Supporting Information for

Balancing UV-to-Blue Light Conversion by Membrane-Embedded AIE Antennas for Enhanced Photosynthesis

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Materials and Instruments

C_8-TPE-C_4 and C_4-TPE-C_8 were synthesized referring to the previous report.[1] Propidium iodide (PI, 98%) was purchased from Sigma Aldrich. 1,1'-Dioctadecyl-3,3,3',3'-tetramethylindocarbocyanine perchlorate (DiI), plant protoplasts isolation kit, enhanced ATP assay kit, enhanced $NADP^+$/NADPH assay kit, total superoxide dismutase (SOD) assay kit with AST-8 and lipid peroxidation MDA assay kit were purchased from Beyotime. Rubisco assay kit was purchased from Solarbio. 2',7'-Dichlorofluorescein diacetate (DCFH-DA, 97%) was obtained from Energy Chemical. 2,6-Dichlorophenolindophenol (DCPIP, 97%) was purchased from Macklin. Phosphate buffered saline (1× PBS, pH 7.4) was obtained from WISENT. *Chlorella pyrenoidosa* (*C. pyre*, FACHB-9) and BG11 medium were obtained from Freshwater Algae Culture Collection at the Institute of Hydrobiology, FACHB. *C. pyre* cells were incubated in an illumination incubator (BIC-250, Shanghai Boxun Industrial Co. Ltd., China). Spectrum of the light source in the incubator was measured using a handheld spectrometer (HP330, LCE Intelligent, China). UV-vis absorption and fluorescence spectra were measured on a spectrophotometer (UV-6100, Mapada, China) and a spectrofluorometer (F7000, Hitachi, Japan), respectively. Size distribution and zeta potential results were measured on Nano ZS (ZEN3690, Malvern). Fluorescence images were collected on a confocal laser scanning microscopy (LSM 880NLO, Carl Zeiss, Germany). Flow cytometric analysis was performed on a flow cytometry (LSRFortessa^{TM}, BD, USA). Morphology of algae was observed by scanning electron microscopy (SEM, GeminiSEM 300, Carl Zeiss,

Germany). The oxygen evolution was measured on liquid-phase oxygen electrode systems (Chlorolab-2, Hansatech, UK). The ATP, NADPH content and SOD activity were measured on a microplate reader (Spark, Tecan, Switzerland). The chlorophyll parameters were tested using Chlorophyll fluorescence monitor (Aquapen AP 110-C, Photon Systems Instruments, Czech Republic).

Experimental methods

Microalgal incubation. *C. pyre* cells were incubated in BG11 medium in an illumination incubator (light source spectrum shown in Fig. S26) under controlled conditions: temperature at 25 ºC, light intensity of 27.6 μmol·m^{-2}·s^{-1}, with 12 h light and 12 h dark cycle. The culture flasks were shaken manually three times a day. The concentration of *C. pyre* suspensions was evaluated by measuring the optical density at 680 nm (OD_{680}).

Fluorescence imaging of microalgae. *C. pyre* cells (2 mL, OD_{680} = 2.0) were incubated with 20 μM of C_8-TPE-C_4 or C_4-TPE-C_8 in BG11 medium for 30 min at 25 ºC. The supernatant was removed via centrifugation (7000 rpm, 5 min), and the harvested *C. pyre* cells were resuspended with 50 μL of PBS. 5 μL of the prepared samples were placed on a glass slide and imaged on a confocal laser scanning microscopy with a ×100 oil lens. Imaging conditions: λ_{ex} = 405 nm and λ_{em} = 450-600 nm for AIEgens; λ_{ex} = 488 nm and λ_{em} = 650-750 nm for *C. pyre*.

Flow cytometric analysis of microalgae binding with AIEgens. 2 mL of *C. pyre* suspensions (OD_{680} = 2.0) were incubated with 20 μM of C_8-TPE-C_4 or C_4-TPE-C_8 in

BG11 medium for 30 min. Then the samples were centrifuged at 7000 rpm for 5 min to remove the supernatant. The collected *C. pyre* cells were resuspended with 500 μL of PBS and transferred to a sample tube. Fluorescence signals from about 20000 *C. pyre* cells were collected under the Qdot 565 channel using a flow cytometer.

Cell membrane localization. *C. pyre* protoplasts were first prepared using a plant protoplast isolation kit. Briefly, 5 mL of *C. pyre* suspensions (OD_{680} = 2.0) were centrifuged at 3000 rpm for 5 min to harvest the cells. 5 mL of cell wall digestion solution was added, and the mixture was subjected to vacuum treatment for 30 min, followed by 3 h incubation at room temperature. After centrifugation (3000 rpm, 5 min), the supernatant was discarded, and the remaining protoplasts were resuspended with 5 mL of protoplast dilution buffer. Following another centrifugation (3000 rpm, 5 min) and removal of the supernatant, 2 mL of resuspension buffer was added, and the obtained protoplast suspension was stored on ice. Next, 1 mL of the prepared protoplast suspension was treated with the AIEgen (20 μM) for 30 min and stained with DiI (10 μM) for 10 min at 25 ºC, and then imaged. Imaging conditions: λ_{ex} = 405 nm and λ_{em} = 450-600 nm for AIEgens; λ_{ex} = 543 nm and λ_{em} = 550-650 nm for DiI.

Microalgae morphology observed by SEM. 2 mL of *C. pyre* cells (OD_{680} = 2.0) were incubated with C_8-TPE-C_4 or C_4-TPE-C_8 (20 μM) in BG11 for 30 min at 25 ºC. The cells were collected by centrifugation (7000 rpm, 5 min), washed three times with PBS, and then suspended in 50 μL of PBS. 5 μL of the prepared samples were placed on a silicon slice, dried naturally, and then fixed with 2.5% glutaraldehyde solution

for 6 h at 4 ºC. The samples were washed three times with PBS, and then dehydrated in a gradient of ethanol solutions (50%, 70%, 80%, 90%, 95% and 100%, each for 15 min). After vacuum drying, the samples were coated with platinum for SEM observation. As a control, *C. pyre* cells without AIEgen treatment performed the same pretreatment steps.

Zeta potential measurements. 2 mL of *C. pyre* cells were treated with C_8-TPE-C_4 or C_4-TPE-C_8 (20 μM) in BG11 solution for 30 min at 25 ºC. After centrifugation (7000 rpm, 5 min) to remove the unbound AIEgens, the remaining cells were suspended in 2 mL BG11 solution. The samples were transferred to a DTS1070 disposable capillary cell, and their zeta potential was measured on Nano ZS with a He-Ne laser of 632.8 nm at a scattering angle of 173º.

PI staining to assess the effect of AIEgen on algal membrane. *C. pyre* cells (2 mL, OD_{680} = 2.0) were incubated with 20 μM of C_8-TPE-C_4 or C_4-TPE-C_8 for 30 min. The samples were centrifuged (7000 rpm, 5 min) and the supernatant was discarded. The remaining *C. pyre* cells were suspended in 2 mL of PBS and stained with PI (5 μg/mL) for 10 min. After centrifugation (3000 rpm, 5 min) to remove the supernatant, and the remaining droplets were resuspended with 500 μL of PBS, and then transferred to the sample tube. The fluorescence signal of PI from about 20000 cells was analyzed using the PE-Texas Red channel on a flow cytometry.

Growth curves of microalgae. *C. pyre* cells were diluted to an initial OD_{680} of about 0.3 with BG11 medium for growth curve measurements. Different concentration of

C_8-TPE-C_4 or C_4-TPE-C_8 were added to 25 mL of *C. pyre* suspensions. Then the cultures were incubated in an illumination incubator, with manual shaking three times a day. The OD_{680} values of the *C. pyre* suspensions were recorded daily for a period of 14 days. Each experiment was performed in triplicate.

SOD activity. The SOD activity of *C. pyre* cells without and with the AIEgens was evaluated using total SOD assay kit with WST-8. Briefly, *C. pyre* cells (initial OD_{680} = 0.3) were treated with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) for 14 days in an illumination incubator. 2 mL of the samples were centrifuged (7000 rpm, 5 min) to collect the cells. The cells were resuspended with 1 mL SOD lysis buffer, sonicated in an ice bath for 30 min, and then centrifuged at 4 ºC (10000 rpm, 10 min) to obtain the supernatant. The supernatant was transferred to a 96-well plate, and SOD activity of *C. pyre* cells was measured using the SOD activity assay kit by recording the absorbance at 450 nm on a microplate reader.

MDA content. *C. pyre* cells (initial OD_{680} = 0.3) were incubated with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) for 14 days. Then the samples were processed, and their MDA content was measured using a lipid peroxidation MDA assay kit following the procedure detailed in previous report.[2]

Oxygen evolution. 2 mL of *C. pyre* suspensions (OD_{680} = 2.0) were incubated with varying concentration of AIEgens in BG11 medium for 30 min at 25 ºC. The suspensions were purged with nitrogen for 5 min to remove dissolved oxygen in the BG11 medium. The prepared samples were transferred to the oxygen electrode

chamber, and oxygen evolution was monitored under different illumination intensities at 25 ºC on a liquid-phase oxygen electrode system.

ATP content. *C. pyre* suspensions (2 mL, OD_{680} = 2.0) were cultivated with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) in BG11 medium for 30 min at 25 ºC. The samples were irradiated with white light (1200·μmol·m^{-2}·s^{-1}) for 30 min, and then were centrifuged at 7000 rpm for 5 min to harvest *C. pyre* cells. The cells were resuspended in 200 μL lysis buffer and sonicated in an ice bath for 20 min. Next, the samples were centrifuged at 10000 rpm for 10 min at 4 ºC to obtain the supernatant. The supernatant was transferred to a black 96-well plate, and ATP content was evaluated using an enhanced ATP assay kit by recording the luminescence intensity on a microplate reader. *C. pyre* cells treated without AIEgen following the same steps served as the control group.

NADPH content. Following the pretreatment steps for ATP content measurement, the harvested *C. pyre* cells were resuspended in 1.0 mL lysis buffer and sonicated in an ice bath for 20 min. The samples were centrifuged (10000 rpm, 10 min) at 4 ºC to separate the supernatant. The supernatant was added to a 96-well plate, and NADPH content were assessed using an enhanced $NADP^+$/NADPH assay kit by reading the absorbance at 450 nm on a microplate reader.

Rubisco activity. 2 mL of *C. pyre* cells (OD_{680} = 2.0) were treated with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) following the pretreatment steps for ATP content measurement. Subsequently, the Rubisco activity of *C. pyre* cells was tested using a

Rubisco activity assay kit, according to the procedure detailed in the reference.[3]

Lipid production. 20 mL *C. pyre* cells (initial OD_{680} of about 0.3) were cultured in the presence and absence of C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) for 14 days in an illumination incubator. After cultivation, the lipid content of *C. pyre* cells was evaluated by organic solvent extraction method, following the detailed procedure outlined in the previous report.[4]

Electron generation. The electron generation rate of *C. pyre* cells without and with AIEgens was evaluated using the DCPIP probe. 2 mL *C. pyre* suspensions (OD_{680} = 2.0) were incubated with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) for 15 min in BG11 medium. 100 μM of DCPIP was added to the as-prepared *C. pyre* suspensions, and the absorbance of DCPIP at 600 nm was measured under white light (1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) or UV light (4.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$) irradiation for different time.

Chlorophyll fluorescence parameters. 2 mL of *C. pyre* suspensions (OD_{680} = 2.0) were incubated with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) in BG11 medium for 30 min. The prepared *C. pyre* suspensions were transferred to the sample cells. Chlorophyll fluorescence parameters after 30 min dark adaptation or 30 light adaptation were measured using the saturation pulse method on a chlorophyll fluorescence monitor.

ROS generation. ROS generation in *C. pyre* cells without and with AIEgens under irradiation was measured using the DCFH-DA probe. 2 mL *C. pyre* suspensions (OD_{680} = 2.0) were cultured with the C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) in

BG11 medium for 30 min. DCFH-DA (50 μM) was added, and the fluorescence emission of the probe was recorded under white light (1200 μmol·m^{-2}·s^{-1}) irradiation for different time on a fluorescence spectrometer, λ_{ex} = 488 nm.

Growth of mung bean sprouts. 20 mung bean seeds of similar size and weight were placed into a 100 mL beaker. 10 mL of C_8-TPE-C_4 aqueous solution at different concentrations were added. The mung beans were incubated in an illumination incubator at 25 ºC under light condition (12 h light of 27.6 μmol·m^{-2}·s^{-1} and 12 h dark cycle) or complete darkness. After 5 days, the sprouts were harvested. Mung bean seeds were incubated with pure water as the control group. All experiments were performed in triplicate.

Fluorescence imaging of mung bean sprouts. Mung bean seeds were cultured with 20 μM of C_8-TPE-C_4 aqueous solution in an illumination incubator at 25 ºC under light condition (12 h light of 27.6 μmol·m^{-2}·s^{-1} and 12 h dark cycle) for 5 days. The mung bean sprouts were cleaned with deionized water to remove the residual C_8-TPE-C_4 solution. Then, the leaf was cut into pieces and imaged on a confocal laser scanning microscopy with a ×10 lens. Imaging conditions: λ_{ex} = 405 nm and λ_{em} = 450-600 nm.

Root vigor of mung bean sprouts. Triphenyltetrazolium chloride reduction method was used to assess the root vigor of mung bean sprouts. Mung bean seeds were incubated for 5 days at 25 ºC in the presence and absence of 10 μM C_8-TPE-C_4 aqueous solution under dark or light conditions (12 h light of 27.6 μmol·m^{-2}·s^{-1} and

12 h dark cycle). After harvesting the bean sprouts, 0.5 g of roots were collected and washed with deionized water. The roots were dried with filter paper, pretreated, and their vigor was measured according to the detailed procedure in the reference.[5]

Carbohydrate content of mung bean sprouts. Mung bean seeds were treated with 20 μM C_8-TPE-C_4 for 5 days at 25 ºC under light condition (12 h light of 27.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 12 h dark cycle). After harvesting the mung bean sprouts, the carbohydrate content in the leaves and stems was assessed by the anthrone method, following the detailed procedure outlined in the reference.[5a]

Statistical analysis. Quantitative data are presented as mean ± standard deviation (SD). The significance of differences between two groups was assessed using one-way analysis of variance (ANOVA) with Origin 2025 software. $P < 0.05$ is the accepted level of significance, specifically, $^*P < 0.05$, significant; $^{**}P < 0.01$ and $^{***}P < 0.01$, highly significant. $P > 0.05$, ns, not significant.

Supplementary figures

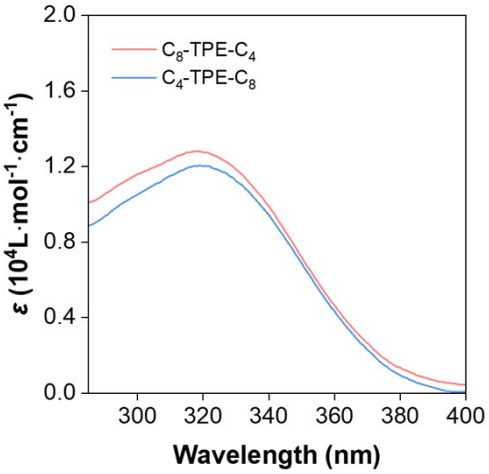

Fig. S1 Absorption spectra of 20 μM C_8-TPE-C_4 and C_4-TPE-C_8 in DMSO.

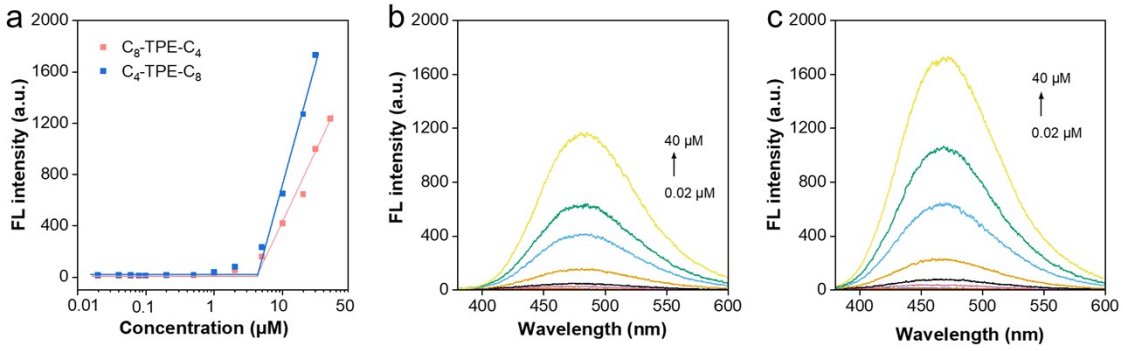

Fig. S2 (a) The change in the maximum emission intensity of two AIEgens versus their concentration in BG11 solution. (b) and (c) Fluorescence spectra of C_8-TPE-C_4 and C_4-TPE-C_8 with different concentrations in BG11 solution, respectively. λ_{ex} = 340 nm.

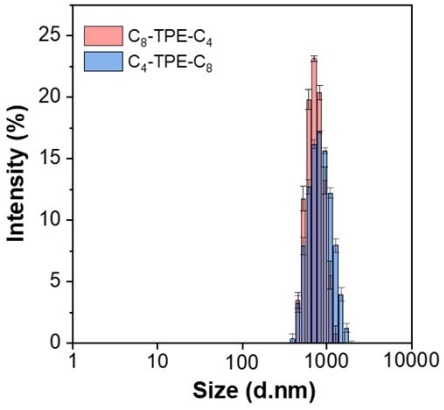

Fig. S3 Size distribution of C_8-TPE-C_4 and C_4-TPE-C_8 (20 μM) in BG11 solution.

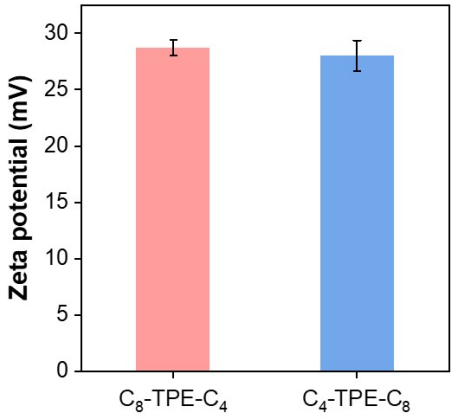

Fig. S4 Zeta potential results of C_8-TPE-C_4 and C_4-TPE-C_8 (20 μM) in BG11 solution. Error bars: mean ± SD (n = 3).

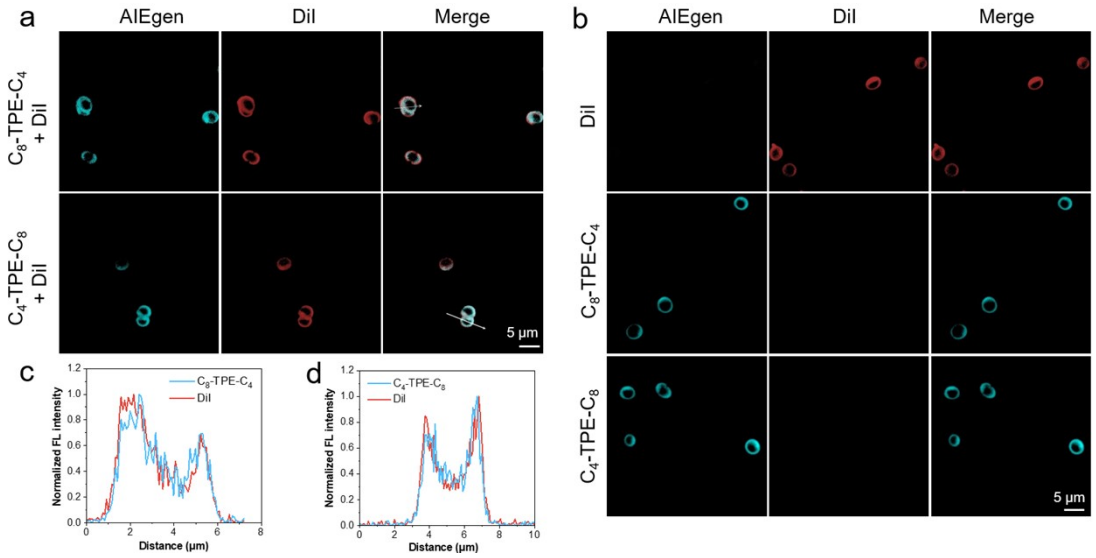

Fig. S5 (a) CLSM images of *C. pyre* protoplasts treated with C_8-TPE-C_4 or C_4-TPE-C_8 (20 μM) for 30 min and then stained with DiI (10 μM) for 10 min. λ_{ex} = 405 nm and λ_{em} = 450-600 nm for the AIEgen, λ_{ex} = 543 nm and λ_{em} = 550-650 nm for DiI. (b) CLSM images of *C. pyre* protoplasts stained with DiI (10 μM) for 10 min or the AIEgen (20 μM) for 30 min. (c) and (d) Intensity profiles of C_8-TPE-C_4 and DiI as well as C_4-TPE-C_8 and DiI along a straight line crossing a protoplast in Fig. S5a, respectively.

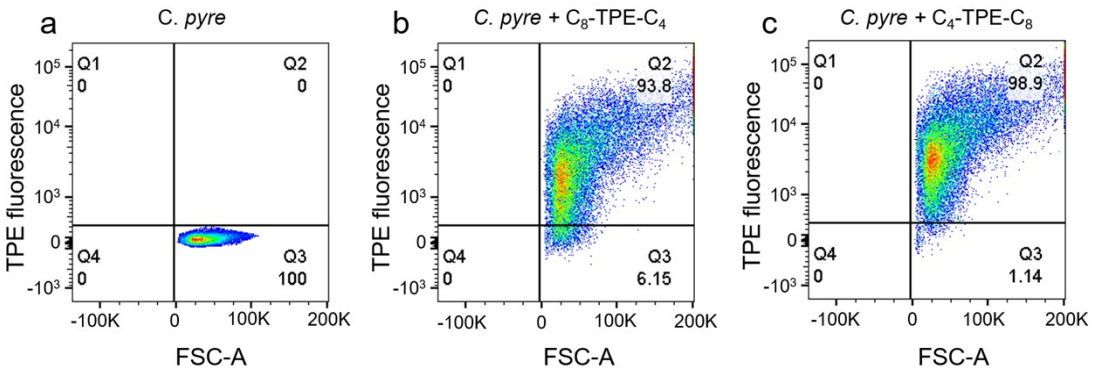

Fig. S6 (a)-(c) Flow cytometric analysis of *C. pyre* cells (OD_{680} = 2.0) without (a) and with incubated by 20 μM C_8-TPE-C_4 (b) and C_4-TPE-C_8 (c) for 30 min under the Qdot 565-A channel.

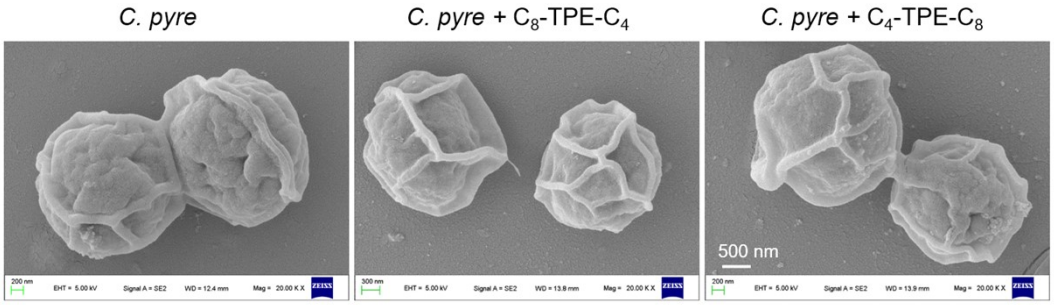

Fig. S7 SEM images of *C. pyre* (OD_{680} = 2.0) without and with treated by C_8-TPE-C_4 and C_4-TPE-C_8 (20 μM) for 30 min.

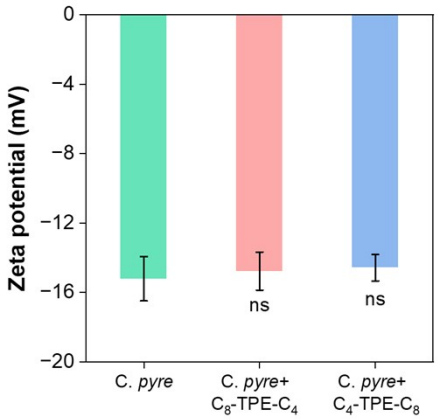

Fig. S8 Zeta potential results of *C. pyre* (OD_{680} = 2.0) before and after incubation with C_8-TPE-C_4 and C_4-TPE-C_8 (20 μM) for 30 min. Error bars: mean ± SD (n = 3). $P > 0.05$, ns, not significant.

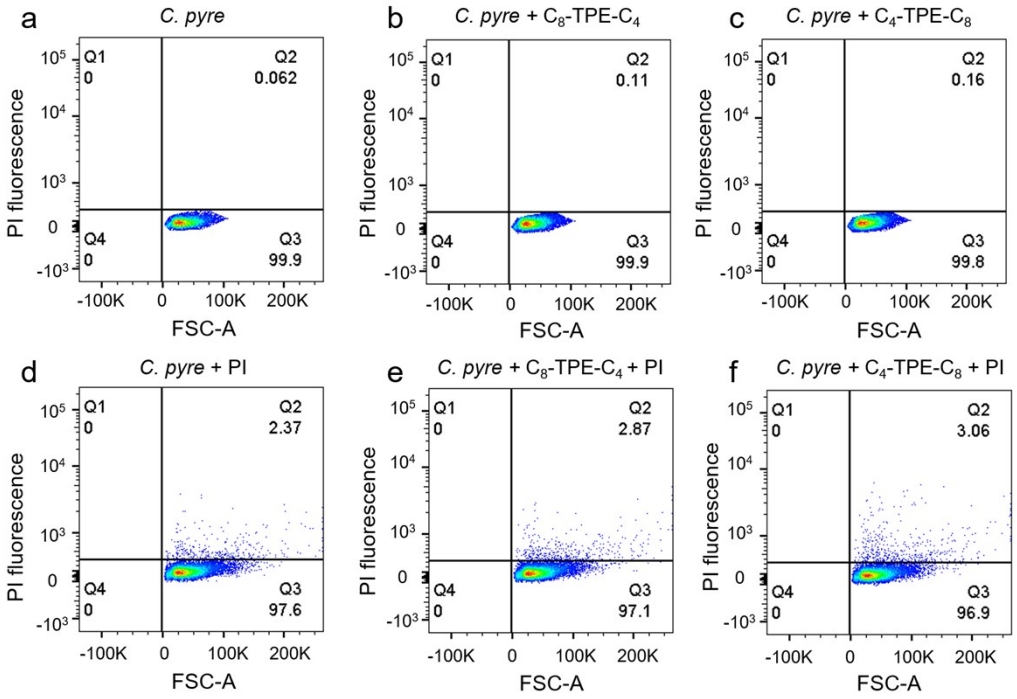

Fig. S9 (a)-(c) Fluorescence-activated cell sorting analysis of *C. pyre* cells (OD_{680} = 2.0) without and with treated by 20 μM C_8-TPE-C_4 and C_4-TPE-C_8 for 30 min under the PE channel, respectively. (d)-(f) Fluorescence-activated cell sorting analysis of *C. pyre* cells stained with 5 μg/mL PI for 10 min in the absence and presence of C_8-TPE-C_4 and C_4-TPE-C_8 under the PE channel, respectively.

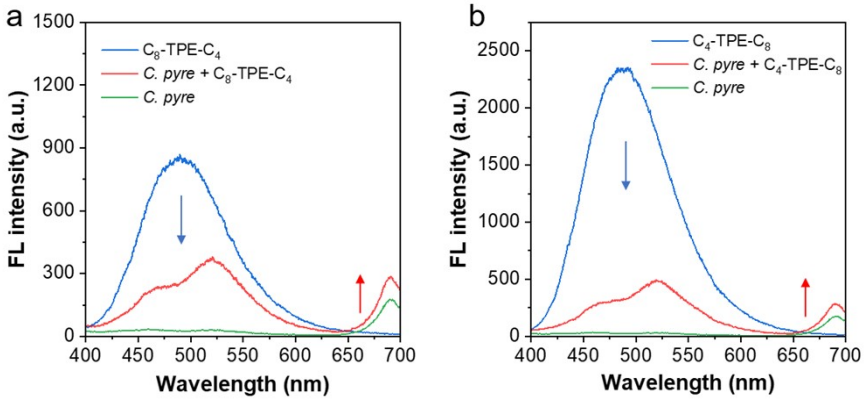

Fig. S10 (a) Fluorescence spectra of C_8-TPE-C_4 (20 μM), and *C. pyre* (OD_{680} = 2.0) before and after incubation with C_8-TPE-C_4 for 30 min. (b) Fluorescence spectra of C_4-TPE-C_8 (20 μM), and *C. pyre* (OD_{680} = 2.0) before and after incubation with C_4-TPE-C_8 for 30 min. λ_{ex} = 360 nm.

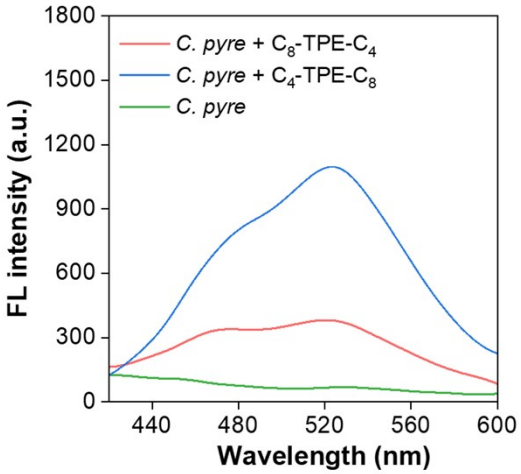

Fig. S11 Fluorescence spectra of C_8-TPE-C_4 and C_4-TPE-C_8 (20 μM) after incubation with *C. pyre* (OD_{680} = 2.0) for 30 min. λ_{ex} = 340 nm.

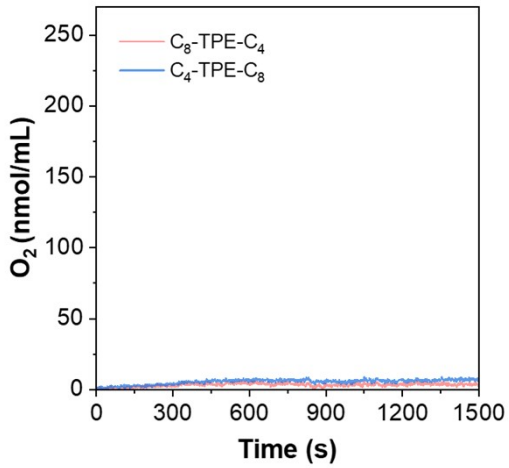

Fig. S12 The time course of oxygen evolution of C_8-TPE-C_4 (0.5 μM) and C_4-TPE-C_8 (1.0 μM) under illumination intensity of 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

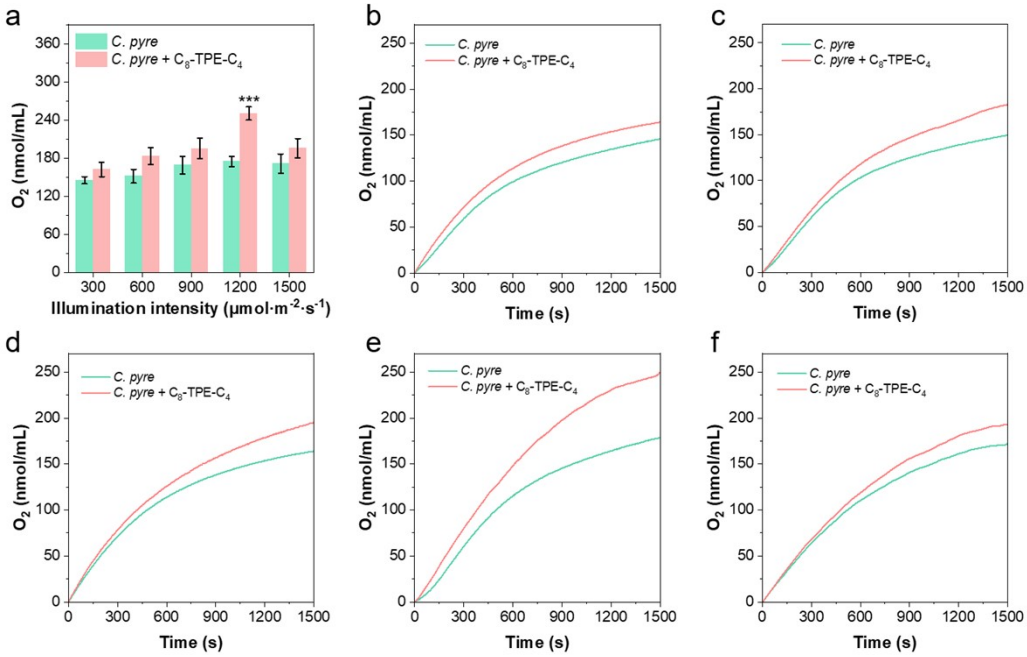

Fig. S13 (a) Oxygen evolution and (b)-(f) time course of oxygen evolution of *C. pyre* cells (OD_{680} = 2.0) without and with 0.5 μM C_8-TPE-C_4 under different illumination intensity for 1500 s, where (b) 300, (c) 600, (d) 900, (e) 1200 and (f) 1500 μmol·m^{-2}·s^{-1}. Error bars: mean ± SD (n = 3).

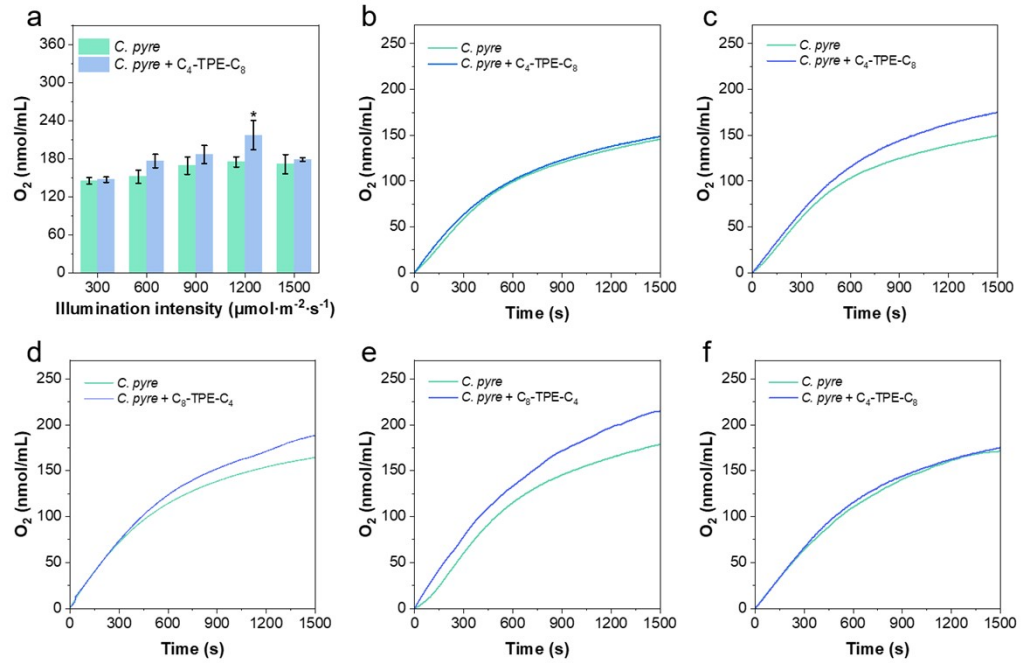

Fig. S14 (a) Oxygen evolution and (b)-(f) time course of oxygen evolution of *C. pyre* cells (OD_{680} = 2.0) without and with 1.0 μM C_4-TPE-C_8 under different illumination intensity for 1500 s, where (b) 300, (c) 600, (d) 900, (e) 1200 and (f) 1500 μmol·m^{-2}·s^{-1}. Error bars: mean ± SD (n = 3).

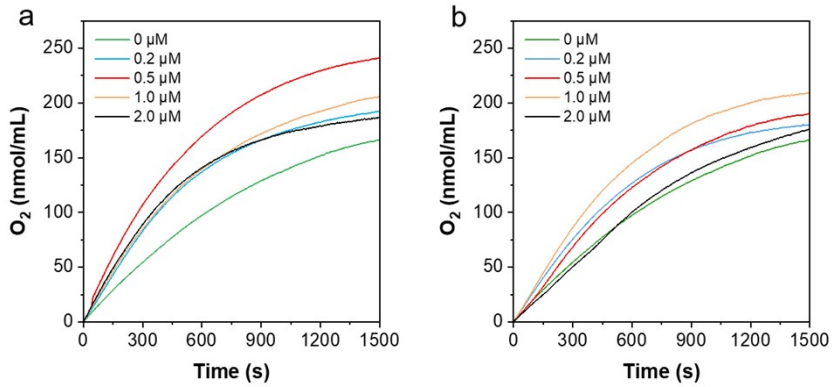

Fig. S15 (a) and (b) Time course of oxygen evolution of *C. pyre* cells after incubation with different concentrations of C_8-TPE-C_4 and C_4-TPE-C_8 for 30 min under illumination of 1200 μmol·m^{-2}·s^{-1}, respectively.

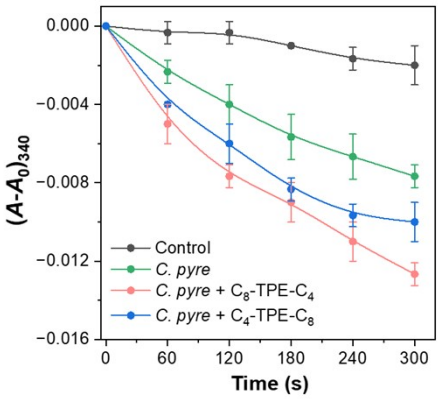

Fig. S16 Absorbance change of NADH at 340 nm in *C. pyre* suspensions (OD_{680} = 2.0) over the reaction time before and after incubation with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) for 30 min. Error bars: mean ± SD (*n* = 3).

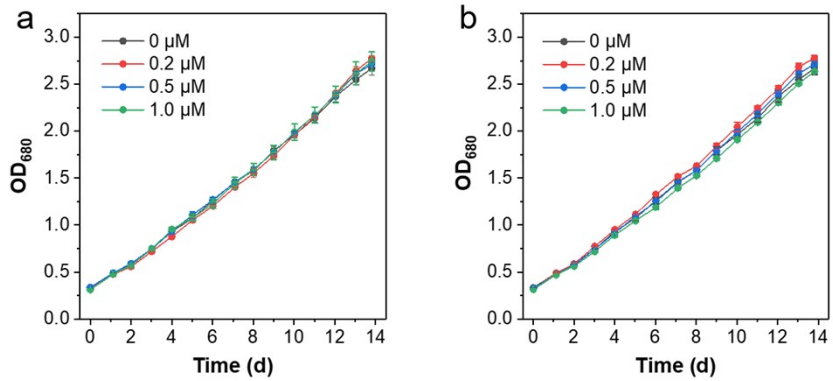

Fig. S17 Growth curves of *C. pyre* cells with different concentrations of C_8-TPE-C_4 (a) and C_4-TPE-C_8 (b) in an illumination incubator. Error bars: mean ± SD (*n* = 3).

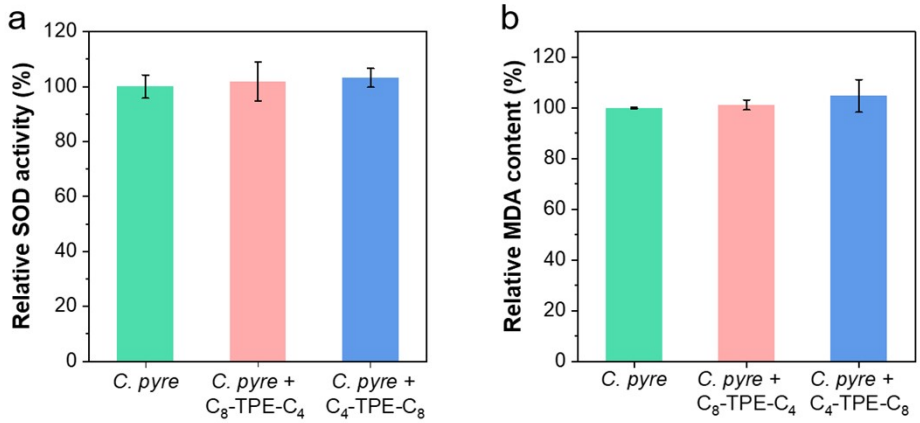

Fig. S18 Relative SOD activity (a) and relative MDA content (b) of *C. pyre* cells without and with treated by C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) for 14 days in an illumination incubator. Error bars: mean ± SD (n = 3).

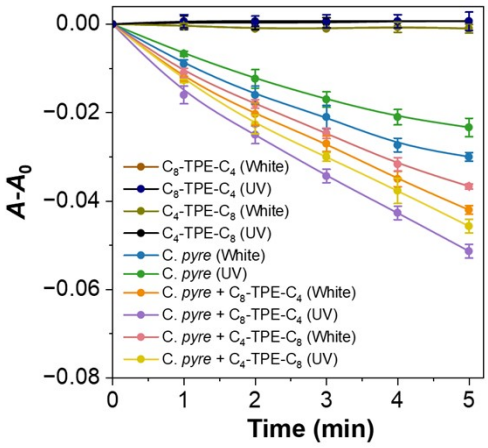

Fig. S19 Absorbance change of DCPIP (100 μM) at 600 nm in *C. pyre* suspensions without and with C_8-TPE-C_4 (0.5 μM) or C_4-TPE-C_8 (1.0 μM) against illumination time under white light (1200 μmol·m^{-2}·s^{-1}) or UV light (1.0 μmol·m^{-2}·s^{-1}). Error bars: mean ± SD (n = 3).

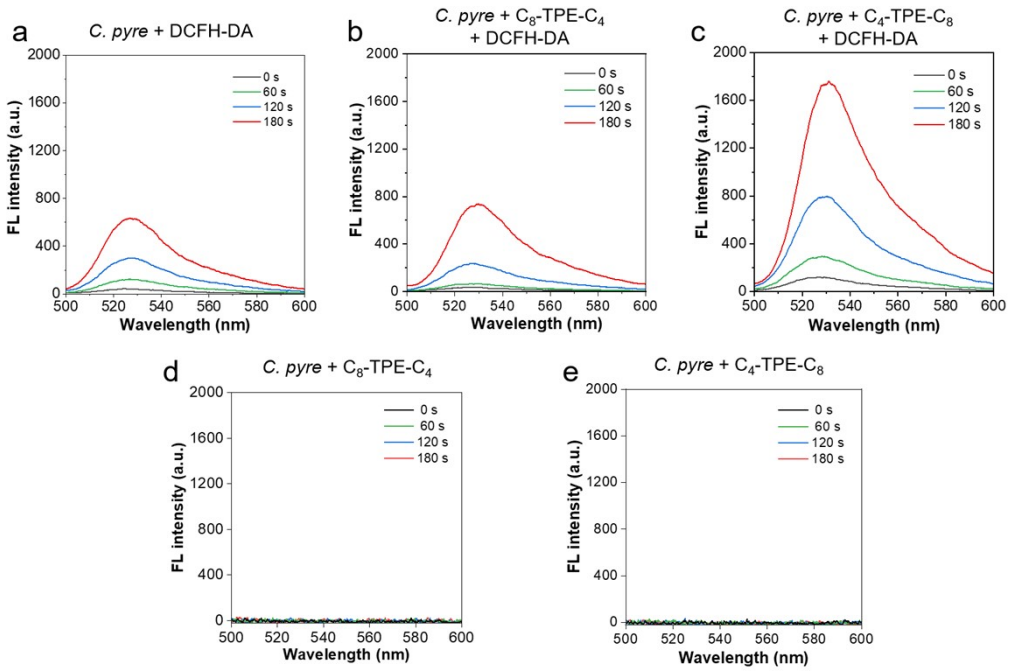

Fig. S20 Intracellular ROS generation in *C. pyre* without and with two AIEgens under white light irradiation (1200 μmol·m^{-2}·s^{-1}) detected by the DCFH-DA (50 μM) probe. (a)-(c) Fluorescence spectra of DCFH-DA in *C. pyre* over irradiation time: (a) without AIEgens, (b) with C_8-TPE-C_4 (0.5 μM) and (c) with C_4-TPE-C_8 (1.0 μM). (d) and (e) Fluorescence spectra of *C. pyre* with C_8-TPE-C_4 (0.5 μM) and C_4-TPE-C_8 (1.0 μM) over irradiation time, respectively. λ_{ex} = 488 nm.

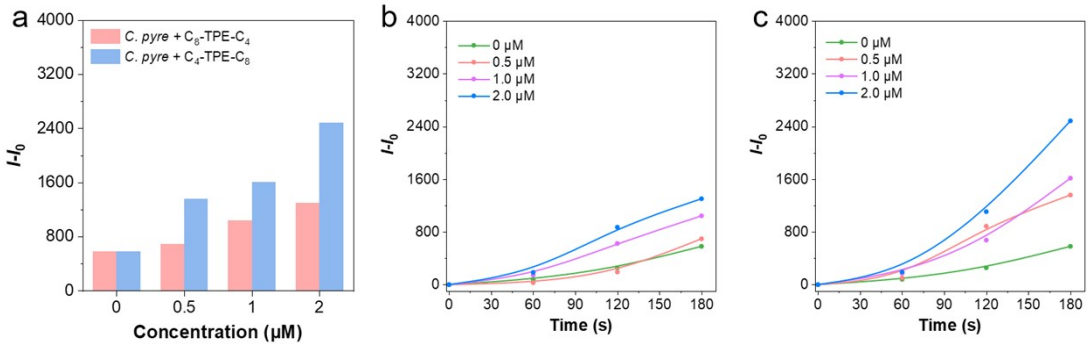

Fig. S21 Intracellular ROS generation in *C. pyre* at different concentrations of AIEgens under white light irradiation (1200 μmol·m^{-2}·s^{-1}) detected by the DCFH-DA probe. (a) Changes in fluorescence intensity of DCFH-DA at 530 nm in *C. pyre* with different concentrations of C_8-TPE-C_4 and C_4-TPE-C_8 after 180 s of irradiation. (b) and (c) Fluorescence intensity changes of DCFH-DA in *C. pyre* with different concentrations of C_8-TPE-C_4 and C_4-TPE-C_8 over the irradiation time, respectively. λ_{ex} = 488 nm.

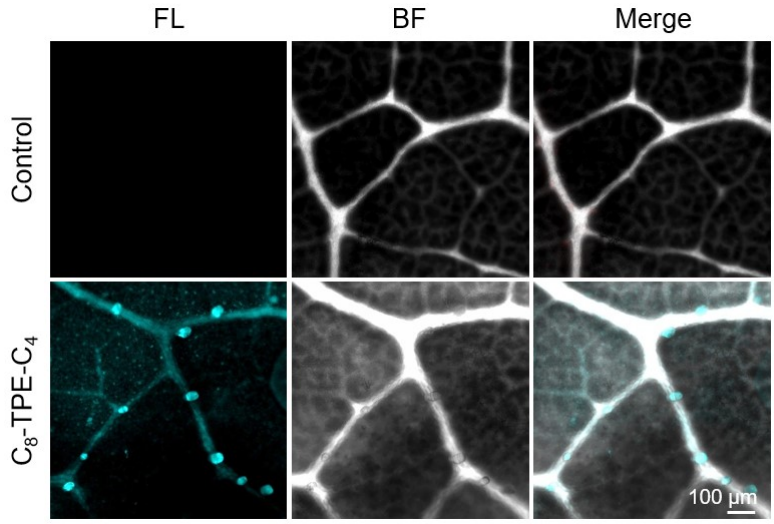

Fig. S22 Fluorescence images of leaf piece of mung bean cultured with water (control) or 20 μM C_8-TPE-C_4 solution for 5 days in an illumination incubator. λ_{ex} = 405 nm and λ_{em} = 450-600 nm.

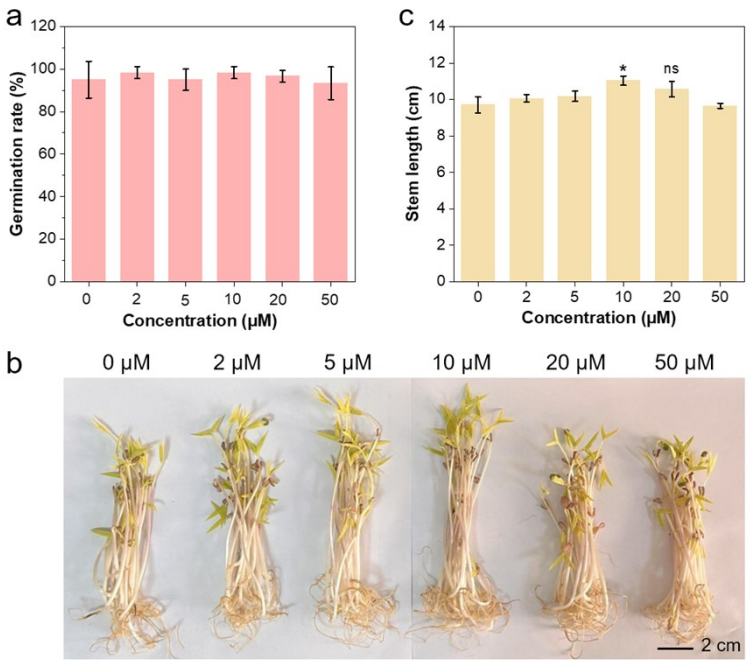

Fig. S23 (a) Germination rate, (b) digital picture and (c) stem length of mung beans incubated by C_8-TPE-C_4 with different concentrations for 5 days under dark condition, respectively. Error bars: mean ± SD (n = 3, with 20 green beans per experiment). *P < 0.05, significant; ns, not significant.

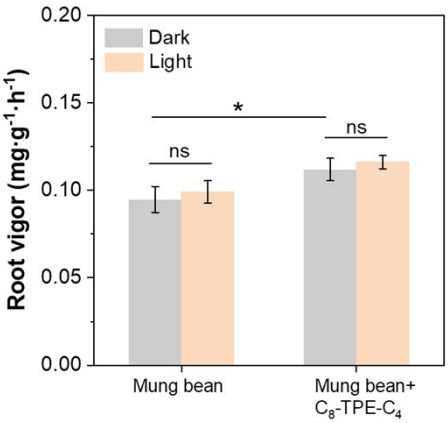

Fig. S24 Root vigor of mung bean incubated without and with 10 μM of C_8-TPE-C_4 solutions for 5 days under dark and light conditions, respectively. Error bars: mean ± SD (n = 3). *P < 0.05, significant; ns, not significant.

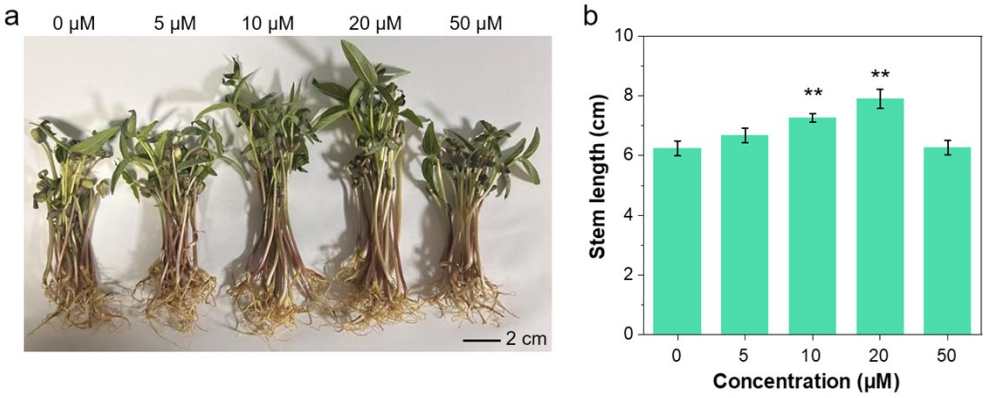

Fig. S25 (a) Digital picture and (b) stem length of mung beans incubated by C_8-TPE-C_4 with different concentrations for 5 days under light conditions. Error bars: mean ± SD (n = 3, with 20 green beans per experiment). **P < 0.01, highly significant.

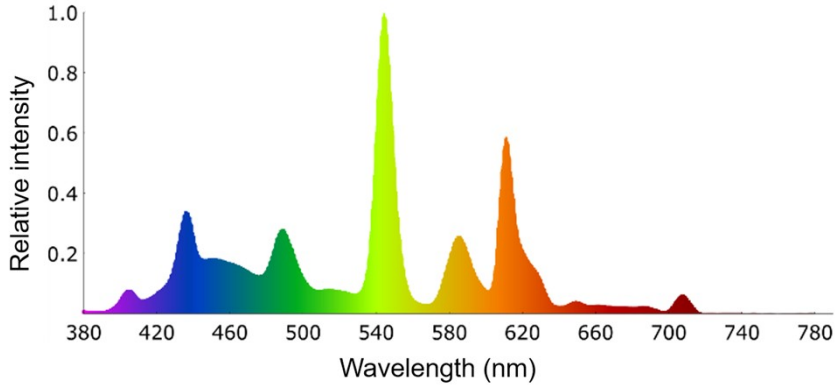

Fig. S26 Spectrum of the light source in the incubator used for *C. pyre* incubation.

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