

A METHOD AND APPARATUS FOR CROP HEALTH MONITORING AND NUTRIENT SUPPLY ANALYSIS FOR CROP CULTIVATION

RELATED APPLICATION

[0001] This application claims the benefit of priority to the Singapore application no. 10202301387S filed May 17, 2023, the contents of which are hereby incorporated by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] The present disclosure relates to a system for crop monitoring, and more specifically to a method and apparatus for crop health monitoring and nutrient supply analysis.

BACKGROUND

[0003] In a modern crop cultivation system such as hydroponics, the essential inputs such as light, water, nutrients, and oxygen are automatically delivered to the plants. In the case of nutrients, fertilizer solutions at the required composition are added into the mixing tank and pumped into the grow tray, which are then absorbed by the roots of the plant for normal functioning and growth. Although nutrient solutions are formulated in ratios that reflect the needs of the crop, the nutrient level will gradually deplete or change from the optimal value by transpiration and the rate of this change depends on the crop type. Nutrient levels outside the sufficiency range of a crop can cause a drop in overall crop growth and a decrease in crop health due to either a deficiency or toxicity.

SUMMARY

[0004] A system for monitoring the crop health and nutrient supply includes: a crop health monitoring unit, and a nutrient monitoring unit. The nutrient monitoring unit includes a sample flow cell, a first optical sensor in combination with a laser, and a spectral analyzer configured to generate an elemental spectral data based on the emission data. The sample flow cell includes a channel connected to the grow tray to receive a sample of the liquid nutrient from the grow tray. The channel

defines a flow path extending across a sampling zone. The first optical sensor is disposed to acquire emission data from a laser interaction with the sample flowing in the sampling zone.

[0005] The system may further include at least one imaging spectroscopy unit configured to monitor the non-root part and the root part of the crop to determine a crop health condition of the crop.

[0006] The system may further include a processor. The processor in operation may be in signal communication with a non-transitory memory storing processor-executable instructions which when executed by the processor cause the processor to: determine the respective quantitative measure of each of a plurality of constituent elements in the sample based on the elemental spectral data; and predict a deviation of a sample composition of the sample from a target nutrient composition using a first machine learning model, the deviation being expressed in terms of a respective quantitative level of deficiency and/or a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample.

[0007] The processor may be caused to predict the crop health condition using a second machine learning model based on an input acquired from the at least one imaging spectroscopy, in which the crop health condition includes any one or more of the following: a growth stage of the crop, a stress condition of the crop, a disorder type of the crop.

[0008] The at least one imaging spectroscopy unit may include: a first imaging spectroscopy and a second imaging spectroscopy. The first imaging spectroscopy may be disposed at the cultivation zone and oriented to acquire leaf images of the non-root part of the crop. The second imaging spectroscopy may be disposed at the cultivation zone apart from the first imaging spectroscopy, with the second imaging spectroscopy being oriented to acquire root images of the root part of the crop, the processor being caused to acquire the leaf images and the root images as the input to the second machine learning model.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] **FIG. 1** schematically illustrates a cultivation zone;

[0010] **FIG. 2** is a schematic diagram of a system according to embodiments of the present disclosure;

[0011] **FIG. 3A** schematically illustrates the system depicted in **FIG. 2** according to embodiments of the present disclosure;

[0012] **FIG. 3B** and **FIG. 3C** schematically illustrate an imaging spectroscope carried by an automated guided vehicle and configurable to acquire images from various cultivation zones disposed at various elevations;

[0013] **FIG. 4** schematically illustrates the nutrient monitoring unit of the system of **FIG. 2** in greater detail;

[0014] **FIG. 5A** to **FIG. 5H** are schematic drawings of various embodiments of the components of a sample handling setup;

[0015] **FIG. 6** schematically illustrates the workflow diagram of the data processing in the system;

[0016] **FIG. 7** is a schematic block diagram of a control loop of the crop health monitoring system;

[0017] **FIG. 8** is a schematic diagram of the Artificial Intelligence/Machine Learning (AI/ML)-driven algorithm of the present system;

[0018] **FIG. 9A** and **Fig. 9B** are schematic block diagrams showing a control loop and a process for nutrient monitoring;

[0019] **FIG. 10** shows the complex interrelationships between nutrient deficiencies and symptoms using an example of the green lettuce;

[0020] **FIG. 11** shows an example of the measurement data collected in the nutrient monitoring unit;

[0021] **FIG. 12A**, **FIG. 12B**, and **FIG. 12C** show the photograph and corresponding spectral plots at 13, 22 and 34 Days After Planting (DAP);

[0022] **FIG. 12D** shows an example of spectral angle mapper classification;

[0023] **FIG. 13** shows an example of the spectrum at DAP 21 and DAP 32 for normal and deficient crops;

[0024] **FIG. 14** shows mean second derivative spectra for control and deficient crops at DAP 21 and DAP 32;

[0025] **FIG. 15A** shows the plot depicting Full Width at Half Maximum (FWHM) changes during crop growth at growth phase;

- [0026] **FIG. 15B** shows the plot depicting FWHM changes during crop growth at senescence phase;
- [0027] **FIG. 16A** shows the plot depicting Full Width at thrice Quarter Maximum (FW3QM) changes during crop growth at growth phase;
- [0028] **FIG. 16B** shows the plot depicting FW3QM changes during crop growth at senescence phase;
- [0029] **FIG. 17A** is a plot showing second derivative peak ratio at growth phase;
- [0030] **FIG. 17B** is a plot showing second derivative peak ratio at senescence phase;
- [0031] **FIG. 18A** shows the spectral image of the root corresponding to amine exudation;
- [0032] **FIG. 18B** shows the corresponding spectral angle mapper (SAM) classification of the root; and
- [0033] **FIG. 19** schematically illustrates a graphical user interface for displaying crop health status and nutrient (elemental composition) status.

DETAILED DESCRIPTION

- [0034] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.
- [0035] The term “and/or” includes any and all combinations of one or more of the associated listed items.
- [0036] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments.
- [0037] As used herein, the singular ‘a’ and ‘an’ may be construed as including the plural “one or more” unless apparent from the context to be otherwise.

[0038] The terms "about" and "approximately" as applied to a stated numeric value encompasses the exact value and a reasonable variance as will be understood by one of ordinary skill in the art, and the terms "generally" and "substantially" are to be understood in a comparable manner, unless otherwise specified.

[0039] Some processes may be described in terms of steps merely to aid understanding and/or for convenient reference. The delineation between one step and another step may be described as such merely for convenient reference in the present disclosure. It will be understood that in actual implementation there may not be a clear division or transition from one step to another subsequent step. There may be a certain amount of overlap among the steps and/or more than one step may occur or be performed concurrently in time, etc.

[0040] As used herein, the terms "concurrent", "concurrently", "simultaneous", or "simultaneously" may be used loosely to refer to two or more processes, steps, or events that at least partially overlap in time. Concurrent processes, steps, or events do not necessarily start at the same time instant and/or end at the same time instant.

[0041] Terms such as "first", "second", "third", etc. may be used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless required by the context.

[0042] For the sake of brevity, as used herein, the terms "AI/ML", "artificial intelligence", and "machine learning" will be used interchangeably.

[0043] To aid understanding and not to be limiting, various embodiments of a device are described below.

[0044] Cultivation zone

[0045] **FIG. 1** is a schematic diagram of a cultivation zone 210 that may be adapted or integrated with a system 100 for monitoring a crop 900 in accordance with various embodiments of the present disclosure. The method and apparatus disclosed herein provides a comprehensive monitoring system that may be implemented in new or existing farms or other infrastructure, including but not limited to hydroponic farms. As used herein, the term "cultivation zone" is used in a generic sense to refer to one or more planters, hydroponic units, hydroponic farms, agricultural setups, vertical farming, etc., where plant or crop may be grown. Within

the claimed scope, variations of the system 100 may be configured to embody a method and apparatus for crop health monitoring and nutrient analysis for a cultivation zone. For the sake of brevity, the terms “crop” and “plant”, and the like, may be used interchangeably in the present disclosure. The cultivation zone 210 may include a support media or a crop support 220 to support or hold the crop 900.

[0046] The crop 900 in the cultivation zone 210 need not be limited to only one species of plant. In some examples, the crop 900 cultivated in the cultivation zone 210 includes a variety of plant species of crops. In some examples, the crop 900 cultivated in the cultivation zone 210 includes only a single plant species.

[0047] The cultivation zone 210 may be of various dimensions. In some examples, the cultivation zone 210 may have one crop 900 or one plant disposed therein. In some examples, the cultivation zone 210 may have various numbers of crop of various varieties or species disposed therein. In some examples, the cultivation zone 210 may have multiple stacks of crops of one or more variety.

[0048] For the sake of brevity, as used herein, the expression “a plurality of the crop” refers to two or more plants, in which the two or more plants may be of the same species or of different species.

[0049] The crop 900 may be disposed on the crop support 220 so that leaves of the crop 900 may be exposed to or exposable to a source of light (light source 240). In some examples, the light source 240 may be a natural light source such as sunlight. In some examples, the light source 240 may be provided by one or more artificial light sources, including but not limited to light emitting diode (LED) bulbs, incandescent lamps, halogen lamps, etc. The non-root part 910 (e.g., leaf) of the plurality of the crop 900 may be at least partially disposed to be exposable or exposed to the light source 910.

[0050] One or more liquid nutrient is provided from a nutrient source 250 to the cultivation zone 210 to feed the crop 900 via a root part 920 of the plurality of the crop 900. In some examples, liquid nutrient 270 may be pumped 601 into a grow tray 230, maintaining a first volume of the liquid nutrient 270 in the grow tray 230 so that at least a part of the roots of the crop 900 can be in contact with the liquid nutrient 270. For example, at least a part of the roots of the crop 900 may be at

least partially submerged in the liquid nutrient 270. The liquid nutrient 270 may alternatively be referred to as the nutrient solution.

[0051] In some other examples, the crop support 220 may be a porous support media that is capable of absorbing the liquid nutrient 270. The crop 900 is disposed on the crop support 220 such that the crop 900 can take in the liquid nutrient 270 from the crop support 220.

[0052] In some other examples, the liquid nutrient 270 may be sprayed towards the root part 920 of the crop 900. The liquid nutrient 270 that is not absorbed or otherwise taken in by the crop 900 will collect in the grow tray 230 that is disposed under the crop support 220.

[0053] The choice of method of feeding the crop 900 with the liquid nutrient 270 may be dependent on the crop 900 to be cultivated. In each of the examples described above, the liquid nutrient 270 is provided to the cultivation zone 210 to feed the crop 900 via a root part 920 of the crop 900.

[0054] The grow tray 230 may be disposed under the crop support 220 to make use of gravity to collect the run-off liquid nutrient (including, for example, the liquid nutrient that is not absorbed by the crop 900, etc.) by gravity. This may mean that the grow tray 230 is at a lower elevation than the crop 900. The grow tray 230 need not be directly under or in alignment with the crops. For example, a run-off manifold may be provided to allow the run-off liquid nutrient from a plurality of the crop 900 to be collected in one container, e.g., in the grow tray 230.

[0055] In some examples, an aerator 260 may provide air or other appropriate gases such as oxygen, nitrogen etc., to a diffuser 262, with the diffuser being disposed in the liquid nutrient 270 to aerate the liquid nutrient 270.

[0056] System overview

[0057] **FIG. 2** is a schematic diagram to illustrate embodiments of the system 100 and the method of the present disclosure.

[0058] The system 100 includes a nutrient monitoring unit 600 and a crop health monitoring unit 300 to be used with a cultivation zone 210.

[0059] The nutrient monitoring unit 600 includes an elemental detection system. As will be further described below with reference to **FIG. 4**, the elemental detection system includes a sampling device, a first optical sensor 620 to acquire data from

a sample of the liquid nutrient, and a spectral analysis unit 622. The elemental detection system also includes a laser 621 (for example, but not necessarily, a pulsed laser), beam shaping optics 623, beam steering optics 624, and focusing optics 625. Embodiments of the optics sub-system (e.g., including beam shaping optics 623, beam steering optics 624, and focusing optics 625) may contain a plurality of optical components (e.g., mirrors, filters, lenses, apertures, etc.) for shaping, routing, and/or focusing the laser beam onto the sample. The beam shaping optics 623, routing optics 624, and focusing optics 625 together or individually may be used to alter the characteristics of the laser 621 such as beam shape, beam size, pulse duration, pulse delay, intensity, polarization, number of beam spots etc. The nutrient monitoring unit 600 may further include one or more environmental sensors to sense environment conditions in the cultivation zone 210, including but not limited to pH level and electroconductivity value (EC) of the liquid nutrient, temperature in the cultivation zone 210, etc.

[0060] The crop health monitoring unit 300 includes a second optical sensor (e.g., a first imaging spectroscopy 311 or Camera 1) and a third optical sensor (e.g., a second imaging spectroscopy 312 or Camera 2). The first imaging spectroscopy 311 captures image data of a non-root part 910 of a crop growing in the cultivation zone 210. For the sake of brevity and to avoid confusion, the image data acquired by the first imaging spectroscopy 311 is referred to as leaf images. The second imaging spectroscopy 312 captures image data of a root part 920 of a crop 900 growing in the cultivation zone 210. For the sake of brevity and to avoid confusion, the image data acquired by the second imaging spectroscopy 312 is referred to as root images. In some embodiments, at least one imaging spectroscopy unit may be provided, in which each imaging spectroscopy unit is one physical apparatus including the first imaging spectroscopy 311 and the second imaging spectroscopy 312 configured to capture spectral images of different parts of the crop 900. In some embodiments, the first imaging spectroscopy 311 and the second imaging spectroscopy 312 are separate physical apparatus. In some embodiments only one imaging spectroscopy, e.g., with a broadband and sufficiently wide field of view camera, may be used to capture spectral images of the whole crop.

[0061] The system 100 may further include an alert/control system 450. The alert/control system 450 may be configured to provide an alert or control in response to an unfavorable condition being predicted or detected.

[0062] The system 100 includes a processor 400 and memory 470 readable by the processor 400. In accordance with embodiments of the present disclosure, the processor 400 may be provided within a computing unit, mobile device or any of the modules provided within the computing unit and/or mobile device to carry out any of the functions described herein. One skilled in the art will recognize that the exact configuration of each processor 400 may vary and the arrangement illustrated is provided by way of example only.

[0063] In embodiments of the disclosure, the system 100 may comprise the processor 400 and one or more interface 500. A user interface 500 may be connected to enable manual interactions between a user and the processor 400. The user interface 500 may include input/output components required for a user to enter instructions to the processor 400. The user interface 500 may vary from embodiment to embodiment. In some examples, the user interface 500 may include one or more of the components such as a display, a keyboard, touch-sensitive screen, a joystick, a microphone, a speaker, and a mouse device.

[0064] A communications interface 460 may be provided in some embodiments to enable communication between two computing units and/or mobile devices. The communications interface may take the form of a network card. The network card may, for example, be utilized to send data via a wired or wireless network to other processing devices or to receive data via the wired or wireless network. Wireless networks that may be utilized by the network card include, but are not limited to, Wireless-Fidelity (Wi-Fi), Bluetooth, Near Field Communication (NFC), cellular networks, satellite networks, telecommunication networks, Local Area Networks (LAN), Wide Area Networks (WAN), etc.

[0065] The computing unit or mobile device may include a memory 470. The memory 470 may include both volatile and non-volatile memory and more than one of each type of memory, including Random Access Memory (RAM), Read Only Memory (ROM), and a mass storage device, the last comprising one or more solid-state drives (SSDs), Hard disks (HDDs), or memory cards. One skilled in the art will

recognize that the memory 470 described include non-transitory computer-readable media and may be taken to include all computer-readable media except for a transitory, propagating signal. Instructions may be stored as program code in the memory and/or be hardwired. The memory 470 may include a kernel and/or programming modules such as a software application that may be stored in either volatile or non-volatile memory.

[0066] As used herein, the term “processor” is used to refer generically to any device or component that can process computer-readable instructions. As used herein, the term “processor” may include, but is not limited to, a microprocessor, microcontroller, programmable logic device or other computational device. That is, the processor 400 may be provided by any suitable logic circuitry for receiving inputs, processing the inputs in accordance with instructions stored in the memory, and generating outputs (for example, to the memory components or an interface). In this embodiment, the processor 400 may be a single core or multi-core processor with memory addressable space.

[0067] One skilled in the art will recognize that certain functional units in the present disclosure may be referred to as modules. The person skilled in the art will also recognize that a module may be implemented as circuits, logic chips or any sort of discrete component. Furthermore, one skilled in the art will also recognize that a module may be implemented in software which may then be executed by a variety of processor architectures. In embodiments of the present disclosure, a module may also include computer instructions or executable code that may instruct a computer processor to carry out a sequence of events based on instructions received.

[0068] System description

[0069] **FIG. 3A** is a schematic diagram of an embodiment of the present disclosure. The crop health monitoring unit 300 is configured to monitor the growth of various plant parts (crop parts) such as leaf 910, root 920, and produce (e.g., fruit) at different stages of the crop life cycle. The nutrient monitoring unit 600 is configured to analyze the elemental composition of the nutrient supply in the cultivation zone 210.

[0070] The first imaging spectroscopy 311 and the second imaging spectroscopy 312 may be disposed at the cultivation zone 210 to enable the first imaging spectroscopy 311 and the second imaging spectroscopy 312 to capture different physical parts of the crop 900. The two separate imaging spectroscopies 310 (e.g., the first imaging spectroscopy 311 and the second imaging spectroscopy 312) may be used for monitoring two different parts of the crop 900, namely, the crop body in air (e.g., leaf, flower, fruit, stem, etc.) and the crop body in water, or the cultivation media, or liquid nutrient (root). In some embodiments, the imaging spectroscopies 310 may be configured to analyze a large wavelength of spectrum range from UV-visible region to near Infrared. For example, the imaging spectroscopies 310 may cover the whole UV-Vis-NIR spectrum (ultraviolet-visible-near infrared spectrum from about 200 nanometers to 1800 nanometers). The system 100 may use fast, compact and light-weight (<2 kg) imaging spectroscopies 310 that work in either point-scan, line-scan, spectral-scan, or full-field mode.

[0071] First imaging spectroscopy 311 / Monitoring of non-root part

[0072] For example, the first imaging spectroscopy 311 may be disposed at the cultivation zone 210 and oriented to acquire leaf images of the non-root part 910 of the crop 900. In the example illustrated, the first imaging spectroscopy 311 is positioned over the crop 900. In other examples, the first imaging spectroscopy 311 may be disposed to one side to the non-root part 910 of the crop 900 and oriented to capture images ("non-root images") of the non-root part 910. As used herein, the expression "non-root part" may refer to the crop part that is in the air (e.g., the leaf, flower, fruit, stem, etc.) or a crop part that is not submerged in the liquid nutrient.

[0073] Second imaging spectroscopy 312 / Monitoring of root part

[0074] For example, the second imaging spectroscopy 312 may be disposed at the cultivation zone 210 and oriented to acquire images ("root images") of the root part 920 of the crop 900 or a crop part that is disposed in the liquid nutrient or cultivation media.

[0075] The grow tray 230 where the crop 900 is grown may be fitted with a transparent window made of a transparent material. In some examples, the grow tray 230 is at least partially made of a transparent material. Suitable transparent

materials include, but are not limited to, glass, quartz, polycarbonate (PC), Perspex, polypropylene (PP), and/or polyethylene terephthalate (PET), etc.

[0076] In some examples, the grow tray 230 or the crop support 220 may be lifted, tilted, or otherwise oriented to facilitate inspection and/or image capture by the second imaging spectroscopy 312. In some examples, both the grow tray 230 and the crop support 220 are configured to cooperatively enable the second imaging spectroscopy 312 to capture images of the root part 920 of the crop 900. In the non-limiting example illustrated in **FIG. 3A**, the crop support 220 holds the crop 900 near the base of a stem and disposes the root part 920 above a grow tray 230. Feed tubes deliver liquid nutrient to the root part 920. In this example, the feed tubes are configured to spray liquid nutrient towards the root part 920 of the crop 900. A first volume of the liquid nutrient that is not taken in by the root part 920 is collected in the grow tray 230 under the crop 900.

[0077] Large area monitoring / vertical farms

[0078] The system 100 of the present disclosure is not limited to any particular size or configuration of the cultivation zone 210. As used herein, reference to an item being disposed at the cultivation zone 210 may refer to the item being disposed inside the cultivation zone 210 (e.g., where a room or a building structure serves the cultivation zone 210), or it may refer to the item being disposed outside the cultivation zone 210. The crop health monitoring unit 300 may also be used in a vertical farm 200 in which a plurality of the cultivation zones 210 are vertically and/or horizontally distributed on a rack.

[0079] In some examples, large area monitoring of the vertical farms 200 may be achieved either by optical modification of the field of view of the imaging spectroscopy 310 or by mounting at least a part of the system 100 on automated translation rails 320 or on robots 290. In some examples, a plurality of the crop 900 may be distributed in a horizontal array or row (or a somewhat horizontal array or row). Each of the first imaging spectroscopy 311 and the second imaging spectroscopy 312 may be supported on a rail system. For example, the first imaging spectroscopy 311 may be slidably (or otherwise) displaced vertically to accommodate a growing plant. For example, the first imaging spectroscopy 311 may be slidably (or otherwise) displaceable from one crop to a next crop (e.g., along

a row or an array of a plurality of the crops) to inspect in turn each of the plurality of the crop 900. For example, the second imaging spectroscopy 312 may be slidably (or otherwise) displaceable from one crop to a next crop (e.g., along a row or an array of a plurality of the crops) to inspect in turn each of the plurality of the crop 900.

[0080] In some examples, a plurality of the first imaging spectroscopy 311 and/or a plurality of the second imaging spectroscopy 312 may be used to acquire images of each plant. **FIG. 3B** schematically illustrates two different stages of an imaging spectroscopy 310 (e.g., the first imaging spectroscopy 311, the second imaging spectroscopy 312) carried on a robot 290 with a configurable arm 292. The configurable arm 292 may be configured to position the imaging spectroscopy 310 at different heights (e.g., be characterized by an adjustable height) and/or different horizontal positions. The imaging spectroscopy 310 may be carried on the robot 290 or by an automated guided vehicle (AGV) to move between different racks 213, in which each shelf 214 of the rack 213 can carry one or more cultivation zone 210. The imaging spectroscopy (e.g., the first imaging spectroscopy 311, the second imaging spectroscopy 312) may be configured to acquire images from each of the vertically distributed cultivation zones 210 in turn (e.g., in a vertical farm 200).

[0081] In another embodiment and as illustrated schematically in **FIG. 3C**, the system 100 may be configured as a mobile robot 290. For example, the mobile robot 290 may include the crop health monitoring system 300 and the nutrient monitoring unit 600, as well as the processor 400 and other components of the system 100, including user interface 500 such as a display/input screen. As shown, the two imaging spectroscopies 310 may be positioned by a robotic arm 292. The two imaging spectroscopies 310 may function independently on separate moving platforms (e.g., **FIG. 3B**), or combined into a single unit, or mounted on the same moving platform (e.g., **FIG. 3C**).

[0082] Nutrient monitoring unit

[0083] **FIG. 4** schematically illustrates the nutrient monitoring unit 600 of the system 100 according to embodiments of the present disclosure.

[0084] The nutrient monitoring unit 600 is configured to extract liquid nutrient 270 from the cultivation zone 210 and deliver a sample of the liquid nutrient 270 to

sampling zone 611. More specifically, the liquid nutrient extracted is taken from the liquid nutrient provided to the crop 900 but not taken up by the crop 900.

[0085] For example, the liquid nutrient may be provided from a nutrient source 250 to the cultivation zone 210. Some of the liquid nutrient is taken up or absorbed by the crop 900. Some of the liquid nutrient is not taken up by the crop 900, and at least some of this liquid nutrient 270 remain in or flow to the grow tray 230 (referred to generically as “collected in the grow tray 230” for the sake of brevity). The nutrient monitoring unit 600 of the present disclosure draws from the liquid nutrient 270 collected in the grow tray 230 to form the sample of the liquid nutrient 270.

[0086] The nutrient monitoring unit 600 may include a sampling zone 611 defined by a sample flow cell 610 through which a sample of the liquid nutrient can flow in a manner suitable for optical sensing (e.g., including but not limited to a microfluidic cell or microfluidic flow path). The sampling zone 611 may be coupled in fluidic communication with a fluid pump 601. In operation, an amount of the liquid nutrient 270 is extracted from the grow tray 230 and controllably pumped through the sampling zone 611 using the fluid pump 601.

[0087] In the example illustrated, a laser 621 is passed through beam shaping optics 623, routing optics 624, and focusing optics 625 to excite the sample of liquid nutrient in the sampling zone 611. The first optical sensor 620 is positioned and oriented to sense the emissions from the plasma created from the sample of the liquid nutrient 270 when the sample is flowing through the sampling zone 611.

[0088] The nutrient monitoring unit 600 may further include one or a plurality of laser system 621 emitting in a spectral region including UV (180 nm to 400 nm), visible (400 nm to 700 nm), and IR (700 nm to 3000 nm) wavelengths. The laser radiation on the sample of liquid nutrient in the sampling zone 611 generates plasma from the sample, and the emission data from this plasma is sensed or collected using collection optics 629. The collection optics 629 include the first optical sensor 620 and one or a plurality of spectral analyzer 622. The first optical sensor 620 may include an optical fiber 628 fitted with appropriate lens. In some embodiments, the acquisition of the emission data may be done in free space.

[0089] The nutrient monitoring unit 600 may include one or a plurality of spectral analyzer 622 selected from the various spectral analyzers available commercially.

The spectral analyzer may be described as a spectral measurement apparatus made up of optical elements, spectral dispersion units, and optical detectors. The collected emission data may be analyzed using the spectral analyzer. The spectral analyzer 622 may also include necessary electronics to time and gate the emission data with respect to the laser pulses. The spectral analyzer is configured to generate an elemental spectral data based on a first signal (e.g., the collected emission data) acquired from the first optical sensor 620.

[0090] Sample handling

[0091] The nutrient monitoring unit 600 includes a sample handling setup. The sample handling setup of the system 100 includes a sampling zone 611 that is configured to expose the sample of the liquid nutrient to laser excitation. In some examples, the sample handling setup of the system 100 may enable a sample of the liquid nutrient to flow as a micro-flow in the sampling zone 611. As used herein, the term "micro-flow" refers to a relatively small volume of liquid (as compared to the volume of liquid that may be in the grow tray 230 or in the nutrient source 250. For example, the volume of a micro-flow of liquid in the sampling zone 611 may be of the order of a few tens of microliters. The term "micro-flow" may further refer to liquid being in a stream, a sheet, a droplet, a film, a pool, etc., in which at least one dimension of the micro-flow is in the micrometer scale. Examples of micro-flow include but are not limited to microfluidic flow of liquid.

[0092] For example, the sample handling setup may include a sample flow cell 610. In some examples, the sample flow cell 610 may be in the form of a micro-flow cell or a body defining a channel of a microfluidic or micro-scale feature. In other examples, the sample flow cell 610 may provide a moving/flowing sample in the form of a thin sheet of liquid. In yet other examples, the sample flow cell 610 may form a linearly flowing sample, a radially flowing sample, or a sample of the liquid nutrient moving under centrifugal forces. The sample flow cell 610 defines a sample flow path extending between a sample inlet 602 and a sample outlet 603. The sample flow path extends across a sampling zone 611, such that a sample of the liquid nutrient flows from the sample inlet 602 to the sample outlet 603 in the course of being sensed by the first optical sensor 620. The body of the sample flow cell 610 may be at least partially made of a transparent material through which the first

optical sensor 620 may sense the sample in the sampling zone 611. Alternatively, the body may define an opening (a window) through which the first optical sensor 620 may sense the emissions from the sample in the sampling zone 611.

[0093] In some embodiments, the sample flow cell 610 facilitates the sample to flow along a flow path in the sampling zone 611.

[0094] For example, the system 100 (e.g., nutrient monitoring unit 600 or the sample handling unit of the system 100) may include a device with an inlet pipe that is in connection with the nutrient liquid in the grow tray 230 of the cultivation zone 210. The device may include an outlet that outputs a second volume of the liquid nutrient, in which the second volume of the liquid nutrient may be smaller than the first volume of the liquid nutrient. A receptacle may be disposed downstream of the outlet to receive the liquid nutrient. The receptacle is downstream from the outlet to define the sampling zone 611 between the outlet and the receptacle.

[0095] Various embodiments of the sample handling setup and components thereof are described below with reference to **FIG. 5A** to **FIG. 5H**.

[0096] **FIG. 5A** schematically illustrates one embodiment of the sample handling setup. The sample handling setup may include a sample flow cell 610 defining a channel having a circular cross-section. The channel is fed by a sample inlet 602 that is connected to the nutrient solution in grow tray 230. The sample inlet 602 includes a relatively small opening or a nozzle 650. In this example, the nozzle 650 is in the form of a micro drop jet nozzle 651 to deliver the sample in the form of micro-droplets 661. An example of the jet nozzle 651 is shown in **FIG. 5B**. The jet nozzle 651 ejects the sample of liquid nutrient in droplets 661 that pass through the sampling zone 611. As the micro-scale or microfluidic-scale droplets of liquid nutrient traverses the sampling zone 611, the first optical sensor 620 captures emission data from the plasma created from respective droplets that are irradiated by the laser in the sampling zone 611.

[0097] **FIG. 5C** schematically illustrates another embodiment of the sample handling setup. The sample handling setup may include a sample flow cell 610 defining a channel having a rectangular cross-section. The channel is fed by a sample inlet 602 that is connected to the nutrient solution in the grow tray 230. The channel inlet 602 includes a rectangular nozzle 652 or a relatively narrow and flat

mouth such that the sample flows in the channel in the form of a sheet of flowing liquid or a liquid sheet 662. An example of the line nozzle 652 is shown in **FIG. 5D**. The line nozzle 652 may be configured to eject the sample of liquid nutrient in a sheet-like form as the sample passes through the sampling zone 611. As the sheet of liquid nutrient with a "small thickness" (usually of micrometer-scale) traverses the sampling zone 611, the first optical sensor 620 captures emission data from the plasma formed from the "thin" layer of liquid nutrient irradiated by the laser.

[0098] **FIG. 5E** schematically illustrates another aspect of the sample handling setup. The sample handling setup may include a sample tank 653 with a much smaller volume than the first volume of the grow tray 230. The liquid nutrient in the sample tank 653 may be allowed to accumulate to facilitate sensing by the first optical sensor 620. Here the sampling zone 611 may be very close to the liquid meniscus, or may be inside the bulk of the liquid in the sample tank 653. The liquid nutrient in the sample tank 653 may be drained out periodically, or re-circulated back to the grow tray 230 by operation of a valve 680.

[0099] **FIG. 5F** schematically illustrates another embodiment of the sample handling setup in which the sample flow cell 610 is connected to a rotatable stage 654. The sample handling setup includes a pipe device to provide a flow path from the grow tray 230 to the rotatable stage 654. The rotatable stage defines the sampling zone 611. In operation, the rotatable stage 654 is controllably rotated to centrifugally spread out the liquid nutrient received from the outlet of the micro flow cell. The centrifugally spread-out film 664 may be collected by the receptacle from an outer edge of the rotatable stage. The first optical sensor 620 may be kept close to the rotatable stage 654 to sense the emissions from the sample plasma, where the plasma is formed on the thin sample layer formed on the rotatable stage 654 when irradiated by the laser.

[00100] **FIG. 5G** shows another embodiment of the sample handling setup in which a micro-flow of the liquid nutrient is formed in a straight capillary channel 656 of a sample flow cell 610 in the form of a micro-flow cell. The micro-flow cell may be substantially transparent or may include a transparent window of an opening to facilitate data collection by the first optical sensor 620. The micro-flow cell may be provided with mounting flanges 658 to facilitate positioning of the capillary channel

656 in a designated sampling zone 611. The channel inlet 602 of the capillary channel 656 may be coupled to the outlet of the pipe device. The channel outlet 603 of the capillary channel 656 may lead to the receptacle to drain the liquid or to re-circulate it to the grow tray 230.

[00101] **FIG. 5H** illustrates yet another embodiment of the sample handling setup in which the sample flow cell 610 is a micro-flow cell in which the capillary channel 656 is tilted relative to a mounting flange 658. The capillary channel 656 may include a section that exposes a sample of the liquid nutrient in the capillary channel 656 for sensing by the first optical sensor 620.

[00102] The sample handling setup may be embodied in various forms as illustrated by the examples described above. The sample handling setup enables a relatively small volume of a sample of the liquid nutrient to be routed to the sampling zone 611 where optical measurement methods may be used to acquire measurements or data on the elemental composition of the sample of the liquid nutrient. The volume of liquid nutrient serving as the sample under sensing at any instant is much smaller (typically < 0.01%) than the volume of liquid nutrient that is collected in the grow tray 230 of the cultivation zone 210. The sample handling setup enables a microfluidic flow path to be integrated with the larger manifold serving the vertical farm 200 with liquid nutrient.

[00103] After passing through the sampling zone 611, the sample of the liquid nutrient may be returned to the grow tray 230 or the cultivation zone 210, or in some examples, to the source of liquid nutrient. In some examples, the sample may be discarded or used for other purposes.

[00104] Method of monitoring / control

[00105] **FIG. 6** is a schematic diagram showing the artificial intelligence/machine learning (AI/ML) approach in the nutrient monitoring system of the present disclosure integrating a crop health monitoring system. One skilled in the art would appreciate that variations may be made to the control circuits without going beyond the scope of the present disclosure. These examples are therefore provided merely to illustrate and aid understanding, and not to be limiting.

[00106] The system 100 includes a machine learning module operable by the processor in accordance with instructions and data stored in the non-transitory

memory. The machine learning module may include a crop phenotyping module. The machine learning module may include a crop identification module. The machine learning module may include a growth-stage classification module. The machine learning module may include a nutrient disorder classification module. The machine learning module may include a crop disease classification module.

[00107] In general, the system 100 may be described as including a machine learning module that is configured to receive as input / training data the output from a nutrient monitoring unit 600, the nutrient monitoring unit 600 being configured to monitor a micro-flow of samples of the liquid nutrient sampled from the cultivation zone 210. The machine learning module is further configured to receive as input / training data the output from a crop health monitoring unit 300. A selected reference library specific to the crop type (crop species) is used to facilitate accurate classification of the type of crop (crop species), the symptoms / phenotypes, the possible cause(s) of a disorder affecting the crop 900. For the sake of brevity, the term "disorder" as used herein may refer generically to growth abnormalities, nutrient deficiencies, diseases, stress, etc.

[00108] The present system 100 is characterized by analysis of the liquid nutrient at the element level to pin-point relevant nutrient supplements to be added for adjusting the elemental nutrient composition of liquid nutrient, in the context of the crop type (crop species), the growth phase of the crop 900, etc.

[00109] Crop health monitoring

[00110] **FIG. 7** is a schematic block diagram of the AI/ML controller-based control loop of the crop health monitoring system of the present disclosure. **FIG. 8** is a schematic diagram of the AI/ML-driven algorithm for identifying different growth stages and diseases (disorders) of the crop 900 using the system 100 described above.

[00111] Spectral imaging data from the first imaging spectroscopy 311 and the second imaging spectroscopy 312 are processed by the processor (data processor) with reference to the reference library for the specific crop. The images may be classified using a classification module. The classified data may serve as input to a machine learning model (e.g., in the form of an AI/ML controller) to identify the growth stage of the crop 900 and, with respect to the identified growth stage, to

predictively determine if the crop 900 is healthy or is characterized by a disease, deficiency in nutrition, or under stress. The data obtained from the imaging spectroscopes 310 are processed to obtain specific spectral signatures from the crops (including customized vegetation indices and spectral indices) using custom written software codes. Based on the spectral differences and phenotyping information the crops can be classified.

[00112] The deliverables of the crop health monitoring unit 300 may be in multiple aspects. For example, the crop health monitoring unit 300 may generate an alert that a certain plant at a specific location in the farm 200 is diseased and requires treatment. For example, the crop health monitoring unit 300 may also be used to inform or increase the accuracy of identifying a nutrient deficiency.

[00113] The term "crop type" as used herein may refer to the species of the crop 900. In some embodiments, the crop type may be further defined as a specified species of the crop grown hydroponically. The crop type may serve as a crop identifier associated with a plant species characterized by a set of preferred or optimal plant phenotypes of a healthy specimen (generally referred to as a target crop health condition). Alternatively described, the spectral imaging data from both the root images and the non-root (leaf) images may be compared against a reference library for the same crop type.

[00114] Reference spectral library

[00115] Each reference library may be specific to a crop type. For example, the system 100 may include a reference library for a species of tomato and another reference library for a species of cabbage. The reference library on the tomato species may include data pertaining to the tomato species alone, including, for example, data on macronutrients and micronutrients requirements, stress conditions, plant phenotypes, and growth stages, etc. The reference library on the cabbage species may include data pertaining to the cabbage species alone, including, for example, data on macronutrients and micronutrients requirements, stress conditions, plant phenotypes, and growth stages, etc.

[00116] According to embodiments of the present disclosure, the processor in operation is in signal communication with a non-transitory memory storing processor-executable instructions, which when executed by the processor cause

the processor to create a reference spectral library for each of various species of crops. The reference spectral library may be described as a dedicated and lean spectral library in that the reference spectral library contains data relating to only one specific crop 900. The reference spectral library includes emission spectra data as well as spectral imaging data acquired from sensing the specific crop 900. The emission spectra data refers to the data acquired by the first optical sensor 620 and the one or more environmental sensor. The spectral imaging data refers to the data acquired by the first imaging spectroscopy 311 and the second imaging spectroscopy 312.

[00117] In some embodiments, the images captured from the imaging spectroscopy may be collected by a data processor to generate reference spectral libraries for different types of crops. The data processor may be configured to classify and identify the crop growth, health, and disease state. In some embodiments, the data processor may be provided with classifications and dimensions reduction techniques to analyze the data cubes recorded.

[00118] In operation, the first imaging spectroscopy 311 and the second imaging spectroscopy 312 are configured to capture spectral images of the crop 900 at several wavelengths. The captured spectral images are processed to form the data cube. As used herein, the term “data cube” refers to a three-dimensional (3D) entity in which two of the dimensions provide spatial information, and a third dimension provides spectral information. The processor may be configured to construct a data cube for each crop 900 to store a wealth of information that uniquely characterizes the crop 900. For example, in a data cube, the data used may include spectral data associated with each pixel of each image.

[00119] The spectral ranges and resolutions of the crop health monitoring system are two parameters for monitoring the features of interest.

[00120] Nutrient monitoring

[00121] **FIG. 9A** is a schematic diagram showing an implementation algorithm for an AI/ML controller-based control loop for a laser spectroscopy-based embodiment of the nutrient monitoring system 600. **FIG. 9B** is a schematic block diagram showing a method of nutrient monitoring/delivery.

[00122] The system 100 is configured to acquire elemental data of the sample of the liquid nutrient (also referred to as the nutrient solution) utilizing atomic emission spectroscopy using the nutrient monitoring system 600.

[00123] The method includes identifying the nutrient constituents taken up by the crop at the elemental level, determining a state of the crop (e.g., crop health, etc.) based on the elemental data provided by the nutrient monitoring unit 600 and based on information obtained from the crop health monitoring unit 300 on the crop. The identifying of the nutrient constituents at the elemental level and the determining of a state of the crop is also based on a selected reference library. The selected reference library is chosen from multiple reference libraries developed by the system 100. As described above, the reference library may be developed based on data provided by the crop health monitoring unit 300 and the nutrient monitoring unit 600.

[00124] The collected emission data or spectra are analyzed in real-time using the data processing unit with AI and machine learning capabilities to determine the specific element and concentration levels. By incorporating AI and ML capabilities and referencing the reference spectral libraries created, the system 100 automates the supply of the nutrient components to maintain the optimum nutrient levels in the nutrient supply. This would prevent toxicity and deficiency to the crops thereby enhancing crop yield. Unlike the invention disclosed here, conventional systems currently employed in vertical farms 200 supplement the whole nutrient solution without any specificity based on EC and pH values to the system instead of specifically required nutrient components. This could make the nutrient supply to deviate from the optimal composition, making some components to be present in excess amount, resulting in toxicity to the crops and thereby affecting the crop yield.

[00125] The system 100 is configured to predict a health state of the crop based on the elemental data acquired from the first optical sensor 620, the other data acquired from the first imaging spectroscopy 311 and the second imaging spectroscopy 312, and the selected reference library. The system 100 also enables accurate, on-site quantitative chemical composition (elemental composition) analysis of the nutrient solution. The system 100 may further be operated as a real-time, individual component level nutrient monitoring system.

[00126] Warning / alert

[00127] If the crop is determined to be at risk, e.g., diseased or suffering from other conditions (generally referred to as a disorder), suffering from a deficiency in any one or more elemental nutrient, overdosed or having a (potentially) toxic level of any one or more elemental nutrient, etc., a warning or a feedback (referred to generically as an alert) may be generated.

[00128] The alert may be pushed to a user for manual action. The alert may notify a user (via a user interface 500 or by other means) to take action. Alternatively, or additionally, the alert may trigger a nutrient delivery unit 252 to adjust the amount of respective relevant elemental nutrients in the liquid nutrient supplied to the cultivation zone 210.

[00129] A nutrient delivery unit 252 may serve as a nutrient source 250 or a source of the liquid nutrient, and may be configurable to adjust the composition of the liquid nutrient upstream of the cultivation zone 210. As the system 100 is configured to carry out elemental detection of the individual components in the nutrient supply, a more detailed and crop-specific result on any deficiency or toxicity at the elemental level can be obtained. Specific nutrient components can be replenished as required, thereby enabling improved crop growth and a more efficient nutrient supply.

[00130] For example, the system 100 is configured to predict a deviation, e.g., determine if any one or more of the following constituent elements in the sample is/are quantitatively below a target quantity (nutrient deficiency) or above a target quantity (toxicity): nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), magnesium (Mg), carbon (C), oxygen (O), hydrogen (H), iron (Fe), boron (B), chlorine (Cl), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), sodium (Na), and nickel (Ni). The deviation may be expressed in terms of a respective quantitative level of deficiency and/or a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample. The processor may be configured to be responsive to the deviation.

[00131] If it is determined that there is a quantitative level of deficiency of any one or more of the plurality of constituent elements in the sample, one or more nutrient supplement may be dispensed to the liquid nutrient in the cultivation zone, the one or more nutrient supplement being selected to have a supplement composition

selected to replenish the one or more of the plurality of constituent elements predicted to have a quantitative level of deficiency.

[00132] The nutrient delivery unit may be configured to be responsive to the deviation being a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample. In some cases, the nutrient supplement may be selected to have a supplement composition selected to form a neutralizing precipitate with the one or more of the plurality of constituent elements predicted to have a quantitative level of toxicity. In some other cases, the nutrient delivery unit may be configured to calculate the dilution required to reduce or minimize the deviation, and to add the calculated volume of water to the liquid nutrient to dilute the liquid nutrient fed to the crops.

[00133] Experimental Results

[00134] A prototype of the system 100 was fabricated and experiments conducted to verify the viability of the proposed system 100. As an illustrative example and not to be limiting, crops of green lettuce were cultivated using the cultivation zone 210.

FIG. 10 shows the complex interface between elemental constituents of a liquid nutrient and some corresponding symptoms that may appear if any of the required elemental nutrients are deficient. Using only conventional methods, parts of a healthy green lettuce and a green lettuce with only one of the symptoms had to be cut from the plant, and undergo destructive processing and wet chemistry methods in order to identify the elements present in the plant part tested. Even with such a relationship chart on hand, it may not be apparent from observing plant phenotypes, exactly which elemental nutrient is deficient and to what extent. Relying on conventional methods, the user could only resort to adding a general mixture of nutrients in an attempt to boost the overall nutritional value of the liquid nutrient. Nonetheless, the user could only wait and observe how the crop subsequently grow in order to know whether the added nutrients could help resolve the disease/disorder observed. Such a trial-and-error method is time consuming and essentially based on guesswork. In some cases, providing a general nutrient boosting mixture may end up overdosing the crop in one element and underdosing the crop in another, resulting in poor crop yield.

[00135] In contrast, using the present system, a reference library could be created for the specific crop type of green lettuce without the need for destructive testing or wet chemistry processes, and specific elemental nutrient needs can be identified comparatively quickly without the need to destroy any part of the crop.

[00136] For the purpose of the experiments, a publicly available machine learning module may be used such as Support Vector Machine (SVM), Random Forest (RF) etc. Experimental results discussed below.

[00137] **FIG. 11** is an example of emission spectral data obtained using a nutrient monitoring unit 600 in which an indicative liquid nutrient sample in a sample flow cell 610 was analyzed using a laser-based elemental emission spectroscopy according to embodiments of the present disclosure. **FIG. 11** shows spectral lines that correspond to various constituent elements. In particular, elemental constituents such as potassium (K) and nitrogen (N) could be clearly identified.

[00138] Two crops of green lettuce were hydroponically grown in separate grow trays 230. Exemplary spectral signatures of the leaf (non-root part 910) of the crop 900 could be obtained from the first imaging spectroscopy 311. Exemplary spectral signatures of the root part 920 of the crop 900 could be obtained from the second imaging spectroscopy 312. Data cubes could be formed based on the data acquired by the first imaging spectroscopy 311 and the second imaging spectroscopy 312, and input to the reference library for the specific crop type of green lettuce.

[00139] **FIG. 12A** to **FIG. 12C** shows the spectral plots extracted from the data cubes recorded using the proposed crop health monitoring unit 300 and taken from the reference library created for green lettuce. Leaf data cubes refer to data cubes containing at least spectral data of the non-root part 910 of the crop 900. Root data cubes refer to data cubes containing at least the spectral data of the root part 920 of the crop 900. In this example, **FIG. 12A** shows an image of the two crops (Crop 1 and Crop 2) of green lettuce at 13 days after planting (DAP) with corresponding spectral plot obtained by the first imaging spectroscopy 311 by imaging the leaves (non-root part 910) of the crop 900. **FIG. 12B** shows an image of the two crops (Crop 1 and Crop 2) of green lettuce at 22 DAP with corresponding spectral plot obtained by the first imaging spectroscopy 311 by imaging the leaves (non-root part 910) of the crop 900. **FIG. 12C** shows an image of the two crops (Crop 1 and Crop

2) of green lettuce at 34 DAP with corresponding spectral plot obtained by the first imaging spectroscopy 311 by imaging the leaves (non-root part 910) of the crop 900.

[00140] The images captured by the first imaging spectroscopy 311 and the second imaging spectroscopy 312 may be processed using a classifying algorithm such as a spectral angle mapper (SAM) to obtain a classified image suitable for use in crop phenotyping and/or detection of disorders/diseased crop. To illustrate, **FIG. 12D** shows an RGB (Red Green Blue) image of a leafy part of the crop 900 generated by the first imaging spectroscopy 311 before classification and a corresponding reflectance spectrum. In this example, the reflectance Spectrum 1 and reflectance Spectrum 2 correspond to Area 1 and Area 2 of the crop 900, respectively. The classified image can be generated based on the reflectance spectra obtained from the first imaging spectroscopy 311. The information on the crop 900 can be recorded for use to build up the reference library for this particular species of the crop 900.

[00141] In some experiments, crops of the same crop type were grown in two separate grow trays 230. The crops in a first grow tray 230 (also referred to as the reference grow tray 230 or the control for convenience) were grown using a liquid nutrient having a target elemental composition. The crops in a second grow tray 230 were provided with a liquid nutrient having a second elemental composition different from the target elemental composition. In one experiment, the liquid nutrient in the second grow tray 230 was deficient in multiple constituent elements. For example, the liquid nutrient provided to the second grow tray 230 was 78% deficient in Ca, 65% deficient in K, and 95% deficient in Fe (compared to the target elemental composition). A multiband analysis was performed on the extracted derivative reflectance spectra (on the data recorded using the crop monitoring system 300) to capture the finer changes along a wider wavelength range. **FIG. 13** shows the resulting first derivative of the reflectance spectra at 21 DAP for a normal crop, at 21 DAP for a crop with a deficiency, at 32 DAP for a normal crop, at 32 DAP for a crop with a deficiency. **FIG. 14** shows the mean second derivative spectra which can also be used to provide a sensitive method to detect a deficiency/disorder in a crop 900.

[00142] In the experiment, it was observed that the crops with a deficiency/disorder exhibited narrowed peaks at approximately 705 nm wavelength when compared to healthy crops grown in the control grow tray 230. Quantitative measures such as full width at half maximum (FWHM) and full width at thrice quarter maximum (FW3QM) were used to quantify the narrowing of the first derivative peaks at about 705 nm.

[00143] In addition, in some examples, a nutrient deficiency may result in a slower development of the internal leaf structures. This also can be analyzed using the data cubes recorded with the crop monitoring system 300.

[00144] **FIG. 15A** is a plot of FWHM over time during a growth phase of the two set of crops - a control crop and a crop with a nutrient deficiency/disorder. **FIG. 15B** is a plot of FWHM over time during a senescence phase (biologically aging phase) of a similar crop type - a control crop and a crop with a nutrient deficiency. (Note that the dotted line is only a guide to the eye.)

[00145] It can be seen from the FWHM plots that, during the growth phase of the control crop, the FWHM exhibits a generally steadier increase than a crop with a nutrient deficiency.

[00146] The difference is even more striking during the senescence phase. During the senescence phase, the control crop showed less change in the quantitative measure of FWHM, and the crop with the nutrient deficiency exhibited irregular changes, e.g., hardly any change from 31 DAP to about 34 DAP, a rapid decrease from hence to about 36 DAP, a faster rate of increase from 36 DAP to 38 DAP, from whence the FWHM again decreased.

[00147] Similar quantifiable changes may be observed in the plots of FW3QM over time during a growth phase of crop growth and during a senescence phase, as depicted in **FIG. 16A** and **FIG. 16B**, respectively.

[00148] Both of the FWHM-based method and the FW3QM-based method can be used to distinguish a crop with a deficiency/disorder from a crop without the nutrient deficiency. The FW3QM-based method is observed to provide a higher sensitivity to a nutrient deficiency.

[00149] **FIG. 17A** and **FIG. 17B** shows plots of a ratio of the second derivative peaks along the wavelength window I and wavelength window II (in this example,

wavelength window I is defined from 500 to 550 nm with a peak around 520 nm; wavelength window II is defined from 690 to 750 nm with a peak around 705 nm) for a crop 900 in a control grow tray 230 (normal crop) and for a crop with a nutrient deficiency. In general, the crop with deficiency/disorder shows higher values for the ratio when the crop with nutrient deficiency is compared to the normal crops in the control grow tray 230 (reference grow tray 230) throughout the whole growth cycle, providing an effective deficiency detection index.

[00150] The root images may be classified in a similar manner as that described in respect of the non-root (leaf 910) images. **FIG. 18A** shows a spectral image of a root corresponding to amine exudation. **FIG. 18B** shows a corresponding spectral angle mapper (SAM) classification of the root. The classified image may then be used to build up a reference library and used in identifying the type of the crop 900, the growth phase of the crop 900, the development of the root system, etc. The processor may be configured to determine a change in the spectral data over a period of time or in comparison with one or more reference spectral libraries, and based on the change, determine a growth stage of the crop and/or determine if the crop is characterized by a nutritional issue or other health issues, e.g., deficiency or disorder.

[00151] The foregoing examples described the analysis using leaf data cubes as examples. Root data cubes may be similarly processed separately or in conjunction with leaf data cubes. Like the earlier examples, FWHM, FW3QM, first and second derivatives, derivative ratios etc. can also be used for the classification of the roots.

[00152] A system 100 and method of monitoring nutrient and crop health in a cultivation zone 210. The system 100 is configured to perform crop health monitoring and analysis, including crop leaf health monitoring, crop root health monitoring, plant growth stages, stress and disease monitoring, root growth stages, disease/deficiency monitoring, and exudates monitoring. The system 100 is configured to perform nutrient monitoring and analysis using elemental emission analysis, quantitative chemical composition analysis, including the nutrient levels in the system 100 and specific components of the nutrients. The nutrient monitoring and analysis are done in real-time with onsite monitoring capability and reuseable samples, with no sample preparation required. The analysis may be based on

reference libraries as training data for machine learning models. Machine learning-based classification is applied to help crop phenotyping and disease detection (including customized vegetation indices and spectral indices), in which the spectral information is associated with two-dimensional spatial information to identify the plant. The system 100 may include at least two UV-Vis-NIR (200 nm – 1800 nm) imaging spectroscopes 310, a laser-based elemental emission spectroscopy, and a sample flow cell 610. The system 100 may include automated translation and positioning on rails 320 or robots 290 for large area monitoring.

[00153] Practical Applications

[00154] The proposed system 100 can provide a relatively comprehensive real-time monitoring system specifically suitable for large scale, indoor, vertical farms 200. The system 100 includes plant health monitoring, root health monitoring, and monitoring of the elemental composition of the nutrient supply of the indoor farm 200. The processor may be configured to present a real-time update on the crop health status as well as a real-time update on the status of nutrient supply at the elemental level, with early alerts and control feedbacks provided in the event of a nutrient deficiency or a crop disease/disorder is predicted. A non-limiting exemplary user interface 500 may be configured to provide an electronic status report or control panel as schematically illustrated in **FIG. 19**. The system 100 can provide an on-going, real-time report as the monitoring can be conducted non-invasively and automatically. The system 100 is particularly useful for large-scale vertical farm 200. In the event a crop 900 is showing signs of stress, the system 100 can alert the user to take remedial action. In the example, the liquid nutrient in the cultivation zone 210 can be analyzed down to the elemental level such that adjustment to the composition of the liquid nutrient can be specific to the respective elemental constituents.

[00155] The system 100 described herein enables relatively quick, automated large area monitoring capabilities. The crop health monitoring employed is an image-based technique, and can be used for plant phenotyping that could help in an automatic detection of the crop type and automated selection of the reference libraries. The proposed system 100 can be implemented to fully automate monitoring of the whole farm 200. In addition, the component level (elemental level)

of nutrient supply monitoring capability of the system 100 enables automatic optimization of the liquid nutrient composition at an elemental level such that the farm 200 (which can be made up of a plurality of cultivation units 210 in the farm 200).

[00156] Further, the crop-monitoring method proposed herein is non-contact and non-invasive and does not affect the plants being monitored. The present system 100 enables the detection of plant stresses and plant disease at an early stage so that the proper mitigation strategies can be adopted at right time. The crop health monitoring extends to the root health. Root health is vital to for plant physiology and function. With better monitoring of the roots, crop yield and resource efficiency can be increased.

[00157] The present system 100 may also be implemented to automatically and relatively quickly classify crops, including for post-harvest quality determination of the crop.

[00158] According to various embodiments of the present disclosure, a system for monitoring the crop health and nutrient supply includes: a nutrient monitoring unit. The nutrient monitoring unit includes a sample flow cell, a first optical sensor in combination with a laser, and a spectral analyzer configured to generate an elemental spectral data based on the emission data. The sample flow cell includes a channel connected to the grow tray to receive a sample of the liquid nutrient from the grow tray. The channel defines a flow path extending across a sampling zone. The first optical sensor is disposed to acquire emission data from a laser interaction with the sample flowing in the sampling zone.

[00159] The system may further include at least one imaging spectroscopy unit configured to monitor the non-root part and the root part of the crop to determine a crop health condition of the crop.

[00160] The system may further include a processor. The processor in operation may be in signal communication with a non-transitory memory storing processor-executable instructions which when executed by the processor cause the processor to: determine the respective quantitative measure of each of a plurality of constituent elements in the sample based on the elemental spectral data; and predict a deviation of a sample composition of the sample from a target nutrient

composition using a first machine learning model, the deviation being expressed in terms of a respective quantitative level of deficiency and/or a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample.

[00161] The system may further include a nutrient delivery unit, the nutrient delivery unit being in signal communication with the processor and controllable by the processor to dispense one or more nutrient supplement responsive to the deviation predicted.

[00162] The system may be configured to be responsive to the deviation being a quantitative level of deficiency of any one or more of the plurality of constituent elements in the sample, one or more nutrient supplement is dispensed to the liquid nutrient provided to the crop in the cultivation zone, the one or more nutrient supplement having a supplement composition selected to replenish the one or more of the plurality of constituent elements predicted to have a quantitative level of deficiency.

[00163] The system may be configured to be responsive to the deviation being a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample, in which the nutrient supplement is selected to have a supplement composition selected to form a neutralizing precipitate with the one or more of the plurality of constituent elements predicted to have a quantitative level of toxicity.

[00164] The system may be configured to be responsive to the deviation being a quantitative level of toxicity in any one or more of the plurality of constituent elements in the sample, in which the nutrient delivery unit is configured to add a calculated volume of water to dilute the liquid nutrient.

[00165] The system may be configured to monitor and adjust any two or more of the following constituent elements in the sample: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), magnesium (Mg), carbon (C), oxygen (O), hydrogen (H), iron (Fe), boron (B), chlorine (Cl), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), sodium (Na), and nickel (Ni).

[00166] The system may be configured to monitor changes in the respective quantitative measure of each of the plurality of constituent elements at predetermined time intervals.

[00167] The processor may be caused to predict the crop health condition using a second machine learning model based on an input acquired from the at least one imaging spectroscopy, in which the crop health condition includes any one or more of the following: a growth stage of the crop, a stress condition of the crop, a disorder type of the crop.

[00168] The at least one imaging spectroscopy unit may include: a first imaging spectroscopy and a second imaging spectroscopy. The first imaging spectroscopy may be disposed at the cultivation zone and oriented to acquire leaf images of the non-root part of the crop. The second imaging spectroscopy may be disposed at the cultivation zone apart from the first imaging spectroscopy, with the second imaging spectroscopy being oriented to acquire root images of the root part of the crop, the processor being caused to acquire the leaf images and the root images as the input to the second machine learning model.

[00169] The processor may be configured to determine one or more vegetation indices and one or more spectral signatures of the crop based on a plurality of data cubes acquired by the at least one imaging spectroscopy unit, the plurality of data cubes comprising a plurality of leaf data cubes of the non-root part of the crop and a plurality of root data cubes of the root part of the crop.

[00170] The processor may be configured to determine a root growth, a root disease, and a root extrudate based on the root data cubes.

[00171] The second machine learning model may be trained using one or more reference libraries, each of the one or more reference libraries including training data pertaining to a respective specific crop type.

[00172] The at least one of the one or more reference libraries may include: one or more disorder types associated with the specific crop type; and one or more growth stages associated with the specific crop type.

[00173] The processor may be caused to create the one or more reference libraries, each one of the one or more reference libraries including the elemental spectral data relating to a specific nutrient type.

[00174] The system may further include: one or more environmental sensors configured to obtain measurements of one or more environmental conditions, the one or more environmental sensors including a pH meter configured to measure a

pH of the liquid nutrient in the source; and to provide the measurements of the one or more environmental conditions to the processor as input to the second machine learning model.

[00175] The processor may be further configured to: determine a change, the change being in a spectral data for the crop from the one or more reference spectral libraries or in a spectral data over a period of time; and based on the change, determine a growth stage of the crop and/or determine if the crop is characterized by a deficiency/disorder.

[00176] The sample flow cell may include a rotatable stage controllably rotatable to centrifugally spread out the sample.

[00177] The system may include a user interface which in operation may be in signal communication with the processor to provide an alert/feedback responsive to any one or both of the deviation of the sample composition and the crop health condition.

[00178] The system may include a plurality of the crop in the cultivation zone, in which the at least one imaging spectroscopy unit may be coupled to a robot, the robot being controllable by the processor to acquire a plurality of leaf data cubes and a plurality of root data cubes of respective ones of the plurality of the crop.

[00179] The nutrient monitoring unit may be configured to discard or recycle the sample downstream of the sampling zone.

[00180] The cultivation zone may include a crop support and a grow tray. The crop support is configured to support the crop. The non-root part of the plurality of the crop is at least partially disposed to be exposable to a light source. The grow tray is placed under the crop support. The grow tray is configured to collect a first volume of the liquid nutrient. The liquid nutrient is provided to the root part of the crop.

[00181] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding, and are not intended to be limiting or exhaustive. Modifications may be made by one of ordinary skill in the art without departing from the scope of the claimed invention.

CLAIMS

1. A system for monitoring a crop and nutrient supply in a cultivation zone, comprising:

a nutrient monitoring unit, comprising:

a sample flow cell, the sample flow cell including a channel configured to receive a sample of a liquid nutrient from the cultivation zone, the channel defining a flow path extending across a sampling zone;

a first optical sensor in combination with a laser, the first optical sensor being disposed to acquire emission data from the laser interaction with the sample flowing in the sampling zone; and

a spectral analyzer, the spectral analyzer being configured to generate an elemental spectral data based on the emission data.

2. The system as recited in claim 1, further comprising at least one imaging spectroscopy unit, the at least one imaging spectroscopy unit being configured to monitor a non-root part and a root part of the crop to determine a crop health condition of the crop.

3. The system as recited in claim 2, further comprising:

a processor, the processor in operation being in signal communication with a non-transitory memory storing processor-executable instructions which when executed by the processor cause the processor to:

determine the respective quantitative measure of each of a plurality of constituent elements in the sample based on the elemental spectral data; and

predict a deviation of a sample composition of the sample from a target nutrient composition using a first machine learning model, the deviation being expressed in terms of a respective quantitative level of deficiency and/or a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample.

4. The system as recited in claim 3, further comprising a nutrient delivery unit, the nutrient delivery unit being in signal communication with the processor and controllable by the processor to dispense one or more nutrient supplement responsive to the deviation predicted.

5. The system as recited in claim 4, responsive to the deviation being a quantitative level of deficiency of any one or more of the plurality of constituent elements in the sample, one or more nutrient supplement is dispensed to the liquid nutrient provided to the crop in the cultivation zone, the one or more nutrient supplement having a supplement composition selected to replenish the one or more of the plurality of constituent elements predicted to have a quantitative level of deficiency.

6. The system as recited in claim 4, responsive to the deviation being a quantitative level of toxicity of any one or more of the plurality of constituent elements in the sample, the nutrient supplement is selected to have a supplement composition selected to form a neutralizing precipitate with the one or more of the plurality of constituent elements predicted to have a quantitative level of toxicity.

7. The system as recited in claim 3, responsive to the deviation being a quantitative level of toxicity in any one or more of the plurality of constituent elements in the sample, the nutrient delivery unit is configured to add a calculated volume of water to dilute the liquid nutrient.

8. The system as recited in any one of claims 3 to 7, wherein the plurality of constituent elements in the sample comprise any two or more of the following: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), magnesium (Mg), carbon (C), oxygen (O), hydrogen (H), iron (Fe), boron (B), chlorine (Cl), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), sodium (Na), and nickel (Ni).

9. The system as recited in any one of claims 3 to 8, wherein the system may be configured to monitor changes in the respective quantitative measure of each of the plurality of constituent elements at predetermined time intervals.

10. The system as recited in any one of claims 2 to 9, wherein the processor is caused to predict the crop health condition using a second machine learning model based on an input acquired from the at least one imaging spectroscopy, the crop health condition comprising any one or more of the following: a growth stage of the crop, a stress condition of the crop, a disorder type of the crop.

11. The system as recited in claim 10, the at least one imaging spectroscopy unit comprising:

a first imaging spectroscopy, the first imaging spectroscopy being disposed at the cultivation zone and oriented to acquire leaf images of the non-root part of the crop; and

a second imaging spectroscopy, the second imaging spectroscopy being disposed at the cultivation zone apart from the first imaging spectroscopy, the second imaging spectroscopy being oriented to acquire root images of the root part of the crop, the processor being caused to acquire the leaf images and the root images as the input to the second machine learning model.

12. The system as recited in claim 11, wherein the processor is configured to determine one or more vegetation indices and one or more spectral signatures of the crop based on a plurality of data cubes acquired by the at least one imaging spectroscopy unit, the plurality of data cubes comprising a plurality of leaf data cubes of the non-root part of the crop and a plurality of root data cubes of the root part of the crop.

13. The system as recited in claim 12, wherein the processor is configured to determine a root growth, a root disease, and a root extrudate based on the root data cubes.

14. The system as recited in any one of claims 10 to 13, wherein the second machine learning model is trained using one or more reference libraries, each of the one or more reference libraries comprising training data pertaining to a respective specific crop type.

15. The system as recited in claim 14, wherein at least one of the one or more reference libraries comprise: one or more disorder types associated with the specific crop type; and one or more growth stages associated with the specific crop type.

16. The system as recited in claim 14, wherein the processor is caused to create the one or more reference libraries, each one of the one or more reference libraries comprising the elemental spectral data relating to a specific nutrient type.

17. The system as recited in any one of claims 10 to 16, further comprising:
one or more environmental sensors configured to obtain measurements of one or more environmental conditions, the one or more environmental sensors including a pH meter configured to measure a pH of the liquid nutrient in the source;
and
providing the measurements of the one or more environmental conditions to the processor as input to the second machine learning model.

18. The system as recited in claim 14, the processor being further configured to:
determine a change, the change being in a spectral data for the crop from the one or more reference spectral libraries or in a spectral data over a period of time;
and
based on the change, determine a growth stage of the crop and/or determine if the crop is characterized by a deficiency/disorder.

19. The system as recited in claim 1, wherein the sample flow cell comprises a rotatable stage, the rotatable stage being controllably rotatable to centrifugally spread out the sample.

20. The system as recited in claim 3, further comprising a user interface, the user interface in operation being in signal communication with the processor to provide an alert/feedback responsive to any one or both of the deviation of the sample composition and the crop health condition.

21. The system as recited in claim 2, comprising a plurality of the crop in the cultivation zone, wherein the at least one imaging spectroscopy unit is coupled to a robot, the robot being controllable by the processor to acquire a plurality of leaf data cubes and a plurality of root data cubes of respective ones of the plurality of the crop.

22. The system as recited in any one of claims 1 to 21, wherein the nutrient monitoring unit is configured to discard or recycle the sample downstream of the sampling zone.

23. The system as recited in any one of claims 1 to 22, comprising:

a crop support, the crop support being configured to support the crop, the non-root part of the plurality of the crop being at least partially disposed to be exposable to a light source; and

a grow tray, the grow tray being disposed under the crop support, the grow tray being configured to collect a first volume of the liquid nutrient, the liquid nutrient being provided to the root part of the crop.