

LIGHTING DEVICE AND METHOD FOR ENHANCING PLANT GROWTH

Cross Reference to Related Application(s)

- 5 The present disclosure claims the benefit of Singapore Patent Application No. 10202008843T filed on 10 September 2020, which is incorporated in its entirety by reference herein.

Technical Field

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The present disclosure relates to a lighting device and method for enhancing plant growth.

Background

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Indoor farming offers a sensible solution for sustainable food production, especially in land scarce countries like Singapore. One example is vertical farming which is the practice of growing agricultural crops, or plants in general, in vertically stacked layers and in a controlled environment. Light may be artificially generated to complement
20 natural sunlight for photosynthesis. Plants also need different lighting conditions during their different phases or stages of growth, including germination, vegetation, and flowering stages.

Traditionally, farmers switch between metal halide lamps and high-pressure sodium
25 lamps or incandescent lamps when the plants change from the vegetative stage to the flowering stage. High-pressure sodium lamps and incandescent lamps emit warm yellow light that promotes rapid growth during the flowering stage. Metal halide lamps emit cool white light, which has comparatively more blue light, that prevents stretching of plants during the vegetative stage.

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Currently, indoor farming commonly uses light emitting diodes (LEDs) to create artificial lighting conditions for plant growth because LEDs are more energy efficient and sustainable than high-pressure sodium lamps and incandescent lamps. Despite

the energy efficiency, energy consumption by LEDs contributes the major portion of the maintenance cost of indoor farming. Notably, LEDs account for about 80% of the total energy consumption followed by 10% for air conditioning.

- 5 Red and blue LEDs are used to match the light absorption peaks of chlorophyll *a* and chlorophyll *b*. Recent research has shown that green light has deeper penetration into the lower canopy of plants and is important for leaf growth during the vegetation stage. Specifically, green light can penetrate through leaf surfaces much better than red or blue light to reach the lower canopy and increase photosynthesis, thus enhancing leaf
- 10 expansion and vertical growth. Far red light is introduced during the flowering stage to support growth of leaves, reduce time to flower, increase flowering rate, and increase the number of buds during the flowering and fruiting stage.

Figure 1 shows a schematic diagram of an existing lighting device 100 that has an

15 array of narrowband LEDs 110 (red, green, blue, and far red colours) to create different lighting conditions. The lighting conditions are tunable or adjustable by individually controlling the intensity of each coloured LED 110 to produce different colour emissions. Red and blue LEDs have wall-plug efficiencies of about 0.3% to 0.5%, while green and yellow LEDs have wall-plug efficiencies of about 0.17% and 0.1%,

20 respectively. The poorer efficiencies of green and yellow narrowband LEDs is due to the lack of direct bandgap material. This is commonly known as the green gap (from 480 nm to 620 nm wavelengths) and the loss of efficiency in the green gap is partly due to degradation of indium gallium nitride (InGaN) crystal quality at high indium content.

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Moreover, complex electrical circuitry is needed to individually control the LEDs 110, especially when a large number of LEDs 110 is used in each lighting device 100. Each lighting device 100 is costly and it would be too expensive and not practical to use multiple lighting devices 100 for the large scale needed in indoor farming. Such

30 sophisticated lighting devices 100 are not suitable for indoor farming whereby only a few lighting conditions are required to enhance plant growth in the various stages.

Therefore, in order to address or alleviate at least one of the aforementioned problems and/or disadvantages, there is a need to provide an improved lighting device and method for enhancing plant growth.

5 Summary

According to a first aspect of the present disclosure, there is a lighting device for enhancing plant growth. The lighting device comprises a set of panel assemblies, each panel assembly comprises a set of light sources for emitting incident light and a plurality of lighting panels, each lighting panel comprising a fluorescent material that emits fluorescent light upon exposure to the incident light, the fluorescent light and transmitted incident light combining as plant lighting for enhancing plant growth. The lighting device further comprises an actuation mechanism coupled to the panel assemblies for rearranging the lighting panels of each panel assembly to redirect the plant lighting, wherein for each panel assembly, the fluorescent materials of the lighting panels have different compositions, such that the resulting plant lighting are different for different stages of plant growth.

According to a second aspect of the present disclosure, there is a method for enhancing plant growth. The method comprises:

operating a lighting device comprising a set of panel assemblies for emitting plant lighting towards plants to enhance plant growth, each panel assembly comprising a set of light sources and a plurality of lighting panels;

receiving, by the lighting panels, incident light emitted from the light sources, each lighting panel comprising a fluorescent material that emits fluorescent light upon exposure to the incident light, the fluorescent light and transmitted incident light combining as the plant lighting;

arranging a first lighting panel of each panel assembly to direct first plant lighting from the first lighting panels to the plants, the fluorescent materials of the first lighting panels having a same first composition;

emitting the first plant lighting from the first lighting panel to the plants for enhancing a first stage of plant growth;

arranging a second lighting panel of each panel assembly to direct second plant lighting from the second lighting panels to the plants, the fluorescent materials of the second lighting panels having a same second composition different from the first composition; and

- 5 emitting the second plant lighting from the second lighting panel to the plants for enhancing a second stage of plant growth after the first stage.

A lighting device and method for enhancing plant growth according to the present disclosure are thus disclosed herein. Various features, aspects, and advantages of the
10 present disclosure will become more apparent from the following detailed description of the embodiments of the present disclosure, by way of non-limiting examples only, along with the accompanying drawings.

Brief Description of the Drawings

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Figure 1 is a schematic illustration of an existing lighting device.

Figures 2A and 2B are illustrations of a lighting device for enhancing plant growth, the lighting device having two lighting panels in the panel assemblies, according to
20 embodiments of the present disclosure.

Figures 3A to 3C are illustrations of the lighting device for enhancing plant growth with three lighting panels in the panel assemblies, according to embodiments of the present disclosure.

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Figures 4A and 4B are illustrations of a fluorescent material of the lighting panels, according to embodiments of the present disclosure.

Figures 5A to 5E are illustrations of tests performed on the lighting panels, according
30 to embodiments of the present disclosure.

Figures 6A to 6D are illustrations of a lighting panel with the fluorescent material being directly lit, according to embodiments of the present disclosure.

Figures 7A to 7C are illustrations of a lighting panel with the fluorescent material being lit from the edge, according to embodiments of the present disclosure.

- 5 Figures 8A and 8B are illustrations of the lighting device arranged horizontally and vertically for agriculture, according to embodiments of the present disclosure.

Detailed Description

- 10 For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to a lighting device and method for enhancing plant growth, in accordance with the drawings. While aspects of the present disclosure will be described in conjunction with the embodiments provided herein, it will be understood that they are not intended to limit the present disclosure to these embodiments. On
15 the contrary, the present disclosure is intended to cover alternatives, modifications and equivalents to the embodiments described herein, which are included within the scope of the present disclosure as defined by the appended claims. Furthermore, in the following detailed description, specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be recognized by
20 an individual having ordinary skill in the art, i.e. a skilled person, that the present disclosure may be practiced without specific details, and/or with multiple details arising from combinations of aspects of particular embodiments. In a number of instances, well-known systems, methods, procedures, and components have not been described in detail so as to not unnecessarily obscure aspects of the embodiments of the present
25 disclosure.

- In embodiments of the present disclosure, depiction of a given element or consideration or use of a particular element number in a particular figure or a reference thereto in corresponding descriptive material can encompass the same, an equivalent,
30 or an analogous element or element number identified in another figure or descriptive material associated therewith.

References to “an embodiment / example”, “another embodiment / example”, “some embodiments / examples”, “some other embodiments / examples”, and so on, indicate that the embodiment(s) / example(s) so described may include a particular feature, structure, characteristic, property, element, or limitation, but that not every
5 embodiment / example necessarily includes that particular feature, structure, characteristic, property, element or limitation. Furthermore, repeated use of the phrase “in an embodiment / example” or “in another embodiment / example” does not necessarily refer to the same embodiment / example.

10 The terms “comprising”, “including”, “having”, and the like do not exclude the presence of other features / elements / steps than those listed in an embodiment. Recitation of certain features / elements / steps in mutually different embodiments does not indicate that a combination of these features / elements / steps cannot be used in an embodiment.

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As used herein, the terms “a” and “an” are defined as one or more than one. The use of “/” in a figure or associated text is understood to mean “and/or” unless otherwise indicated. The term “set” is defined as a non-empty finite organization of elements that mathematically exhibits a cardinality of at least one (e.g. a set as defined herein can
20 correspond to a unit, singlet, or single-element set, or a multiple-element set), in accordance with known mathematical definitions. The recitation of a particular numerical value or value range herein is understood to include or be a recitation of an approximate numerical value or value range. The terms “first”, “second”, etc. are used merely as labels or identifiers and are not intended to impose numerical requirements
25 on their associated terms.

In representative or exemplary embodiments of the present disclosure, as shown in Figure 2A, there is a lighting device 200 for enhancing plant growth. The lighting device 200 includes a set of one or more panel assemblies 210. Each panel assembly 210
30 includes a set of one or more light sources 220 for emitting incident light and a plurality of lighting panels 230. Each lighting panel 230 includes a fluorescent material 240 that emits fluorescent light upon exposure to the incident light. The fluorescent light and transmitted incident light combine as plant lighting for enhancing plant growth. For

example, the incident light from the light sources 220 is blue light. Some blue incident light is transmitted through the fluorescent material 240, and some is absorbed by the fluorescent material 240. The fluorescent material 240 converts the absorbed blue light into fluorescent light of other colours, such as green, yellow, or red light. Part of the
5 blue incident light that is transmitted through the fluorescent material 240 and the green, yellow, or red fluorescent light emitted from the fluorescent material 240 combine as the plant lighting having the desired wavelength spectrum that is eventually emitted outwards from the lighting panel 230.

10 The lighting device 200 further includes an actuation mechanism 250 coupled to the panel assemblies 210 for rearranging the lighting panels 230 of each panel assembly 210 to redirect the plant lighting. In many embodiments, the actuation mechanism 250 is configured to rotate the lighting panels 230 to change the lighting panel 230 facing the plants 300 and redirect the plant lighting. The actuation mechanism 250 may be
15 configured to rearrange the lighting panels 230 of each panel assembly 210 independently from the other panel assemblies 210. Alternatively, the actuation mechanism 250 may be configured to rearrange the lighting panels 230 of the panel assemblies 210 collectively or in unison.

20 For example, in a first rotated position, the plant lighting from a first lighting panel 230 is directed towards the plants 300, and in a second rotated position, the plant lighting from a second lighting panel 230 is directed towards the plants 300. This exposes the plants 300 to different lighting conditions at different times depending on their phases or stages of growth, including the germination or seedling stage, vegetation stage, and
25 flowering stage. More specifically, for each panel assembly 210, the fluorescent materials 240 of the lighting panels 230 have different compositions, such that the resulting plant lighting from the lighting panels 230 are different for the different stages of plant growth. The resulting plant lighting can thus be chosen specifically to target the different stages of plant growth.

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In many embodiments, the lighting panels 230 of a panel assembly 210 are arranged around a core region 212 of the panel assembly 210 and the actuation mechanism 250 is configured to rotate the lighting panels 230 around the core region 212. The

number of different-coloured lighting panels 230 may correspond to the different lighting conditions available for plant growth from germination to flowering stage. The angle of rotation between each lighting panel 230 is preferably 360° divided by the number of lighting panels 230. The number of lighting panels 230 may also depends
5 on the sizes of each lighting panel 230, each set of lighting panels 230, and the panel assembly 210.

In some embodiments as shown in Figures 2A and 2B, each panel assembly 210 has two lighting panels 230 sandwiching the core region 212. In some embodiments as
10 shown in Figure 3A, each panel assembly 210 has three lighting panels 230 triangulating the core region 212. It will be appreciated that each panel assembly 210 can have other numbers of lighting panels 230, such as four, five, or more. It will also be appreciated the panel assemblies 210 can have the same or different number of lighting panels 230 among each other.

15 In various embodiments of the present disclosure, there is a method for enhancing plant growth. The method may be performed using various lighting devices or systems, including the lighting device 200 as described herein. In these embodiments of using the lighting device 200, the method includes a step of operating the lighting device 200
20 including the panel assemblies 210 for emitting plant lighting towards plants 300 to enhance plant growth, each panel assembly 210 having the light sources 220 and lighting panels 230. The method includes a step of receiving, by the lighting panels 230, incident light emitted from the light sources 220, each lighting panel 230 including the fluorescent material 240 that emits fluorescent light upon exposure to the incident
25 light, the fluorescent light and transmitted incident light combining as the plant lighting.

In some embodiments, each panel assembly 210 includes a first lighting panel 230 and a second lighting panel 230. The first lighting panels 230 have the same first composition, and the second lighting panels 230 have the same second composition
30 that is different from the first composition. The method includes a step of arranging the first lighting panel 230 of each panel assembly 210 to direct first plant lighting from the first lighting panels 230 to the plants 300. The method includes a step of emitting the

first plant lighting from the first lighting panel 230 to the plants 300 for enhancing a first stage of plant growth.

5 The method includes a step of arranging the second lighting panel 230 of each panel assembly 210 to direct second plant lighting from the second lighting panels 230 to the plants 300. The method includes a step of emitting the second plant lighting from the second lighting panel 230 to the plants 300 for enhancing a second stage of plant growth after the first stage. For example, the first plant lighting is used to promote plant growth during the germination stage, and the second plant lighting is used to promote
10 plant growth during the vegetation stage, the first and second plant lighting being of different colours or wavelengths.

In some embodiments, each panel assembly 210 further includes a third lighting panel 230. The third lighting panels 230 have the same third composition that is different
15 from the first and second compositions. The method further includes a step of arranging the third lighting panel 230 of each panel assembly 210 to direct third plant lighting from the third lighting panels 230 to the plants 300. The method further includes a step of emitting the third plant lighting from the third lighting panel 230 to the plants 300 for enhancing a third stage of plant growth after the second stage. For
20 example, the first plant lighting is used to promote plant growth during the germination stage, the second plant lighting is used to promote plant growth during the vegetation stage, and the third plant lighting is used to promote plant growth during the flowering stage, the first to third plant lighting being of different colours or wavelengths.

25 Each lighting panel 230 has a specific composition of the fluorescent materials 240 to create optimal emission wavelengths and resultant plant lighting that would meet the lighting needs of the plants 300 at the various stages. Lighting panels 230 with green plant lighting can be arranged to face the plants 300 during the vegetation stage and later changed to lighting panels 230 with far red plant lighting during the flowering
30 stage. Typically, red and blue light are used for photosynthesis, but the addition of green and far red plant lighting at the respective stages of plant growth are important for optimizing crop yield. Thus, providing optimal plant lighting for the plants 300 can maximize crop yield and quality in large area agriculture.

In some embodiments as shown in Figure 2B, each panel assembly 210 has two lighting panels 230. The actuation mechanism 250 is configured to rotate the lighting panels 230 to change the lighting panel 230 and redirect the plant lighting. The lighting panels 230 can be rotated in unison similar to the mechanism used in louvre blinds. The actuation mechanism 250 includes a head rail 251 having gears 252, drums 253, and a pulley 254 connected together via a tilt rod 255. A string 256 for retracting the panel assemblies 210 is connected from the pulley 254 to the panel assemblies 210. String ladders 257 are connected from the drums 253 to the panel assemblies 210. A tilt wand 258 is connected from the gears 252 to the panel assemblies 210. A stepper motor 259 is connected to the gears 252 to control rotation of the tilt rod 255 to thereby switch the lighting panels 230 collectively. The stepper motor 259 can be controlled by a microcontroller for automatic control of the rotation angle, for example to rotate the tilt rod 255 over an angle of 360° divided by the number of lighting panels 230, i.e. 180° , to switch to the next lighting panels 230 for the next stage of the plant growth. Instead of having to control the intensity of a large number of LEDs in each lighting panel 230 which would require complex circuitry, the lighting panels 230 can be collectively rotated with less complexity using the stepper motor 259 and microcontroller. Optionally, the stepper motor 259 and microcontroller may be remotely controlled so that the switching can be done remotely. Automated and remote control of the panel assemblies 210 and lighting panels 230 can offer a path for development of a smart, automated farming system.

In some embodiments as shown in Figure 3A, each panel assembly 210 has three lighting panels 230 arranged in a triangle around a rotating shaft 230 disposed at the core region 212 of the panel assembly 210. The actuation mechanism 250 is configured to rotate the lighting panels 230 about the rotating shaft 260 to change the lighting panel 230 and redirect the plant lighting. A similar stepper motor 259 and microcontroller is connected to the rotating shaft 260 to rotate the lighting panels 230 by 120° to switch to the next lighting panels 230 for the next stage of the plant growth.

The panel assembly 210 has a set of light sources 220, such as LEDs, that emit incident light which the fluorescent materials 240 of the lighting panels 230 are

exposed to. Preferably, the incident light includes red, blue, or ultraviolet light, but can be of other wavelengths useful for plant growth. The panel assembly 210 may include suitable heat sinks 222 and/or LED drivers to provide better ventilation and reduce temperature of light sources 220.

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In some embodiments as shown in Figures 3B and 3C, the light sources 220 may be disposed in the core region 212 and arranged to emit the incident light towards the lighting panels 230. More specifically, the light sources 220 are supported by a fixed shaft 261 joined to, and preferably coaxial to, the rotating shaft 260, and the light
10 sources 220 are arranged to emit the incident light in a particular direction such that only one lighting panel 230 will be exposed to the incident light. For example, only the bottom lighting panel 230 will be exposed to the incident light emitted by the light sources 220 above it and the plant lighting from the exposed lighting panel 230 will be directed to the plants 300 beneath it.

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In some embodiments, the fluorescent material 240 of a lighting panel 230 has a plurality of fluorescent material sections. The fluorescent material sections have different compositions, such that the resulting plant lighting from the fluorescent material sections are different. For example, the fluorescent material 240 of one
20 lighting panel 230 is divided into three fluorescent material sections. The first fluorescent material section has a first composition, the second fluorescent material section has a second composition, and the third fluorescent material section has a third composition, wherein the first to third compositions are different from each other. Accordingly, a single lighting panel 230 can produce plant lighting with different
25 wavelength spectrum. The fluorescent material sections may be formed on a flexible substrate to facilitate rotation of the fluorescent material sections around the core region 260.

In some embodiments as shown in Figure 2A, the light sources 220 are disposed at
30 edge regions 232 of the lighting panels 230 and arranged to emit the incident light into the lighting panels.

Each lighting panel 230 includes a fluorescent material 240 that emits fluorescent light 241 upon exposure to incident light 221 from the light sources 220. The fluorescent material 240 may be in the form of a colloid which is a mixture in which microscale and/or nanoscale fluorescent particles 242 of a first substance are suspended
5 throughout a solvent or substrate 244 of a second substance. The fluorescent material 240 is able to convert part of the incident light 221 efficiently into other colours of longer wavelengths. For example, the incident light 221 is blue and the fluorescent material 240 converts part of the blue light into green, yellow, or red fluorescent light 241, while the rest of the blue incident light 221 transmits through the fluorescent material 240.
10 The thickness of the fluorescent material 240 or the concentration of the fluorescent particles 242 affect the ratio of converted light to transmitted blue light. The blue incident light 221 that transmits through the fluorescent material 240 and the fluorescent light 241 emitted by the fluorescent material 240 combine as plant lighting 301.

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In some embodiments as shown in Figure 4A, the fluorescent particles 242 are quantum dots that are suspended in the substrate 244 which may be made of a resin material such as epoxy. Quantum dots are semiconductor nanoparticles that glow a particular colour within a narrow band of wavelengths after being illuminated by the
20 incident light 221 which has shorter wavelengths. When the quantum dots are illuminated, some electrons in the quantum dots can be excited to a state of higher energy. This corresponds to the electrons transitioning from the valence band to the conduction band, and when the electrons drop back into the valence band, energy is released from the quantum dots in the form of coloured fluorescent light 241. The
25 colour of the fluorescent light 241 depends on the energy difference between the valence band and conduction band, and the emission wavelength can be controlled by the composition of the fluorescent material 240 and the particle size of the quantum dots. The smaller the quantum dots, the higher the energy difference between the valence band and conduction band, which would shift the spectral wavelengths of the
30 fluorescent light 241 towards the blue wavelengths.

Notably, blue incident light 221 has shorter wavelengths than the green, yellow, or red fluorescent light 241 from the quantum dots. Incident light 221 with longer wavelengths

than the emission wavelength of the fluorescent light 241 from the quantum dots can transmit through the fluorescent material 240 with minimal interaction with the quantum dots. For example, red incident light 221 can transmit through quantum dots that would have emitted green, yellow, or red fluorescent light 241. By leveraging on
5 these optical properties, specific compositions of the fluorescent materials 240 and quantum dots can be determined to emit specific spectral wavelengths that target the photoreceptors like chlorophyll *a* and chlorophyll *b* of the plants 300.

The quantum dots preferably have a core-shell structure and the core-shell quantum
10 dots include one or more of the formulae CdSeZnS/ZnS, CIS/ZnS, InP/ZnSeS, CZIS/ZnS, and Mn:ZnSeS/ZnS. These dots have a core material with lower bandgap, surrounded by larger bandgap materials like zinc selenide (ZnSe), zinc sulphide (ZnS) or an alloy of both. It will be appreciated that the quantum dots may have other suitable materials as will be readily known to the skilled person. The quantum dots are
15 preferably non-toxic as they will be used for illuminating organic plants 300.

In some embodiments as shown in Figure 4B, the lighting panel 230 includes an optical reflector 234 for reflecting the fluorescent light 241 and/or an optical diffuser 236 for uniformly scattering the plant lighting 301. The optical reflector 234 and optical diffuser
20 236 are disposed on opposite sides of the lighting panel 230. Other optical elements can be applied to the lighting panel 230 such as polarizers, gratings, or an anti-reflective coating for reducing reflection from outside the lighting panel 230, particularly light reflection from the plants 300. Different lighting panels 230 may have different configuration of optical components with various optical properties, and these lighting
25 panels 230 can be switched around to provide corresponding optical functionalities to the plants 300.

The optical reflector 234 allows for transmission of light of selected wavelengths and reflects light of other wavelengths. For example, the optical reflector 234 allows blue
30 incident light 221 from the light sources 220 to transmit through and reflects fluorescent light 241, which are of other colours such as green, yellow, or red, emitted from the quantum dots. As fluorescence is an isotropic emission process and the fluorescent light 241 is emitted from the quantum dots in all directions, the optical

reflector 234 can reflect the fluorescent light 241, that is emitted away from the plants 300, back towards the direction of the plants 300, thereby enhancing efficiency of the plant lighting 301. The optical reflector 234 may include a Bragg reflector, dichroic mirror, or metallic reflective film.

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The optical diffuser 236 has a rough outer surface that promotes out-coupling of the plant lighting 301, which is a combination of the incident light 221 from the light sources 220 and fluorescent light 241 from the quantum dots, and uniformly scatters the plant lighting 301 in a particular direction towards the plants 300. With the optical diffuser 236, uniform plant lighting 301 with reduced hot and cold spots from the lighting panel 230 can be obtained. As shown in Figure 5A, the optical diffuser 236 eliminates hot spots and distributes the plant lighting 301 uniformly when the lighting panel 230 is placed under two light sources 220. Fewer or no hot spots would reduce heat stress and damage to the plants 300. This means that the lighting panels 230 can be placed
10 closer to the plants 300 without photobleaching or burning the leaves. This can in turn reduce the energy needed to power the light sources 220. For example, if the distance between the lighting panels 230 and the plants 300 is reduced by 4 cm or 5 cm from 12 cm initially, the energy consumption can be reduced by 13% and 24%, respectively. The reduced distance can also improve the crop density and yield in vertical farming.
15 As the plant lighting 301 is more uniform and homogeneous due to the optical diffuser 236, fewer light sources 220 or LEDs would be needed, further reducing the energy consumption of the lighting device 200. The optical diffuser 236 includes a low refractive material such as, but not limited to, polycarbonate or glass material.

25 An exemplary method of forming a highly emissive and efficient lighting panel 230 is described as follows. The quantum dots are first mixed thoroughly in a compatible resin substrate 244 such as epoxy material to form the fluorescent material 240 in the form of a colloid. The fluorescent material 240 is degassed for about an hour under a vacuum environment. The fluorescent material 240 is applied evenly onto the flat inner
30 surface of the optical diffuser 236, such as by blade coating or spray coating. The optical reflector 234 is placed onto the fluorescent material 240, thereby sandwiching or laminating the fluorescent material 240 together with the optical diffuser 236. The fluorescent material 240 is then exposed to ultraviolet light, having a wavelength such

as 365 nm, until the resin substrate 244 is cured and the fluorescent material 240 becomes a solid composite. The quantum dots are embedded or encapsulated in the solidified resin substrate 244 to protect the quantum dots, making them more robust and efficient.

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Tests were performed on sample lighting panels 230 to modulate the emission spectra of the fluorescent materials 240. The sample fluorescent materials 240 have epoxy as the substrate 244 and different concentrations of CIS/ZnS quantum dots as the fluorescent particles 242 suspended in the epoxy substrate 244. With a higher concentration of quantum dots, more incident light 221 would be absorbed and converted into the emission spectrum of the quantum dots. The resultant lighting from the sample lighting panels 230 has a greater yellow spectrum when placed under ultraviolet light compared to under normal room lighting. As shown in Figure 5B, the top-left lighting panel 230 has a higher concentration of quantum dots and was placed under normal room lighting, the top-right lighting panel 230 has a lower concentration of quantum dots and was placed under normal room lighting, the bottom-left lighting panel 230 has a higher concentration of quantum dots and was placed under ultraviolet light, and the bottom-right lighting panel 230 has a lower concentration of quantum dots and was placed under ultraviolet light.

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As shown in Figure 5C, when the sample lighting panels 230 were placed on an array of LEDs that emitted blue incident light 221, the fluorescent material 240 with a higher concentration of CIS/ZnS quantum dots (left lighting panel 230) enabled more conversion of blue light into red light, resulting in coloured lighting that is in a shade of pink with a greater red spectrum. The coloured lighting can be represented by the left CIE colour space 245 and has CIE chromaticity coordinates (0.238,0.142). Comparatively, the fluorescent material 240 with a lower concentration of CIS/ZnS quantum dots (right lighting panel 230) resulted in pink lighting with a greater blue spectrum. The coloured lighting can be represented by the right CIE colour space 245 and has CIE chromaticity coordinates (0.176,0.114).

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Figure 5D shows the intensity distribution in the emission spectra 246a,247a,248a of the blue incident light 221, blue incident light 221 with fluorescent light 241 from the

higher concentration of quantum dots, and blue incident light 221 with fluorescent light 241 from the lower concentration of quantum dots, respectively. Figure 5E shows the normalized intensity distribution in the emission spectra 246b, 247b, 248b, respectively.

- 5 The fluorescent material 240 can achieve a fluorescence quantum yield of about 0.7. Together with the optical reflector 234 and optical diffuser 236, the lighting panel 230 can achieve a light extraction efficiency of about 0.7 or more. With this, the wall-plug efficiency of quantum dots that emit green, yellow, or red fluorescent light 241 was calculated to be able to reach about 0.25. Specifically, the wall-plug efficiency of yellow
- 10 quantum dots was about 0.13 to 0.15, and the wall-plug efficiency of green quantum dots was about 0.21 to 0.25. These wall-plug efficiencies are better than current green and yellow LEDs. Thus, use of quantum dots in the lighting panels 230 can address the poorer efficiencies of green and yellow LEDs, i.e. the green gap 480 nm to 620 nm, thereby improving the energy efficiency of the lighting panel 230. For example,
- 15 use of green quantum dots can reduce energy consumption by about 9% to 19%, while use of yellow quantum dots can reduce energy consumption by about 12% to 20%. Together with the optical diffuser 236, the overall energy consumption of the lighting panel 230 can be reduced by about 20% to 30%.
- 20 In some embodiments, the light sources 220 and lighting panels 230 are arranged such that the incident light 221 is emitted directly towards the whole area of the lighting panels 230. In one embodiment as shown in Figure 6A, the fluorescent material 240 is disposed as multiple portions directly at each light source 220. In one embodiment as shown in Figure 6B, the fluorescent material 240 is disposed as a composite layer
- 25 in front of the light sources 220. Further, the fluorescent material 240 may be flexible such that the lighting panel 230 has a flexible form factor to reduce light leakage. For example, the substrate 244 of the fluorescent material 240 may be made of a flexible material such as epoxy. As shown in Figures 6C and 6D, a rigid and flat lighting panel 230 would result in some of the plant lighting 301 straying beyond the crop area of the
- 30 plants 300, whereas a flexible and curved lighting panel 230 can direct most of the plant lighting 301 to the crop area, thereby reducing light leakage and improving lighting efficiency.

In some embodiments, the light sources 220 are disposed at the edge region 232 of the lighting panel 230 and arranged to emit the incident light 221 into the lighting panel 230. In one embodiment as shown in Figure 7A, the fluorescent material 240 is disposed as a composite layer perpendicularly to the light sources 220. In one
5 embodiment as shown in Figure 7B, the fluorescent material 240 is disposed as a composite layer in front of the light sources 220. In one embodiment as shown in Figure 7C, the fluorescent material 240 is disposed as multiple portions directly at each light source 220. By placing the light sources 220 at the edge region 232, fewer light sources 220 would be used which reduces energy consumption. The lighting panel
10 230 can also be made thinner, more compact, and lightweight, so that they can be tilted easily by the actuation mechanism 250 to interchange between the lighting panels 230.

In some embodiments, the fluorescent particles 242 are conventional phosphor materials instead of, or in addition to, the quantum dots. Like quantum dots, phosphor materials emit fluorescent light 241 when exposed to the incident light 221. The phosphor materials may include materials such as, but not limited to, perovskite, lanthanide compounds, organic dye molecules such as Coumarin, DCQTB, and ceramic materials such as doped yttrium aluminium garnet (YAG) doped with Ce^{3+} , i.e.
20 YAG:Ce³⁺ ceramic.

As described in various embodiments herein, the lighting device 200 can create optimal and targeted plant lighting 301 to address the lighting needs of different species of plants 300 at their various growth stages and to enhance plant growth.
25 Using light sources 220 with fixed emission wavelengths, each lighting panel 230 can emit plant lighting 301 of specific wavelengths that differ among the lighting panels 230, and the lighting panels 230 are interchangeable so that the plants 300 can be exposed to the different plant lighting 301 depending on their growth stage. Different coloured plant lighting 301 can thus be achieved even with a fixed emission
30 wavelengths from the light sources 220 such as LEDs.

The lighting device 200 can provide optimal lighting conditions for plants 300 such as agricultural crops to maximize crop yield and quality in large area agriculture. Figure

8A shows the panel assemblies 210 of the lighting device 200 arranged horizontally such as for indoor farming. Figure 8B shows the panel assemblies 210 arranged vertically such as for vertical farming. The lighting device 200 can be implemented over a large scale for indoor or outdoor farming including greenhouse farming. For example, in greenhouse applications, the lighting device 200 may not need to use the light sources 220 but can instead rely on sunlight as the incident light for the fluorescent materials 240. The lighting device 200 can convert ultraviolet light in the sunlight into useful green or far red light emission for plant growth. Although various embodiments herein describe the lighting device 200 as being used in agriculture and farming, the lighting device 200 may find applications elsewhere such as, but not limited to, horticulture, aquaponics, aquaculture, light guides in living spaces, architectural lighting, and artisan lighting.

In the foregoing detailed description, embodiments of the present disclosure in relation to a lighting device and method for enhancing plant growth are described with reference to the provided figures. The description of the various embodiments herein is not intended to call out or be limited only to specific or particular representations of the present disclosure, but merely to illustrate non-limiting examples of the present disclosure. The present disclosure serves to address at least one of the mentioned problems and issues associated with the prior art. Although only some embodiments of the present disclosure are disclosed herein, it will be apparent to a person having ordinary skill in the art in view of this disclosure that a variety of changes and/or modifications can be made to the disclosed embodiments without departing from the scope of the present disclosure. Therefore, the scope of the disclosure as well as the scope of the following claims is not limited to embodiments described herein.

Claims

1. A lighting device for enhancing plant growth, the lighting device comprising:
a set of panel assemblies, each panel assembly comprising:
5 a set of light sources for emitting incident light; and
a plurality of lighting panels, each lighting panel comprising a
fluorescent material that emits fluorescent light upon exposure to the
incident light, the fluorescent light and transmitted incident light
combining as plant lighting for enhancing plant growth; and
10 an actuation mechanism coupled to the panel assemblies for
rearranging the lighting panels of each panel assembly to redirect the plant
lighting,
wherein for each panel assembly, the fluorescent materials of the lighting
panels have different compositions, such that the resulting plant lighting are
15 different for different stages of plant growth.
2. The lighting device according to claim 1, wherein the actuation mechanism is
configured to rotate the lighting panels of a panel assembly around a core region of
the panel assembly.
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3. The lighting device according to claim 2, wherein the light sources of a panel
assembly are disposed in the core region and arranged to emit the incident light
towards the lighting panels.
- 25 4. The lighting device according to claim 1 or 2, wherein the light sources of a
panel assembly are disposed at edge regions of the lighting panels and arranged to
emit the incident light into the lighting panels.
5. The lighting device according to any one of claims 1 to 4, wherein the actuation
30 mechanism is configured to rearrange the lighting panels of each panel assembly
independently from the other panel assemblies.

6. The lighting device according to any one of claims 1 to 4, wherein the actuation mechanism is configured to rearrange the lighting panels of the panel assemblies collectively.

5 7. The lighting device according to any one of claims 1 to 6, wherein a lighting panel comprises an optical diffuser for uniformly scattering the plant lighting.

8. The lighting device according to claim 7, wherein the optical diffuser comprises a polycarbonate or glass material.

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9. The lighting device according to any one of claims 1 to 8, wherein a lighting panel comprises an optical reflector for reflecting the fluorescent light.

10. The lighting device according to claim 9, wherein the optical reflector comprises
15 a Bragg reflector or dichroic mirror.

11. The lighting device according to any one of claims 1 to 10, wherein a lighting panel comprises an anti-reflective coating for reducing reflection from outside the lighting panel.

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12. The lighting device according to any one of claims 1 to 11, wherein the fluorescent material of a lighting panel comprises a plurality of fluorescent material sections having different compositions, such that the resulting plant lighting from the fluorescent material sections are different.

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13. The lighting device according to any one of claims 1 to 12, wherein the fluorescent material comprises a flexible substrate.

14. The lighting device according to claim 13, wherein the flexible substrate
30 comprises an epoxy resin.

15. The lighting device according to any one of claims 1 to 14, wherein the fluorescent materials comprise quantum dots and/or phosphor materials.

16. The lighting device according to claim 15, wherein the quantum dots comprise a core-shell structure.

5 17. The lighting device according to claim 16, wherein the core-shell quantum dots comprise one or more of the formulae CdSeZnS/ZnS , CIS/ZnS , InP/ZnSeS , CZIS/ZnS , and Mn:ZnSeS/ZnS .

18. A method for enhancing plant growth, the method comprising:

10 operating a lighting device comprising a set of panel assemblies for emitting plant lighting towards plants to enhance plant growth, each panel assembly comprising a set of light sources and a plurality of lighting panels;

receiving, by the lighting panels, incident light emitted from the light sources, each lighting panel comprising a fluorescent material that emits
15 fluorescent light upon exposure to the incident light, the fluorescent light and transmitted incident light combining as the plant lighting;

arranging a first lighting panel of each panel assembly to direct first plant lighting from the first lighting panels to the plants, the fluorescent materials of the first lighting panels having a same first composition;

20 emitting the first plant lighting from the first lighting panel to the plants for enhancing a first stage of plant growth;

arranging a second lighting panel of each panel assembly to direct second plant lighting from the second lighting panels to the plants, the fluorescent materials of the second lighting panels having a same second composition different from the first composition; and
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emitting the second plant lighting from the second lighting panel to the plants for enhancing a second stage of plant growth after the first stage.

19. The method according to claim 18, further comprising:

30 arranging a third lighting panel of each panel assembly to direct third plant lighting from the third lighting panels to the plants, the fluorescent materials of the third lighting panels having a same third composition different from the first and second compositions; and

emitting the third plant lighting from the third lighting panel to the plants for enhancing a third stage of plant growth after the second stage.

20. The method according to claim 18 or 19, wherein emitting the respective plant
5 lighting comprises uniformly scattering the respective plant lighting through an optical
diffuser of the respective lighting panel.

21. The method according to any one of claims 18 to 20, wherein emitting the
respective plant lighting comprises reflecting the respective fluorescent light from an
10 optical reflector of the respective lighting panel.