

METHOD AND APPARATUS FOR ESTABLISHING PARTIAL ROOT ZONE DRYING IN SOILLESS HYDROPONICS

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FIELD OF INVENTION

[0001] This disclosure generally relates to hydroponics, in particular to an apparatus and method for establishing partial root zone drying (PRD) in hydroponics for improving plant root systems.

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BACKGROUND OF INVENTION

[0002] Agriculture uses nearly 70% of global water supply and the ever-growing problem of water scarcity impacts food production for the rapidly increasing world population. One of the more effective methods of fixing this problem is hydroponic farming. As most hydroponics systems are closed and recycle water, they are 90% more efficient in water usage. Moreover, hydroponic plants can be grown in multitier, which increases production 3-10 times in the same amount of space.

[0003] Farmers around the world are constantly striving to improve the vegetative growth, yield, and concentration of health-promoting compounds in vegetables. Although a range of external factors including light intensity and temperature can influence plant growth and nutrient profile, root health is one of the primary factors that influences plant growth, yield, accumulation of micro- and macro- nutrients and senescence. Healthy roots can take up more nutrients from soil and increased availability of nutrients could improve vegetative growth, enhance the levels of health-promoting compounds as well as delay senescence.

[0004] Root morphology and growth conditions are critical factors that improve plant growth, yield, nutrient use efficiency, antioxidant activity, and shelf-life. In soil-grown-plants, PRD has been reported to produce more lateral roots and root hairs resulting in denser and healthier roots.

[0005] PRD is a well-known natural phenomenon in which one half of the root zone is left to dry while the other half is watered. Dry part of the roots signal to shoot for partial stomata

closure leading to the narrowing of the stomatal opening and reduced water loss. Promotion of root growth and development and greater root biomass under PRD conditions have been implicated in increasing nutrient uptake capacity of the roots. In addition, PRD increases fruit size in mango, improves anthocyanin concentrations in wines and promotes crop maturity in tomato. Thus, PRD plants not only have better water use efficiency (WUE), improved nutrient use, and yield, but also produce food with enhanced nutritive and health characteristics.

[0006] Despite the dramatic increase in use of hydroponics systems for crop cultivation, most studies have focused mainly on the effect of light intensity, temperature and aeration for improved plant growth and increased yield. PRD's effects on growth and nutritional values of hydroponic plants is largely unknown.

[0007] Air pruning is an alternative method for producing denser roots. However, air pruning works best for soil-based systems. Hence, there is a need to establish effective systems and methods for improving roots of plants growing in hydroponic systems that can also be beneficial in plant growth and development.

SUMMARY OF INVENTION

[0008] Accordingly, the present invention, in one aspect, is an apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics. The apparatus contains a substrate configured for growing plants and comprising a planting material other than soil, and a porous material at least partially covering the first portion of the substrate and in contact with air. The substrate includes a first portion and a second portion aligned along a longitudinal direction of the substrate. Pores of the porous material are adapted to expose a portion of traversing roots of a plant grown in the substrate to air, thereby establishing a partial root zone drying for improving roots of the plant.

[0009] In some embodiments, the porous material is adapted to allow at least part of the traversing roots of the plant to grow therethrough.

[0010] In some embodiments, the porous material completely wraps around the substrate around a central axis of the substrate that is parallel to the longitudinal direction.

[0011] In some embodiments, the porous material is urged against the substrate.

[0012] In some embodiments, the porous material is hydrophobic.

[0013] In some embodiments, the planting material is hydrophilic.

[0014] In some embodiments, the porous material is chosen from the group consisting of
5 hydrophobic sponge, clay and plastic beads.

[0015] In some embodiments, the planting material is selected from the group consisting of rockwool, peat, perlite, hydrophilic sponge and polyurethane.

[0016] In some embodiments, the apparatus further includes a container in which the porous material is accommodated. The container contains a surface that at least partially
10 covers the first portion of the substrate.

[0017] In some embodiments, the porous material contains clay and/or plastic beads. The clay and/or plastic beads is accommodated in the container to keep a shape of the porous material.

[0018] In some embodiments, the second portion of the substrate is immersed into a nutrient solution, and is adapted to allow a taproot of the plant to grow therealong to contact
15 the nutrient solution.

[0019] In some embodiments, the porous material contains a first piece and a second piece which are separate from each other.

[0020] In some embodiments, the porous material is in a hollow cylindrical shape or a
20 polygonal shape.

[0021] In a further aspect of the invention, there is provided a system for establishing partial root zone drying to improve plant roots in soilless hydroponics. The system contains a receptacle adapted to hold a nutrient solution, and one or more apparatus as mentioned above. A second portion of a substrate in each of the one or more apparatus is in contact
25 with the nutrient solution.

[0022] In some embodiments, a porous material in each of the one or more apparatus are separated from the nutrient solution.

[0023] According to another aspect of the invention, there is provided a method for establishing partial root zone drying to improve plant roots in soilless hydroponics. The method contains the steps of providing a substrate for growing plants, where the substrate includes a planting material other than soil. The substrate also contains a first portion and a second portion aligned along a longitudinal direction of the substrate. The method further includes the steps of covering at least partially the first portion of the substrate using a porous material, transplanting a plant in the substrate, and exposing a portion of traversing roots of the plant to air through the porous material, thereby establishing a partial root zone drying for improving roots of the plant.

[0024] In some embodiments, the method further contains the step of growing at least a part of the traversing roots of the plant through the porous material.

[0025] In some embodiments, the covering step further includes completely wrapping the porous material around the substrate.

[0026] In some embodiments, the porous material contains a first piece and a second piece which are separate from each other. The covering step further contains assembling the first and second pieces together before or during the wrapping step.

[0027] According to another aspect of the invention, there is provided a system for establishing partial root zone drying to improve plant roots in soilless hydroponics. The system includes a planting material other than soil for growing plants, and a length of porous material wrapped around a top portion of the planting material. Air trapped in the pores of the porous material exposes a portion of traversing roots of a plant grown in the planting material to air thereby establishing a partial root zone drying for improving plant root system.

[0028] In some embodiments, growing roots of the plant growing in the planting material grow through the porous material.

[0029] In some embodiments, a middle portion of the roots is exposed to air deprived of water and nutrients.

[0030] In some embodiments, the deprivation of water and nutrient to the roots establishes partial root zone drying thereby inducing formation of secondary and lateral roots.

5 [0031] In some embodiments, the porous material is tightly wrapped around the plant growing material.

[0032] In some embodiments, the porous material is hydrophobic in nature.

[0033] In some embodiments, the porous material is chosen from hydrophobic sponge, or any other functionally equivalent material, optionally clay or plastic beads.

10 [0034] In some embodiments, the clay or plastic beads are tightly packed in a container around the planting material.

[0035] In some embodiments, the planting material is rockwool, peat, perlite, hydrophilic sponge, polyurethane or equivalent.

[0036] In some embodiments, the system is positioned in a receptacle adapted to hold
15 liquid for plant nutrition.

[0037] In some embodiments, the liquid is a solution of plant nutrients, water.

[0038] In some embodiments, the plant nutrient solution is half strength in comparison to a regular plant nutrition.

[0039] In some embodiments, only a basal end of the planting material contacts the nutrient
20 medium.

[0040] In some embodiments, the planting material and the hydrophobic sponge have a common central axis.

[0041] In some embodiments, the medium and the hydrophobic material are vertically disposed against each other.

[0042] In some embodiments, roots growing through the hydrophobic sponge are exposed to dry air, deficient of any water or nutrition within the hydrophobic material.

[0043] In some embodiments, the system can be used for producing dense roots in plants in hydroponics.

5 [0044] In some embodiments, the system can be used for delaying senescence in hydroponics.

[0045] In some embodiments, the system can be used for producing plants with improved fresh weight, antioxidants and nutrients.

10 [0046] In some embodiments, the system can be used for producing improved root systems on half-strength plant nutrition or water.

[0047] In some embodiments, the system can be used for producing plants with higher nitrogen, phosphorus, potassium, calcium, magnesium, copper, iron, zinc, total chlorophyll and reduced levels of senescence response genes ORE1, RNS3, SINA1, SAG29 and VNI2.

15 [0048] According to a further aspect of the invention, there is provided a method for establishing partial root zone drying to improve plant roots in soilless hydroponics. The method includes the steps of providing a planting material other than soil for growing plants, providing a length of porous material wrapped around a top portion of the planting material, and transplanting a plant in the planting material. Air trapped in the pores of the porous material exposes a portion of traversing roots of a plant grown in the planting material to
20 air thereby establishing a partial root zone drying for improving plant root system.

[0049] In some embodiments, growing roots of the plant growing in the planting material grow through the porous material.

[0050] In some embodiments, a middle portion of the roots are exposed to air deprived of water and nutrients.

25 [0051] In some embodiments, the deprivation of water and nutrient to the roots establishes partial root zone drying thereby inducing formation of secondary and lateral roots.

[0052] In some embodiments, the porous material is tightly wrapped around the plant growing material.

[0053] In some embodiments, the porous material is hydrophobic in nature.

[0054] In some embodiments, the porous material is chosen from hydrophobic sponge, or
5 any other functionally equivalent material, optionally clay or plastic beads.

[0055] In some embodiments, the clay or plastic beads are tightly packed in a container around the planting material.

[0056] In some embodiments, the planting material is rockwool, peat, perlite, hydrophilic sponge, polyurethane or equivalent.

10 [0057] In some embodiments, the planting material positioned in a receptacle adapted to hold liquid for plant nutrition.

[0058] In some embodiments, the liquid is a solution of plant nutrients, water.

[0059] In some embodiments, the plant nutrient solution is half strength in comparison to a regular plant nutrition.

15 [0060] In some embodiments, only a basal end of the planting material contacts the nutrient medium.

[0061] In some embodiments, the planting material and the hydrophobic sponge have a common central axis.

[0062] In some embodiments, the medium and the hydrophobic material are vertically
20 disposed against each other.

[0063] In some embodiments, roots growing through the hydrophobic sponge are exposed to dry air, deficient of any water or nutrition within the hydrophobic material.

[0064] In some embodiments, the method can be used for producing dense roots in plants in hydroponics.

[0065] In some embodiments, the method can be used for delaying senescence in hydroponics.

[0066] In some embodiments, the method can be used for producing plants with improved fresh weight, antioxidants and nutrients.

- 5 [0067] In some embodiments, the method can be used for producing improved root systems on half-strength plant nutrition or water.

[0068] In some embodiments, the method can be used for producing plants with higher nitrogen, phosphorus, potassium, calcium, magnesium, copper, iron, zinc, total chlorophyll and reduced levels of senescence response genes ORE1, RNS3, SINA1, SAG29 and VNI2.

- 10 [0069] According to a further embodiment of the invention, there is provided a kit for establishing partial root zone drying to improve plant roots in soilless hydroponics. The kit includes a planting material other than soil for growing plants, and a length of porous material to be wrapped around a top portion of the planting material. Air trapped in the pores of the porous material exposes a portion of traversing roots of a plant grown in the
15 planting material to air thereby establishing a partial root zone drying for improving plant root system.

[0070] In some embodiments, growing roots of the plant growing in the planting material grow through the porous material.

- [0071] In some embodiments, a middle portion of the roots are exposed to air deprived of
20 water and nutrients.

[0072] In some embodiments, the deprivation of water and nutrient to the roots establishes partial root zone drying inducing formation of secondary and lateral roots.

[0073] In some embodiments, the porous material is tightly wrapped around the plant growing material.

- 25 [0074] In some embodiments, the porous material is hydrophobic in nature.

[0075] In some embodiments, the porous material is chosen from hydrophobic sponge or any other functionally equivalent, clay or plastic beads.

[0076] In some embodiments, the clay or plastic beads are tightly packed in a container around the planting material.

- 5 [0077] In some embodiments, the planting material is rockwool, peat, perlite, hydrophilic sponge, polyurethane or equivalent.

[0078] In some embodiments, the planting material positioned in a receptacle adapted to hold liquid for plant nutrition.

[0079] In some embodiments, the liquid is a solution of plant nutrients, water.

- 10 [0080] In some embodiments, the plant nutrient solution is half strength in comparison to a regular plant nutrition.

[0081] In some embodiments, only a basal end of the planting material contacts the nutrient medium.

- 15 [0082] In some embodiments, the planting material and the hydrophobic sponge have a common central axis.

[0083] In some embodiments, the medium and the hydrophobic material are vertically disposed against each other.

[0084] In some embodiments, roots growing through the hydrophobic sponge are exposed to dry air, deficient of any water or nutrition within the hydrophobic material.

- 20 [0085] In some embodiments, the kit can be used for producing dense roots in plants in hydroponics.

[0086] In some embodiments, the kit can be used for delaying senescence in hydroponics.

[0087] In some embodiments, the kit can be used for producing plants with improved fresh weight, antioxidants and nutrients.

[0088] In some embodiments, the kit can be used for producing improved root systems on half-strength plant nutrition or water.

[0089] In some embodiments, the kit can be used for producing plants with higher nitrogen, phosphorus, potassium, calcium, magnesium, copper, iron, zinc, total chlorophyll and reduced levels of senescence response genes ORE1, RNS3, SINA1, SAG29 and VNI2.

[0090] According to another aspect of the invention, there is provided a use of one or more of the apparatus, the method, and the kit as mentioned above, for establishing partial root zone drying for improving root systems of plants growing in a hydroponic farm system.

[0091] According to another aspect of the invention, there is provided a hydroponic planter for growing plants. The hydroponic planter includes a hydrophilic planting material for absorbing a hydroponic solution to grow the plants, and a hydrophobic porous layer surrounding an upper portion of the hydrophilic planting material. The hydrophobic porous layer is for exposing lateral roots of the plants to air in the hydrophobic porous layer, thereby air drying the lateral roots as the lateral roots grow towards the hydroponic solution.

[0092] Beneficial effects of PRD are evident in improved nutrient uptake, crop yield, and better commercial value may be achieved using the hydroponic sponge according to embodiments of the invention.

[0093] The foregoing summary is neither intended to define the invention of the application, which is measured by the claims, nor is it intended to be limiting as to the scope of the invention in any way.

BRIEF DESCRIPTION OF FIGURES

[0094] The foregoing and further features of the present invention will be apparent from the following description of embodiments which are provided by way of example only in connection with the accompanying figures, of which:

[0095] Fig. 1 shows an apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics, according to a first embodiment of the invention.

[0096] Fig. 2a shows a conventional hydroponic system which contains multiple hydroponic plant growing apparatuses.

5 [0097] Fig. 2b shows a PRD hydroponic system which contains multiple hydroponic plant growing apparatuses, according to another embodiment of the invention.

[0098] Fig. 3a shows the photo of a conventional hydroponic plant growing apparatus in an experimental setup.

10 [0099] Fig. 3b shows the photo of a hydroponic plant growing apparatus made according to that shown in Fig. 1, in the experimental setup.

[0100] Fig. 4a is a photo showing multiple conventional hydroponic plant growing apparatuses as that shown in Fig. 3a located in a receptacle in the experimental setup.

[0101] Fig. 4b is a photo showing multiple hydroponic plant growing apparatuses as that shown in Fig. 3b located in a receptacle in the experimental setup.

15 [0102] Fig. 5a is a photo showing the growth of roots of a plant grown on the conventional hydroponic plant growing apparatus as that shown in Fig. 3a in the experimental setup.

[0103] Fig. 5b is a photo showing the growth of roots of a plant grown on the hydroponic plant growing apparatus as that shown in Fig. 3b in the experimental setup.

20 [0104] Fig. 6a illustrates photos of pak choi grown respectively on a “control” apparatus as shown in Fig. 3a and a “partial root zone drying” apparatus as shown in Fig. 3b, in another experimental setup.

[0105] Fig. 6b is chart showing shoot weights of the pak choi grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

25 [0106] Fig. 6c is chart showing number of leaves of the pak choi grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

[0107] Fig. 6d is chart showing some nutrition contents of the pak choi grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

[0108] Fig. 6e is chart showing some other nutrition contents of the pak choi grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

5 [0109] Fig. 7a shows photos of post-harvest senescence of the pak choi grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

[0110] Fig. 7b is a chart showing qRT-PCR analysis of senescence response genes of two leaves of the pak choi grown on the “partial root zone drying” apparatus.

[0111] Fig. 7c is a chart showing the total chlorophyll content of the pak choi grown
10 respectively on the “control” apparatus and the “partial root zone drying” apparatus.

[0112] Fig. 8a is a chart showing the total flavonoid content of the pak choi grown respectively on the “control” apparatus and the “partial root zone drying” apparatus.

[0113] Fig. 8b is a chart showing the DPPH inhibition of the pak choi grown respectively on the “control” apparatus and the “partial root zone drying” apparatus.

15 [0114] Fig. 9a illustrates photos of choy sum grown respectively on a “control” apparatus as shown in Fig. 3a and a “partial root zone drying” apparatus as shown in Fig. 3b, in a further experimental setup.

[0115] Fig. 9b illustrates photos of leaves in the choy sum grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

20 [0116] Fig. 9c is chart showing fresh shoot weight of the choy sum grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

[0117] Fig. 9d is chart showing number of leaves of the choy sum grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

[0118] Fig. 9e is chart showing DPPH inhibition of the choy sum grown respectively on
25 the “control” apparatus and on the “partial root zone drying” apparatus.

[0119] Fig. 9f is chart showing total chlorophyll content of the choy sum grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

[0120] Fig. 9g shows photos of post-harvest senescence of the choy sum grown respectively on the “control” apparatus and on the “partial root zone drying” apparatus.

5 [0121] Fig. 10 shows an apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics, according to a further embodiment of the invention.

[0122] Fig. 11a shows an apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics, according to a further embodiment of the invention.

10 [0123] Fig. 11b is an exploded view showing two pieces of a porous material in the apparatus of Fig. 11a.

[0124] Fig. 12 shows an apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics, according to a further embodiment of the invention.

[0125] Fig. 13 shows an apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics, according to a further embodiment of the invention.

15 [0126] In the drawings, like numerals indicate like parts throughout the several embodiments described herein.

DETAILED DESCRIPTION

[0127] For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to apparatuses, systems and methods for establishing partial root zone drying in plants for improving the plant root systems, 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 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 statements. 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 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 disclosure.

[0128] 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, 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 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.

[0129] 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. 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 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 on their associated terms.

[0130] Terms such as “horizontal”, “vertical”, “upwards”, “downwards”, “above”, “below” and similar terms as used herein are for the purpose of describing the invention in its normal in-use orientation and are not intended to limit the invention to any particular orientation.

[0131] Referring now to Fig. 1, the first embodiment of the present invention is an apparatus **20** that can be used for establishing partial root zone drying to improve plant roots in soilless hydroponics. The apparatus **20** is adapted to grow a plant (not shown) thereon. The apparatus **20** contains a substrate **22** on which the plant can be grown upward in the direction shown in Fig. 1, while a taproot of the plant grows substantially downward within the substrate **22** and may even extend out of the substrate **22**. The substrate **22** has a substantially cylindrical shape, and is composed of a planting material other than soil. The planting material is preferably hydrophilic which possesses high water storage capacity, and for example it can be rockwool, peat, perlite, hydrophilic sponge, polyurethane or their equivalent. On the other hand, there is a length of porous material **24** wrapping around the substrate **22**, and in particular around a central axis **26** of the substrate **22**, and the porous material **24** is thus in a hollow cylindrical shape. The porous material **24** and the substrate **22** are concentrically arranged. The central axis **26** is parallel to a longitudinal direction of the substrate **22**, along which the substrate **22** can be divided roughly into two portions, namely a first portion **22a** and a second portion **22b**, which are aligned along the longitudinal direction. The first portion **22a** is substantially surrounded

by the porous material **24**, while the second portion **22b** is not. The porous material **24** has a radially inward circumferential surface (not shown) that is directly in contact with the substrate **22**, while a radially outward circumferential surface **24a** of the porous material **24** is exposed to and in contact with air. As such, pores of the porous material (not shown) are adapted to expose any portion of roots of a plant grown in the substrate that entered the porous material **24** to air, thereby establishing a partial root zone drying for improving roots of the plant as will be described in more details later.

[0132] Next, Fig. 2b shows a soilless hydroponic system **130** containing a plurality of PRD plant growing apparatus **120**, each of which may be identical or similar to the one shown in Fig. 1. For comparison purposes, a conventional hydroponic system **230** containing plant growing apparatuses is shown in Fig. 2a. In the system **130**, there is a receptacle **132** having a cross-sectional shape like an inverted trapezoid. At the bottom portion of the receptacle **132** that forms a basin, there is a nutrition solution **138** accommodated. The multiple apparatuses **120** each has a substrate **122** which contains a second, lower portion **122b**. As shown in Fig. 2b, all the second portions **122b** of the apparatuses **120** are at least partially immersed in the nutrition solution **138**. However, a porous material **124** in each of the apparatuses **120** which wraps around a first, upper portion (not shown) of the substrate **122** is away from the nutrition solution **138**. A top surface (not shown) of each of the apparatuses **120** is flush with a top surface **132a** of the receptacle. Thus, from the top surface **132a**, plants **134** planted in each of the apparatuses **120** have their stem and leaves growing upward.

[0133] Fig. 2b also shows roots of the plant **134** in an apparatus **120**, which include a taproot **134a** and multiple traversing roots **134b** (also referred to as lateral roots). The traversing direction refers to directions substantially lateral to a growing direction of the plant **134**, which is parallel to the longitudinal direction of the apparatus **120**. The roots of the plant **134** have ready accessibility to the nutrition solution **138** as shown Fig. 2b because of the substrate **122** which is hydrophilic. Nonetheless, Fig. 2b shows that at least a middle portion of the traversing roots **134b** as they extend from the taproot **134a** go into the porous material **124**, and some even penetrate and extend out of the porous material **124** radially outward, the free ends of which being exposed in the air as a result. As the middle zone of

lateral roots is exposed to air which is completely deprived of water and nutrients, formation of new lateral roots and root hairs are initiated by partial root zone drying as shown in Fig. 2b.

[0134] In comparison, in the prior art soilless hydroponic system **230** as shown in Fig. 2a, each plant growing apparatus **220** simply has a basket-like container **224** in which a planting material **222** is held. The container **224** is almost fully immersed in a nutrition solution **238**. One can see that traversing roots **234b** of a plant **234** planted in a plant growing apparatus **220** all grow out of the planting material **222** and extend into the nutrition solution **238**, so they are not exposed to air or are dry.

[0135] An experimental setup intended to compare the outcome of plant growth in a “control” apparatus as the plant growing apparatus **220** in Fig. 2a, and in a “partial root zone drying” apparatus as the plant growing apparatus **120** in Fig. 2b, will now be described. The photos of the “control” apparatus and the “partial root zone drying” apparatus are shown in Figs. 3a and 3b respectively, and one can see that they are of similar dimensions. For the “control” apparatus, rockwool was placed inside a perforated plastic pot and placed in one of the holes of a hydroponic tray (used as a receptacle) containing the nutrient solution. 1-week-old seedlings of are transferred to the center of the rockwool and grown for 4 weeks. A top view of the hydroponic tray and six “control” apparatuses is provided in Fig. 4a. As the roots of “control” plants grown on the “control” apparatus as shown in Figs. 3a and 4a grow out of the rockwool, a photo of which is provided in Fig. 5a, they enter the nutrient solution.

[0136] For the “partial root zone drying” apparatus, two vertically placed rockwools are surrounded by a hydrophobic material, for example, sponge, herein held together using surgical tape, and inserted into the holes of a hydroponic tray (used as a receptacle) containing the nutrient solution. The surgical tape thus urges the hydrophobic material onto the rockwools. Usually 1-week-old seedlings are transferred to the centre of the rockwool and grown for 4 weeks. After harvest, the hydroponic tray can be washed and reused. A top view of the hydroponic tray and six “partial root zone drying” apparatuses is provided in Fig. 4b. The PRD plant grown in the “partial root zone drying” apparatus is subjected to

partial root-zone drying with the help of the hydrophobic material which is porous, i.e., the material should not absorb and retain water / nutrient medium within when in contact with the water / nutrient medium, allow growing plant roots to grow through the porous material while providing support to the growing roots and exposing roots to air when not in contact with water / nutrient medium. A photo of the roots of the PRD plant is provided in Fig. 5b, from which one can see that upon entering the hydrophobic sponge, the root tips of the PRD plant are exposed to air and are deprived of water and nutrients. The dry root-zone would then instigate the formation of new lateral roots and root hairs. As the traversing roots grow and enter the hydrophobic sponge, the traversing roots are partially exposed to air in the sponge. Air-exposed roots are not only deprived of water but also of nutrients due to their inaccessibility to the nutrient solution while penetrating the hydrophobic sponge. Since the roots enter the nutrient solution upon crossing the sponge, a small portion of each root experiences drought stress and nutrient deficiency at all times.

[0137] The hydrophobic sponge provides a dry drought-like medium for the exposed roots so that they can be dried before they continue growing towards the nutrient solution. With the hydrophobic sponge, roots are more likely to grow laterally out of the hydrophilic planting material (e.g. the rockwool) into the hydrophobic sponge, thereby exposing the lateral roots to dry conditions and producing more lateral and secondary roots. Without the hydrophobic sponge, the roots are more likely to grow along the wet surface of the hydrophilic planting material and are less likely to dry. This is because of typical root behavior wherein the root tips look for water and continue to grow in the direction of water.

[0138] Yield, nutritional value and nutrient use efficiency of PRD plants were better than control plants

[0139] To test the yield, nutritional value, and nutrient use efficiency of PRD in hydroponic plants, the preferred leafy vegetable, pak choi plants are grown under existing hydroponic system as control and PRD system with normal or half concentration medium (see Fig. 6a). Even though the pak choi plants grown under control and PRD conditions exhibited similar progression of growth and development as shown in Fig. 6a, PRD plants grown under normal concentration medium bear higher number of leaves and higher shoot biomass than

control and PRD plants of half concentration medium (see Figs. 6b and 6c). The ten macro- and micro- nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) are analyzed. Eight (8) nutrients except for B and Mn are recorder higher in PRD plants in comparison to control plants, and, no significant difference is observed in 3 macro-nutrient analysis (N, P and K) between PRD-normal and PRD-half medium plants. (see Figs. 6d and 6e). In addition, the total flavonoid content and antioxidant activity are also significantly higher in PRD plants when compared to control plants (see test results in Figs. 8a and 8b). Apart from pak choi, choy sum plants, which also belongs to brassica family, and grown under PRD conditions, also showed more leaves, better shoot biomass, and increased antioxidant capacity compared to control plants (see Figs. 9a-9e).

[0140] Effects of the PRD conditions on the growth and nutrient profile of preferred pak choi plants is illustrated in Figs. 6a-6e wherein comparison of fresh shoot weight (Fig. 6b), number of leaves (Fig. 6c), macronutrient content (Fig. 6d) and micronutrient content (Fig. 6e) in control and PRD plants grown under normal concentration medium (denoted as Control-N and PRD-N, respectively) and PRD plants grown under half concentration medium (denoted as PRD-H). N, nitrogen; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Mn, manganese; and Zn, zinc is performed. Data are shown as mean $\pm$ SD of six (Figs. 6b and 6c), and three (Figs. 6d and 6e) biological replicates. Statistical significance of the measurements was determined by Student's *t*-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). *P* values are given in Table 1 below.

	PRD-N	PRD-H
Shoot Weight	0.000986	0.332237
Number of leaves	0.009964	0.284627
N	0.00264	0.00619
P	0.026576	0.000000872
K	0.0000933	0.002017
Ca	0.264301	0.010583

Mg	0.231931	0.031042
B	0.123002	0.096616
Cu	0.154849	0.000846
Fe	0.055723	0.001509
Mn	0.036981	0.000832
Zn	0.019549	0.004441

Table 1

[0141] PRD influences senescence of pak choi plants are shown in Fig. 7a. Visual appearance of control and PRD shoots during dark storage at 22°C for 2 weeks, i.e., D0-D14 (day 0 – day 14). Six biological replicates were used for the experiment and two representatives are shown here. Fig. 7b shows a qRT-PCR analysis of senescence marker genes expression in leaf #3 and leaf #4 of 5-week-old pak choi plants grown under control and PRD conditions. *ACTIN2* expression was used as an internal control. Data are shown as mean $\pm$ SD of three biological and three technical replicates. Fig. 7c depicts comparison of total chlorophyll content in control and PRD plants. Leaves were divided into 3 groups (leaves 1-6, 7-12 and 13-18, numbered from bottom). Data are shown as mean $\pm$ SD of six biological replicates and three technical replicates. Statistical significance of the measurements was determined by Student's *t*-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). *P* values are given in Table 2.

Leaf #3	<i>ORE1</i>	0.00355
	<i>RNS3</i>	0.00146
	<i>SINA1</i>	0.01266
	<i>SAG29A</i>	0.00036
	<i>VNI2</i>	0.00286
Leaf #4	<i>ORE1</i>	0.00109
	<i>RNS3</i>	0.00298

	<i>SINA1</i>	0.01462
	<i>SAG29A</i>	0.00105
	<i>VNI2</i>	0.00361
Total chlorophyll content	1-6	0.03698
	7-12	0.00000
	13-18	0.00628

Table 2

[0142] Partial root-zone drying delayed post-harvest senescence

[0143] Initiation of developmental senescence in 5-week-old control plants but no visible sign of yellowing in the leaves of PRD plants was observed, indicating a delayed developmental senescence (see D0 in Fig. 7a). First yellowing phenotype of old leaves showed in the PRD plants at 10 days (see D10) of post-harvest storage at 22°C under dark condition (see Fig. 7a). In addition, a delayed senescence was also observed in PRD choy sum plants (see Fig. 9g). To confirm the correlation between senescence phenotype and marker gene expression, qRT-PCR analysis of senescence response genes such as *ORE1*, *RNS3*, *SINA1*, *SAG29* and *VNI2* was conducted. The transcript levels of the transcription factor *ORE1*, a positive regulator of age-induced senescence, and its downstream genes *RNS3*, *SINA1*, *SAG29* and *VNI2* were significantly lower in leaf No. 3 and 4 of PRD plants in comparison to control leaves (see Fig. 7b). Correspondingly, PRD pak choi plants as well as PRD choy sum plants possessed higher levels of total chlorophyll than that of control plants (see Fig. 7c and Fig. 9f).

[0144] Nutritional value of control and PRD pak choi plants is illustrated in Figs. 8a and 8b. Comparison of total flavonoid content is provided in Fig. 8a, and comparison of DPPH inhibition is provided in Fig. 8b, for control and PRD plants. Data are shown as mean $\pm$ SD of six biological replicates. Statistical significance of the measurements was determined by student's *t*-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). *P* values are given in Table 3.

Total flavonoid content	0.00065
DPPH inhibition	0.00013

Table 3

[0145] In another experiment setup, whole plant (see Fig. 9a) and leaf arrangement (see Fig. 9b) of 5-week-old control and PRD plants are illustrated. Scale bars in Figs. 9a and 9b are 5cm. In addition, Figs. 9c-9f illustrate comparison of fresh shoot weight (Fig. 9c), number of leaves (Fig. 9d), DPPH inhibition (Fig. 9e), and total chlorophyll content (Fig. 9f) in control and PRD plants. For chlorophyll assay, leaves are divided into two groups (Leaves 1-5 and 6-10) as indicated respectively by Line A and Line B in leaf arrangement of PRD plants (see the bottom part of Fig. 9b). Data are shown as mean $\pm$ SD of eight (Fig. 9c), eleven (Fig. 9d) and six (Figs. 9e and 9f) biological replicates. Statistical significance of the measurements was determined by student's *t*-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). *P* values are given in Table 4.

Shoot weight		0.00080
Number of leaves		0.04704
DPPH inhibition		0.01834
Total chlorophyll content	1-5	0.02167
	6-10	0.72792
DPPH inhibition		0.01834

Table 4

[0146] Root morphology and root function are highly correlated. Plants with well-developed, denser, and healthier root systems are not only more efficient in water and nutrient absorption but also have higher photosynthetic rates. Partial root-zone drying has been shown to improve crop quality and root biomass in many soil-grown-plants. Preferred hydrophilic rockwool substrates surrounded by hydrophobic sponge simulate partial root-zone drying conditions, shoot biomass, flavonoid content, chlorophyll content, antioxidant capacity and levels of macro- and micro-nutrients were significantly increased (see Figs.

6a-9f). Increased shoot biomass could be attributed to the substantial increase in chlorophyll content that improves the photosynthetic capacity. Higher accumulation of flavonoids, phytochemicals with antioxidant capacity and macro- and micro-nutrients in PRD plants can be resulted by more active uptake of nutrients by the mildly stressed roots. Root hairs and lateral roots produced as a response to partial root-zone drying might increase root surface area and aid in nutrient uptake.

[0147] One of the other traits significantly affected in plants that were grown on rockwool surrounded by hydrophobic sponge was the age-induced leaf senescence. PRD plants exhibited late-senescent phenotype, which in several cases has been found to be accompanied by an increased yield and improved quality. Nutrient limitation is a critical factor that induces the onset of senescence in older leaves, which dismantles the functional structures of leaves and generate nutrients that are remobilized to developing organs like young leaves, indicating delayed senescence phenotype of PRD plants might be contributed by the increased availability of nutrients (see Figs. 6d-6e). Especially, consistent with increased Zn ion content in PRD plants which is an antioxidant micro-nutrient, PRD plants have shown higher antioxidant activity than control plants (see Fig. 8b). Furthermore, plants with delayed onset of senescence have shown to have a higher nitrogen-use efficiency than the conventional plants. Thus, delay in leaf senescence of PRD plants may not only prolong the lifespan of leaves but may also improve nutrient use efficiency. Finally, as the delayed-senescent phenotype is an indicative of plant health, it is suggested that PRD plants may have increased tolerance to diseases, pests, and drought. Delayed senescence by root partial zone stress are useful in leafy vegetable cultivation in terms of post-harvest management, mitigating the loss of biomass and commercial value during transportation and storage.

[0148] **Examples**

[0149] Next, some examples of apparatuses, methods and systems for establishing partial root zone drying (PRD) in hydroponics for improving plant root systems according to embodiments of the invention will be briefly discussed, some of which have been described

previously. Experimental setup, analysis principles and methods of grown plants associated with these examples are also briefly discussed below.

[0150] **Material & Methods**

[0151] **Plant materials**

[0152] Pak choi (*Brassica rapa* var. *chinensis*) and choy sum (*Brassica rapa* var. *parachinensis*) seeds were obtained from the authorized sources. The seeds were sterilized and germinated on MS media.

[0153] Preferred plant growth support medium, rockwools were allowed to soak in the hydroponic solution for at least 30 min. 1-week-old seedlings were transferred to the rockwool in a plastic pot (control) and rockwool surrounded by a hydrophobic sponge (PRD) and were grown in a growth chamber at 22°C under white light at 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ with 60% relative humidity in long-day conditions (16 h light/8 h dark). Plants were harvested 4-weeks after transplant and used for all analyses.

[0154] **Example 1**

[0155] In this example, as described above for Figs. 3a-3b, for control plants a length of hydrophilic rockwool was placed in the hydroponic tray using a plastic perforated pot and kept in hydroponic tray (as shown in Fig. 3a). For partial root-zone drying (PRD) setup, one rockwools was placed on top of another rockwool and surrounded by a layer of hydrophobic sponge. The rockwools and hydrophobic sponge were held together using a surgical tape (as shown in Fig. 3d). In use, the tray is filled with a quantity of water / nutritional medium below the level of sponge. Seeds planted in rock wool germinate to produce a shoot and roots. Growing roots traverse through the rockwool, enter the hydrophobic sponge, wherein the growing roots are exposed to air trapped inside the pores of the hydrophobic sponge thereby inducing draught / water stress effects on the roots.

[0156] As the roots grow and enter the hydrophobic sponge, the roots are partially exposed to air in the sponge. Air-exposed roots are not only deprived of water but also of nutrients due to their inaccessibility to the nutrient solution while penetrating the hydrophobic

sponge. Since the roots enter the nutrient solution upon crossing the sponge, a small portion of each root experiences drought stress and nutrient deficiency at all times.

[0157] **Example 2**

[0158] **Total flavonoid content**

[0159] The content of the total flavonoids is determined by the aluminum chloride colorimetric method, which was based on the formation of a complex flavonoid- aluminum (Ordonez et al., 2006). For quantification of total flavonoids, leaf discs were taken from each leaf and extracted using 100% methanol at 4°C in darkness for 24 h. 20 µl of methanol extract was mixed with 60 µl of 100% methanol, 4 µl of 10% aluminum chloride, 4µl of 1M potassium acetate and 112 µl of water. After 30 min incubation at room temperature, the absorbance was measured at 420nm. Final concentrations were calculated from calibration curve obtained from quercetin.

[0160] **Example 3**

[0161] **Antioxidant capacity**

[0162] For antioxidant measurement, leaf discs are taken from each leaf and extracted using 80% acetone at 4 °C in darkness for 24 h. 20 µl of acetone extract was mixed with 180 µl of 0.3mM DPPH in acetone and incubated at room temperature for 2 h. Absorbance at 517 nm was measured using spectrophotometer and DPPH inhibition activity was calculated using $\{(Abs\ control - Abs\ sample) / (Abs\ control)\} \times 100$, where Abs control is the absorbance of DPPH radical + acetone and Abs sample is the absorbance of DPPH radical + sample extract.

[0163] **Example 4**

[0164] **Nutrient analysis**

[0165] For nutrient analysis (N, P, K, Mg, Na, Ca, Mn, Cu, Zn, Fe and B), 150g of freshly harvested leaves were submitted to Animal and Plant Health Centre (APHC), National

Parks of Singapore. All but N were measured using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES). For quantitation of N, CHNS analyzer was used.

[0166] **Example 5**

[0167] **Postharvest senescence**

[0168] For postharvest senescence assay, plants were stored in plastic boxes at 22°C for two weeks under darkness. Images were taken on day 0,3,6,8,10,12 and 14.

[0169] **Example 6**

[0170] **Quantitative real time polymerase chain reaction (qRT-PCR)**

[0171] Total RNA was extracted from frozen crushed crystals of leaves #3 and #4 of control and PRD plants using the Spectrum™ Plant Total RNA Kit (Sigma–Aldrich, St. Louis, MO, USA) according to manufacturer instructions. On column RNase-free DNase I (Qiagen, Hilden, Germany), treatment was carried out to remove the residual genomic DNA. Total RNA was quantified using a NanoDrop 2000 spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA) and stored at –80 °C until use. Complementary DNA (cDNA) was synthesized from 1 µg of the total RNA using iScript RT Supermix (BioRad) according to manufacturer instructions. cDNA was diluted with RNase free water to a final concentration of 10 ng/µL and stored at –20 °C until use.

[0172] qRT-PCR was carried out using SsoAdvanced Universal SYBR Green supermix and CFX Connect Real-Time system (BioRad). A 20 µL reaction mixture was made by adding 1 µL of cDNA, 10 µL of 2 × TAKARA SYBR Premix Ex Taq II, 0.5 µL of 10 µM forward primer, 0.5 µL of 10 µM reverse primer, and 8 µL of water. The plate was covered using a microseal ‘B’ seal (Bio-Rad, Hercules, CA, USA) for optical transparency and centrifuged briefly using a PCR plate spinner (VWR, Radnor, PA, USA). The plate was subjected to the following cycling program: 30 s at 95 °C, followed by 40 cycles of 15 s at 98 °C and 30 s at 60 °C; then final ramping to 95 °C at the rate of 0.5 °C/5 s for melting curve analysis. For verification of a single product amplification, both melting curve analysis and gel electrophoresis were used. Non-template control and non-RTase treated

templates were included to detect and eradicate primer–dimer formation and genomic DNA contamination. All qRT-PCR experiments were carried out in three technical replicates of three biological replicates. Relative quantitation was calculated using $2^{-(\Delta\Delta Ct)}$ where $\Delta\Delta Ct = (Ct_{target} - Ct_{actin})_{PRD} - (Ct_{target} - Ct_{actin})_{control}$ (Livak and Schmittgen, 2001). Gene-specific primers used for qRT-PCR are listed in Table 5 below.

Gene	Forward primer (5'→ 3')	Reverse primer (5'→ 3')
ORE1	TGAAGCCGGTTATTGGAAAG	CAGCACGTTTCTGGAAAACA
RNS3	GTGGATGGCCTCAAACTGT	AGCACAAGTTCCGTGCTTCT
SINA1	CCGGAGAGGTCAACAATGAT	TTGTGACCGTAACAATCCA
SAG29A	AACTCTTTTGGCTGCGTTGT	CCGAGGACAGAGACTTGGAG
VNI2	AAGAGAGCTGGCAGCAAGAG	AGAGCTTGGCAAAAGGTTCA
ACTIN2	TGCTGGATTCTGGTGATGGT	GGCGTGTGGAAGAGAGAAAC

Table 5

[0173] **Example 7**

[0174] **Total chlorophyll content**

[0175] Leaves of 5-week-old control and PRD pak choi plants were divided into 3 groups (leaves 1-6, 7-12 and 13-18). Similarly, leaves of 5-week-old choy sum plants were divided into 2 groups (leaves 1-5 and 6-10). The leaf discs were extracted using 80% acetone at 4 °C in darkness for 24 h. Total chlorophyll content were determined spectrophotometrically according to Porra et al., 1989. Results were expressed as mg/g fresh weight.

[0176] **Statistical analysis**

[0177] For measurement of the growth parameters, at least 18 individual plants from PRD and control trays were analyzed, and the exact number of replicates is given in all Figures and associated Figure legends. Statistical calculations were performed using Microsoft Excel, and mean values for each measured parameter were compared using two-tailed student's *t* test.

[0178] Turning to Fig. 10, an apparatus **320** for establishing partial root zone drying to improve plant roots in soilless hydroponics according to another embodiment of the invention does not have a general cylindrical shape as that shown in Fig. 1. Rather, both the substrate **322** and the porous material **324** wrapping around the substrate **322** have polygonal cross-sectional shapes, which are square shapes as shown in Fig. 10. Apart from the differences in shapes, the function of each portion or component in the apparatus **320**, and the overall working principle of the apparatus **320**, are generally similar to that in Fig. 1 so they will not be described again herein.

[0179] Figs. 11a-11b show an apparatus **420** for establishing partial root zone drying to improve plant roots in soilless hydroponics according to another embodiment of the invention. The apparatus **420** has an appearance generally similar to that in Fig. 1, but instead of a single-piece porous material as in Fig. 1, the porous material in Figs. 11a-11b contains two pieces, i.e., a first piece **424a** and a second piece **424b** each of which having a semicircular cross-sectional shape. The separate pieces **424a**, **424b** of the porous material are each received in a form-fitting plastic case **450** are easier for storage or transportation, and when assembling the apparatus **420** the separate pieces **424a**, **424b** can be assembled around a substrate **422** before or during the assembling of the apparatus **420**, for example by assembling the plastic cases **450** using fasteners or adhesives (both not shown). The plastic cases **450** has perforations **450a** which allows traversing roots of a plant grown on the apparatus **420** to extend out therefrom. The porous material for example may be made from hydrophobic sponge.

[0180] Fig. 12 show an apparatus **520** for establishing partial root zone drying to improve plant roots in soilless hydroponics according to another embodiment of the invention. Similar to the apparatus shown in Figs. 11a-11b, the apparatus **520** also contains a porous material in two pieces **524a**, **524b** which are held respectively in two semicircular plastic cases **550**. However, different from their counterparts in Figs. 11a-11b, the plastic cases **550** are pivotally connected to each other at tips **550b** thereof, so that the porous material may be assembled into a single piece around the substrate **522** or be disassembled along pivoting directions shown by arrow **552**. The pivotally connected plastic cases **550** are easy to open and close so that inner hydroponic substrate can be assembled and removed as

needed. Like the case in Figs. 11a-11b, the plastic cases **550** has perforations **550a** which allows traversing roots of a plant grown on the apparatus **520** to extend out therefrom. The porous material for example may be made from hydrophobic sponge.

[0181] Turning to Fig. 13, which shows an apparatus **620** that generally has the same structure as the apparatus in Fig. 12. However, the porous material in the apparatus **620** is not hydrophobic sponge, but is clay or plastic beads **654**. These clay or beads **654** can be filled in semicircular plastic cases **650** so that they can be kept in a certain shape defined by the plastic cases **650**.

[0182] The exemplary embodiments are thus fully described. Although the description referred to particular embodiments, it will be clear to one skilled in the art that the invention may be practiced with variation of these specific details. Hence this invention should not be construed as limited to the embodiments set forth herein.

[0183] While the embodiments have been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only exemplary embodiments have been shown and described and do not limit the scope of the invention in any manner. It can be appreciated that any of the features described herein may be used with any embodiment. The illustrative embodiments are not exclusive of each other or of other embodiments not recited herein. Accordingly, the invention also provides embodiments that comprise combinations of one or more of the illustrative embodiments described above. Modifications and variations of the invention as herein set forth can be made without departing from the spirit and scope thereof, and, therefore, only such limitations should be imposed as are indicated by the appended claims.

[0184] It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

[0185] In some exemplary embodiments described above (e.g., as illustrated in Figs. 1 and 10), hydrophilic rockwool is surrounded by hydrophobic sponge. Those skilled in the art

should understand that in variations of the preferred embodiments, the inner hydrophilic sponge can be replaced with any hydrophilic materials alternative to rockwools such as polyurethane foams of any shape and form, or equivalents. In fact, the PRD setup can be established for any type of hydroponic substrates as long as the substrates are covered with hydrophobic sponge using a string or a tape.

[0186] In the example shown in Figs. 11a-11b, snap-fit type plastic cases are used to hold hydrophobic sponge as the porous material. In general, in addition to tying or taping the hydrophobic sponge to the substrate, customized snap-type plastic cases like can be used. By using customized plastic cases such as the one in Figs. 11a-13, the cost of vegetable production can be reduced, while simultaneously increasing vegetable yield and nutrition value.

[0187] In exemplary embodiments described above, the substrate and the porous material each contains a single material. However, it should be noted that in variations of the preferred embodiments, the substrate may contain more than one material, e.g., a combination of two or more of rockwool, peat, perlite, hydrophilic sponge and polyurethane. Likewise, the porous material may contain more than one material, e.g., a combination of clay and beads.

[0188] In exemplary embodiments described above, the substrate is fully wrapped by the porous material no matter if they are in cylindrical shapes or in polygonal shapes. However, in variations of the preferred embodiments, the substrate may be only partially covered by the porous material, e.g., certain portions of the substrate in the circumferential direction is not covered at all or is covered by a material different from a porous material.

What is claimed is:

1. An apparatus for establishing partial root zone drying to improve plant roots in soilless hydroponics, the apparatus comprising:
 - a) a substrate configured for growing plants and comprising a planting material other than soil, the substrate comprising an upper portion and a lower portion aligned along a longitudinal direction of the substrate; and
 - b) a porous material covering at least part of the upper portion of the substrate, but not covering the lower portion of the substrate, the porous material exposed to and in contact with air,
wherein pores of the porous material are adapted to expose a portion of traversing roots of a plant grown in the substrate to air trapped in the pores of the porous material, thereby establishing a partial root zone drying for improving roots of the plant.
2. The apparatus of claim 1, wherein the porous material is adapted to allow at least part of the traversing roots of the plant to grow therethrough.
3. The apparatus of claim 1, wherein the porous material completely wraps around the upper portion of the substrate around a central axis of the substrate that is parallel to the longitudinal direction.
4. The apparatus of claim 1 or 3, wherein the porous material is urged against the substrate.
5. The apparatus of any one of the preceding claims, wherein the porous material is hydrophobic.
6. The apparatus of any one of the preceding claims, wherein the planting material is hydrophilic.

7. The apparatus of claim 5, wherein the porous material is chosen from the group consisting of hydrophobic sponge, clay and plastic beads.
8. The apparatus of claim 6, wherein the planting material is selected from the group consisting of rockwool, peat, perlite, hydrophilic sponge and polyurethane.
9. The apparatus of one of the preceding claims, further comprising a container in which the porous material is accommodated; the container comprising a surface that at least partially covers the upper portion of the substrate.
10. The apparatus of claim 9, wherein the porous material comprises clay and/or plastic beads; the clay and/or plastic beads accommodated in the container to keep a shape of the porous material.
11. The apparatus of any one of the preceding claims, wherein the lower portion of the substrate is at least partially immersed into a nutrient solution, and is adapted to allow a taproot of the plant to grow therealong to contact the nutrient solution.
12. The apparatus of any one of the preceding claims, wherein the porous material comprises a first piece and a second piece which are separate from each other.
13. The apparatus of any one of the preceding claims, wherein the porous material is in a hollow cylindrical shape or a polygonal shape.
14. A method for establishing partial root zone drying to improve plant roots in soilless hydroponics, the method comprising steps of:
 - a) providing a substrate for growing plants, the substrate comprising a planting material other than soil, the substrate comprising an upper portion and a lower portion aligned along a longitudinal direction of the substrate;
 - b) covering at least part of the upper portion using a porous material, but not covering the lower portion of the substrate using the porous material;
 - c) transplanting a plant in the substrate; and

d) exposing a portion of traversing roots of the plant to air trapped in the pores of the porous material that is exposed to and in contact with air, thereby establishing a partial root zone drying for improving roots of the plant.

15. The method of claim 14, further comprising the step of growing at least a part of the traversing roots of the plant through the porous material.

16. The method of claim 14 or 15, wherein step b) further comprises completely wrapping the porous material around the upper portion of the substrate.

17. The method of claim 16, wherein the porous material comprises a first piece and a second piece which are separate from each other; and step b) further comprises assembling the first and second pieces together before or during the wrapping step.

18. A system for establishing partial root zone drying to improve plant roots in soilless hydroponics, comprising:

- a) a receptacle adapted to hold a nutrient solution; and
- b) one or more apparatus according to any one of claims 1-13,

wherein a lower portion of a substrate in each of the one or more apparatus is in contact with the nutrient solution.

19. The system of claim 18, wherein a porous material in each of the one or more apparatus is separated from the nutrient solution.