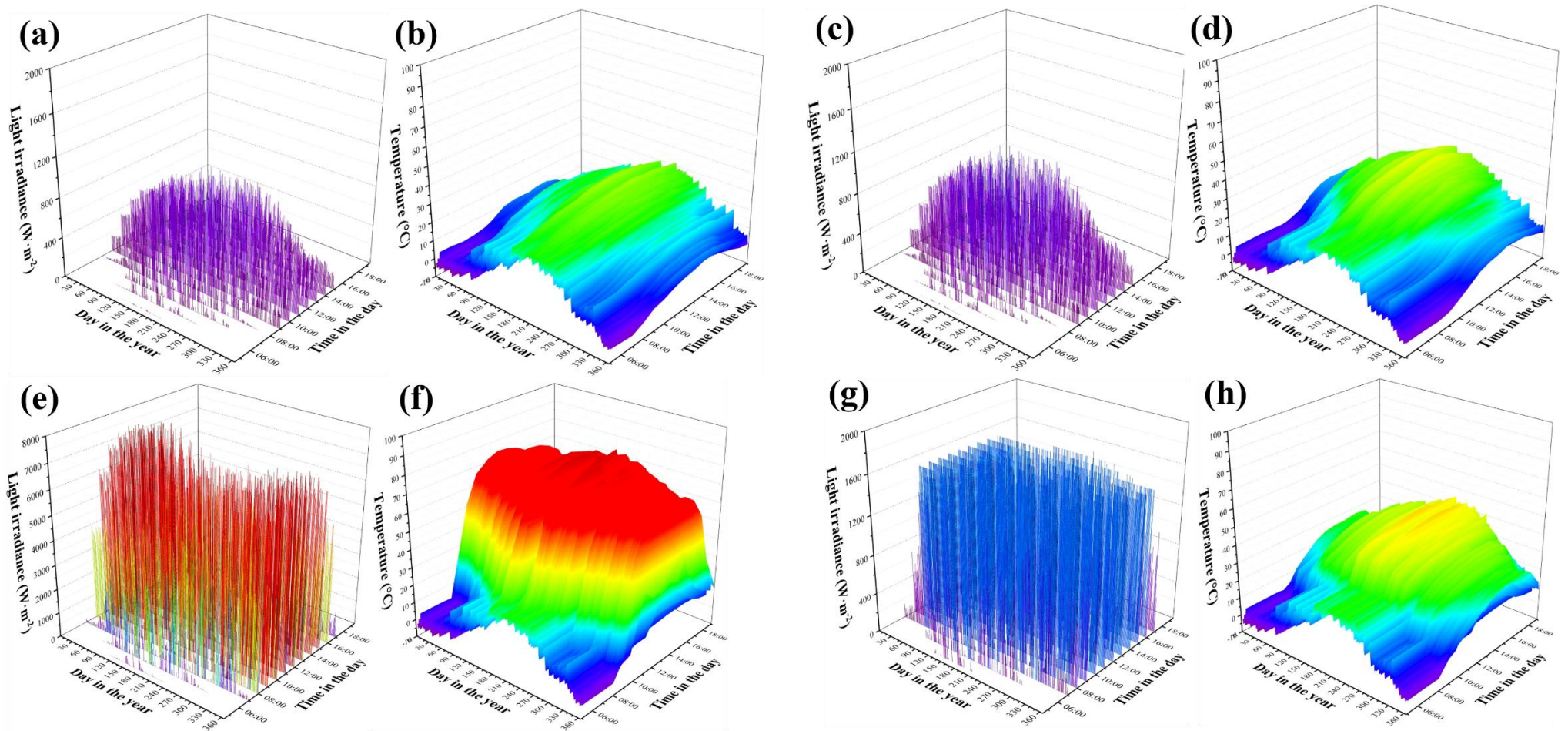


Fig. 7. Evaluation of the light irradiance and temperature in IPC, PTR and SA-PTR during the whole-year time (2022) in Tsukuba area. (a-b): Natural light irradiance and temperature; (c-d) light irradiance and temperature in IPC; (e-f) light irradiance and temperature in PTR; (g-h) light irradiance and temperature in SA-PTR. Data source of natural light and temperature in Tsukuba area in 2022: Japan Meteorological Agency.

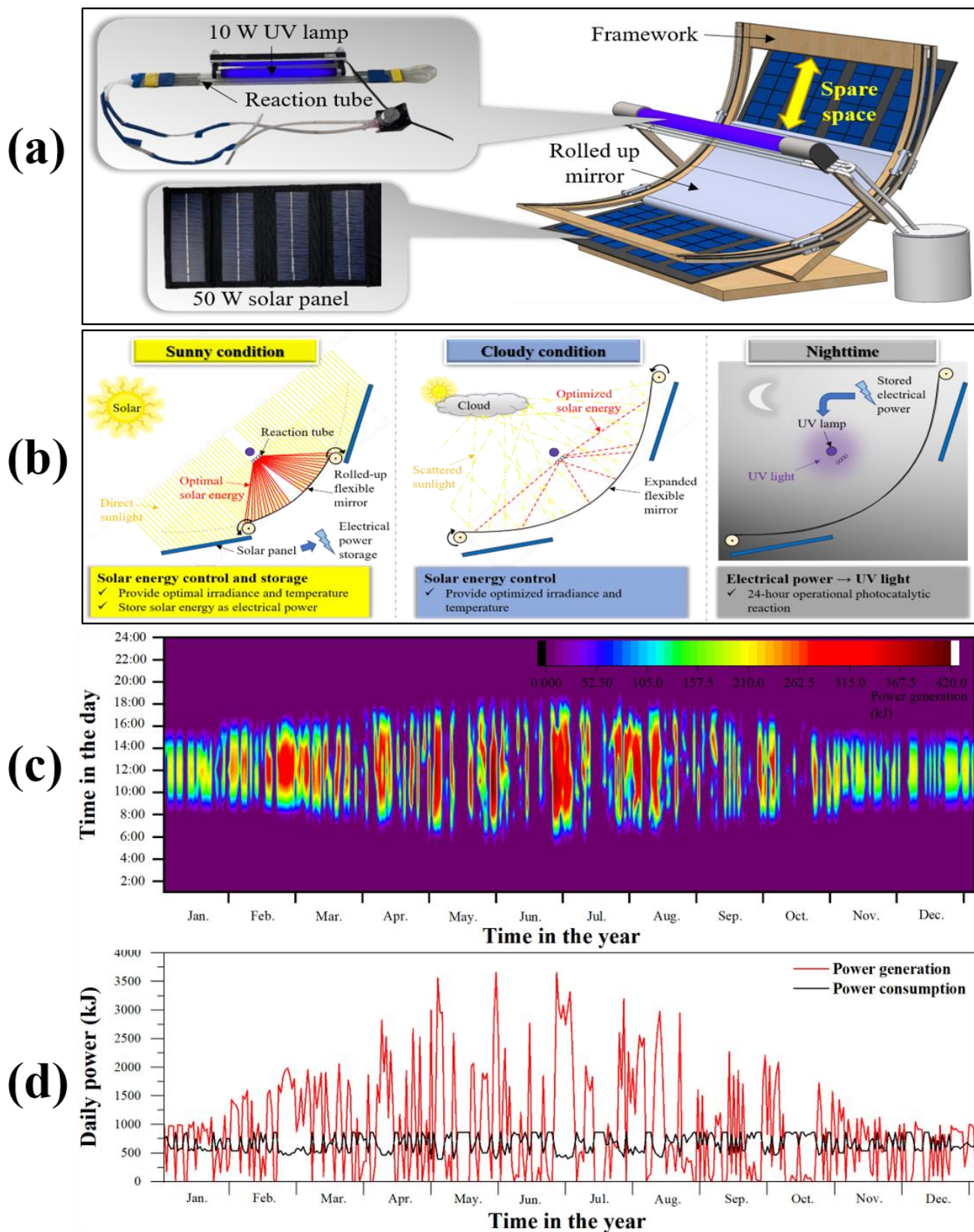


Fig. 8. 24-hour operational SA-PTR. (a) Solar panel and UV lamp integrated in SA-PTR; (b) working principle of SA-PTR for daytime (sunny and cloudy conditions) and nighttime operations; (c) daily power generation capability of SA-PTR; (d) yearly power generation and consumption of SA-PTR. All results were calculated based on the 2022 real weather data of Tsukuba obtained from Japan Meteorological Agency.

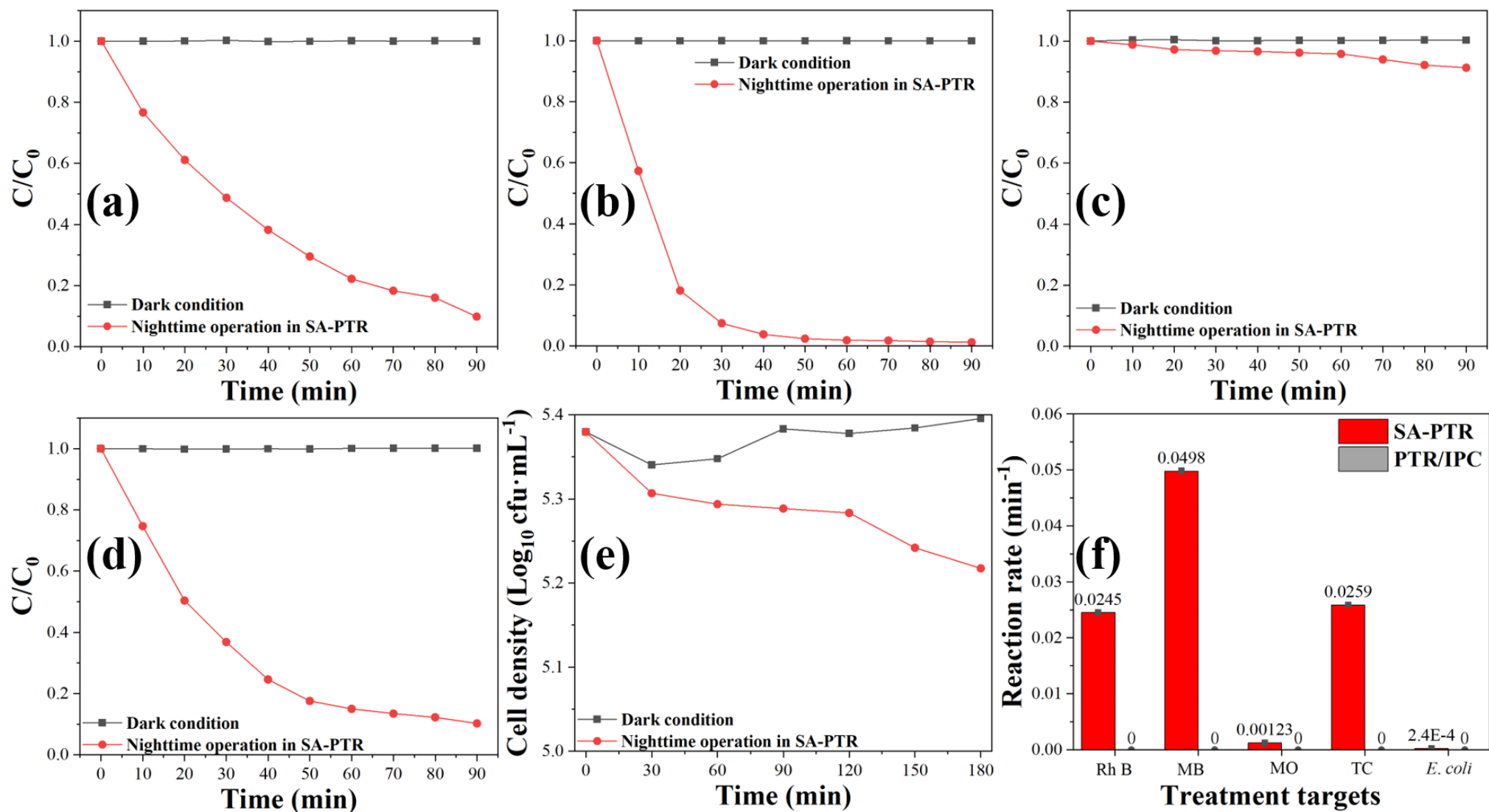


Fig. 9. Comparative experiments of organic pollutants treatment during nighttime in SA-PTR and in dark condition. (a) Rh B degradation (2023-10-02); (b) MB degradation (2023-10-11); (c) MO degradation (2023-10-14); (d) TC degradation (2023-10-12); (e) *E. coli* disinfection (2023-11-03); (f) reaction rates of different targets treatment in SA-PTR and in dark condition.

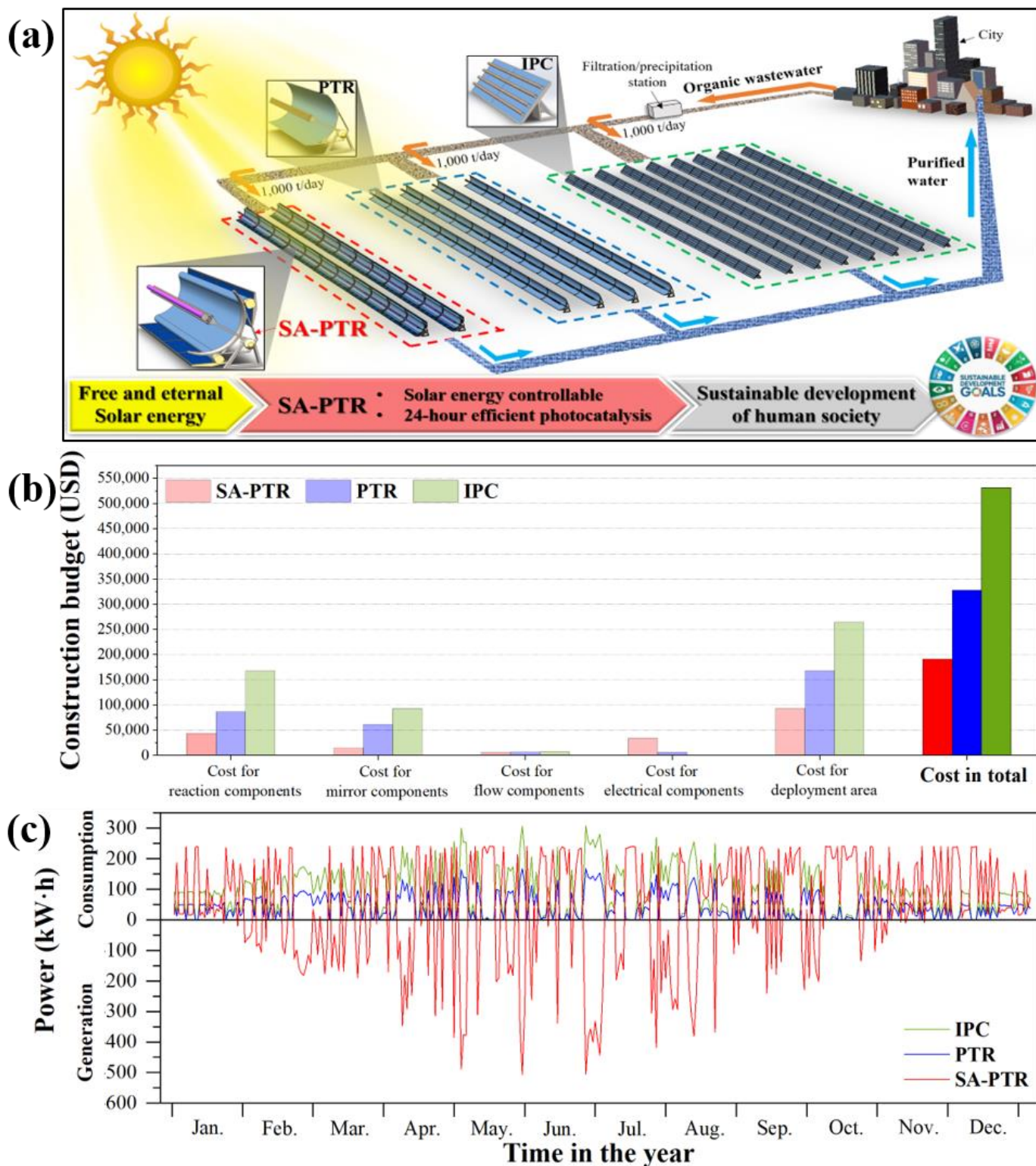


Fig. 10. Economic analysis of SA-PTR, PTR and IPC. (a) Schematic diagram of the proposed SA-PTR, PTR and IPC based photocatalytic systems for daily 1000 m³ organic wastewater treatment in Tsukuba area; (b) evaluation on the construction budgets and (c) estimation of the yearly power requirement of SA-PTR, PTR and IPC based photocatalytic systems. All results were calculated based on the 2022 real weather data of Tsukuba obtained from Japan Meteorological Agency.