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Selection of Newly Developed Artificial Medium for Lettuce Production in a Closed-type Plant Production System

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Abstract

This study evaluated different media for lettuce cultivation in a closed-type plant production system. Lettuce seeds were sown in 128-cell plug trays filled with six different media, and then transplanted at 11 days after sowing in a closed-type plant production system. The used media were commercial media (urethane foam, rockwool, and Q plug), and newly developed media (PU 14-S1, TP-S1, and PU-7B). Higher values were observed for total porosity, container capacity, and air space in urethane foam and PU 14-S1. Bulk density was the greatest in the TP-S1, followed by the Q plug and rockwool. The pH and electrical conductivity (EC) of the medium ranged from 5.17 to 6.50 and 0.01 to 0.31 dS·m^{-1}, respectively. Germination properties were strong in the rockwool, Q plug, and PU-7B media. The initial and final growth of lettuce measured at 11 and 32 days after sowing, respectively, were the best in the Q plug medium, followed by the rockwool and TP-S1 media. These media had higher EC values than the others. The applicability of newly developed medium PU-7B was confirmed for lettuce cultivation in a closed-type plant production system when the EC of PU-7B was regulated similarly to the EC of Q plug medium.

Additional key words: air space, container capacity, electrical conductivity, germination, total porosity

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Introduction

In a closed-type plant production system, usually called plant factories, individual environmental factors, such as temperature, relative humidity, CO_2 concentration, light quality and intensity, and concentration and composition of nutrient solution can be set to the optimal environment depending on the crop. Several different types of artificial media are used in plant factories, such as urethane foam and rockwool, because these are easier to handle and create fewer byproducts, such as particles or dust, than traditional medium. However, it is difficult to maintain proper moisture levels in urethane foam. Moisture is easier to manage with rockwool, and it is considered the best medium for hydroponic cultivation. However, rockwool does not easily decompose and is difficult to dispose of after use, causing environmental pollution, and the import cost is high (Hwang and Jeong, 2002; Kim and Jeong, 2003). In order to solve these problems and increase the competitiveness of the domestic medium industry, the development and application of a medium that is environmentally friendly, low cost, and available in a stable supply is important. Newly developed artificial media are made with peat moss and coir that can decompose naturally, or foam made of phenolic resin, which is biodegradable under biologically active landfill conditions. With these media, the cost per plug tray is 2 - 3 times higher than that of commercial media, but there is an advantage that the seedlings can be shipped in a short time because even if the roots are not wrapped tightly in the medium, transplantation is possible, which balances out the costs when considering the heating and cooling and labor costs. Studies to test the applicability of these newly developed media are needed. Different types of media affect the germination and growth of the plant (Grunert et al., 2008). As an example, it was reported that some inorganic media can make vegetables grow faster, and cucumber (*Cucumis sativus*) showed better growth and higher marketable yield in perlite than in expanded clay pellets (Kacjan Maršić and Jakše, 2010; Olle et al., 2012). Therefore, it is necessary to analyze the properties of the medium.

Lettuce (*Lactuca sativa* L.) is a kind of leafy vegetable and a self-pollinated annual plant of the family Asteraceae. It is grown worldwide for consumption as a salad green (Armas et al., 2017). It is also considered the most suitable crop for a plant factory and is frequently used as a model plant to study plant responses to environmental conditions (Dougher and Bugbee, 2001; Kim et al., 2004).

Therefore, in this study, we used commercial media and newly developed media produced domestically to grow lettuce in plant factory. The objectives of our study were to analyze the physicochemical properties of different media, and to examine the germination and growth of lettuce as affected by the different media in a closed-type plant production system.

Materials and Methods

Plant Material and Growth Conditions

Seeds of lettuce (*Lactuca sativa* L. ‘Seonhongjeockchukmyeon’, Asia Seed Co., Ltd., Seoul, Republic of Korea) were sown in 128-cell plug trays (54 × 28 × 4.8 cm, Bumnong Co., Ltd., Jeongeup, Republic of Korea) filled with different media on Feb. 2, 2016, and were germinated in a closed-type plant production system (C1200H3, FC Poibe Co., Ltd., Seoul, Republic of Korea). Tap water was supplied by sub-irrigation every three days during germination.

Twelve germinated seedlings per treatment were transplanted to a closed-type plant production system at 11 days after sowing, and then grown for 21 days after transplanting at 25 ± 1°C and 60 ± 10% relative humidity under light emitting diodes (LEDs, red:blue = 7:3, L-PEC Co., Ltd., Jeonju, Republic of Korea) with 120 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux density (PPFD) measured in the upper leaves of the plants with a photometer (HD2101.2, Delta Ohm SrL, Selvazzano Dentro, Italy) with a 14/10 (light/dark) photoperiod using a deep floating technique system with recycling of Sonneveld nutrient solution as shown in Table 1 (Sonneveld and Straver, 1994). During the cultivation period, an electrical conductivity (EC) of 2.0 $dS \cdot m^{-1}$ and a pH of 6.5 was maintained in the nutrient solution, and the EC/pH measurement was performed using a pH and EC meter (HI 98130, Hanna Instruments Co., Ltd., MI, USA).

Table 1. Composition of the nutrient solution used in the experiment

Chemical	Conc. ($mg \cdot L^{-1}$)	Chemical	Conc. ($mg \cdot L^{-1}$)
$Ca(NO_3)_2 \cdot 4H_2O$	1,014.8	Fe-EDTA	15.30
KNO_3	919.1	H_3BO_3	1.89
KH_2PO_4	272.0	$CuSO_4 \cdot 5H_2O$	0.20
K_2SO_4	43.5	$Na_2MoO_4 \cdot 2H_2O$	0.13
NH_4NO_3	104.0	$ZnSO_4 \cdot 7H_2O$	1.14
$MgSO_4 \cdot 7H_2O$	196.8		

Media and Physicochemical Properties

The specifications of the media used are shown in Table 2 and include three commercial media [UF (Easyhydro Co., Ltd., Chuncheon, Republic of Korea), RW (Grodan Co., Ltd., Roermond, The Netherlands), and QP (Ihort Co., Ltd., CA, USA)] and three newly developed media [TP, PU14, and PU7B (Smithers Oasis Korea Co., Ltd., Cheonan, Republic of Korea)] (Fig. 1). TP, PU14, and PU7B consist of peat moss and coir blends, polyol and isocyanate mixtures, and phenolic resin, respectively. These media were not the same size and specification as they are commercially available by different manufacturers. If we had modified the physical specifications to be the same, their physical properties could be altered, so they were used in their original form. The cross section of the medium was photographed using a stereoscopic microscope (SMZ-745T, Nikon Co., Ltd., Tokyo, Japan) (Fig. 3). To measure the physical properties of the medium such as total porosity, container capacity, air space, and bulk density, each medium was saturated with water for 48 hours and weighed, then the volume of water was drained for 2 hours at room temperature and the medium was weighed again. The weight of totally dried medium for 72 hours also was measured. The container capacity (CC), air space (AS), total porosity (TP), and bulk density (BD) was calculated using the formula presented by Fonteno (1996) and Choi et al. (1997).

Container capacity (CC) = (volume of water retained / volume of solid) × 100
Air space (AS) = (volume of water drained / volume of solid) × 100
Total porosity (TP) = CC + AS
Bulk density (BD) = dry weight / volume of solid

To measure the pH and EC, indicating the chemical properties of the medium, the same volume of each medium was

Table 2. The type and size of the six media used in the experiment

Medium		Type	Size[z] (mm)
Commercial medium	Urethane foam (UF)	Inorganic material	28 × 30 × 15
	Rockwool (RW)	Inorganic material	32 × 32 × 37
	Q plug (QP)	Mixed material[y]	15 × 15 × 25
Newly developed medium	Oasis TP-S1 (TP)	Mixed material	27 × 25 × 30
	Oasis PU 14-S1 (PU14)	Inorganic material	26 × 27 × 38
	Oasis PU-7B (PU7B)	Inorganic material	27 × 28 × 33

[z]Size expressed as width × length × height.
[y]Mixed material means mixture of organic and inorganic materials.

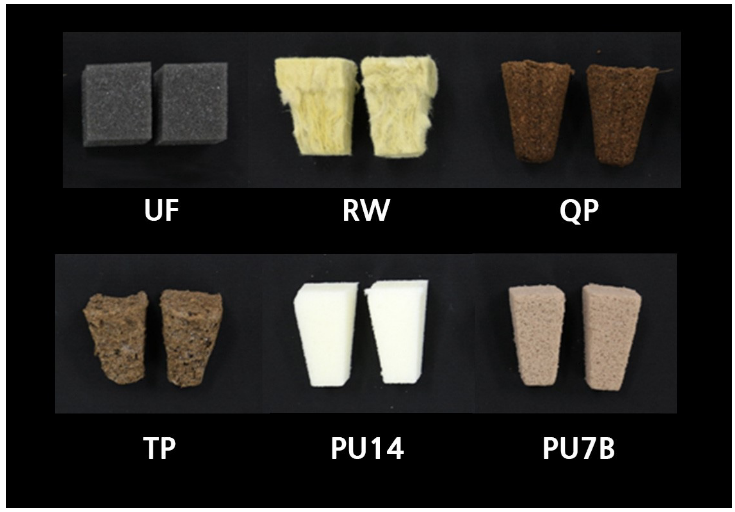

Fig. 1. The six different media used in the experiment. Refer to Table 2 for abbreviations of names of the media.

mixed at a ratio of 1:5 (v/v) with distilled water and shook using a shaker (KS-500, Koencon Co., Ltd., Hanam, Republic of Korea) for 3 hours, and then the pH and EC were measured using a pH and EC meter (HI 98130, Hanna Instruments Co., Ltd., MI, USA) (Kim and Jeong, 2000).

Seed Germination and Growth Characteristics

Germination characteristics of lettuce seeds were calculated, including the initial and final percentage of germination, and the mean daily germination percent (MDG). The percentage of initial and final germination was rated at the third and tenth day after sowing, respectively, as the number of seeds germinated in a total number of plug tray cells [(total germination numbers/plug tray cells) × 100]. MDG was calculated as the number of total germinated seeds/total measuring days. MDG indicates the average number of seeds germinated per day, which shows the vitality of the seeds. Growth characteristics of lettuce were measured at 11 days (just before transplanting) and 32 days (final growth) after sowing. At 11 days, leaf length and width and number of leaves of lettuce were measured, and at 32 days, leaf length and width, number of leaves, leaf area, root length, chlorophyll value (SPAD), and fresh and dry weights of shoots and roots were measured. Leaf length and width was measured as the length of the longest part of the first true leaf. Number of leaves was measured by counting all plant leaves except for the cotyledons. Leaf area was measured using a leaf area meter (LI-3000, LI-COR Inc., Lincoln, NE, USA). SPAD value was measured using a SPAD meter (SPAD-502, Konica Minolta Inc., Osaka, Japan). Fresh weight was measured by an electronic scale (EW 220-3NM, Kern & Sohn GmbH., Balingen, Germany). Dry weight was measured after drying the divided samples of the shoot and root for 72 hours in a drying oven (Venticell-222, MMM Medcenter Einrichtungen GmbH., Munich, Germany) at 70°C.

Statistical Analysis

The experiment was repeated three times with ten plants each in a completely randomized block design, and nine plants per treatment were used to determine plant growth parameters. The statistical analysis was carried out using the statistical analysis system program (SAS 9.1, SAS Institute Inc., Cary, NC, USA). The experimental results were subjected to an analysis of variance (ANOVA) and Duncan's multiple range tests. SigmaPlot program (SigmaPlot 12.0, Systat Software Inc., San Jose, CA, USA) was used for graphing.

Results and Discussion

Physicochemical Properties

The physical properties of the media, which include total porosity, container capacity, air space, and bulk density, are shown in Fig. 2. The pore space can contain air, moisture, and roots. Medium that has high porosity can contain more moisture and oxygen in the pore space, providing an excellent environment for roots (No et al., 2012). Total porosity was the highest in the UF and PU14 media at 96.1 and 96.8%, respectively, and the lowest in the QP medium at 48.6%. When manufacturing UF and PU14 media, the materials are hardened after they are poured in the form of a foam, creating pore spaces. Therefore, the porosity is considered to be high (Fig. 3). Container capacity is the maximum amount of moisture the wetted medium can hold after natural drainage. Container capacity was the highest in the PU14 medium at 87.3%, and the lowest in the QP medium at 45.1%. Total porosity and container capacity showed a similar tendency within each medium. This is thought to be associated with a high porosity. Medium that has a high container capacity can supply the nutrient solution and moisture more efficiently to the crops (Aljibury and May, 1970; Martin et al., 1970). On the other hand, if the container capacity is small, the medium will contain less moisture, and it is difficult to supply sufficient

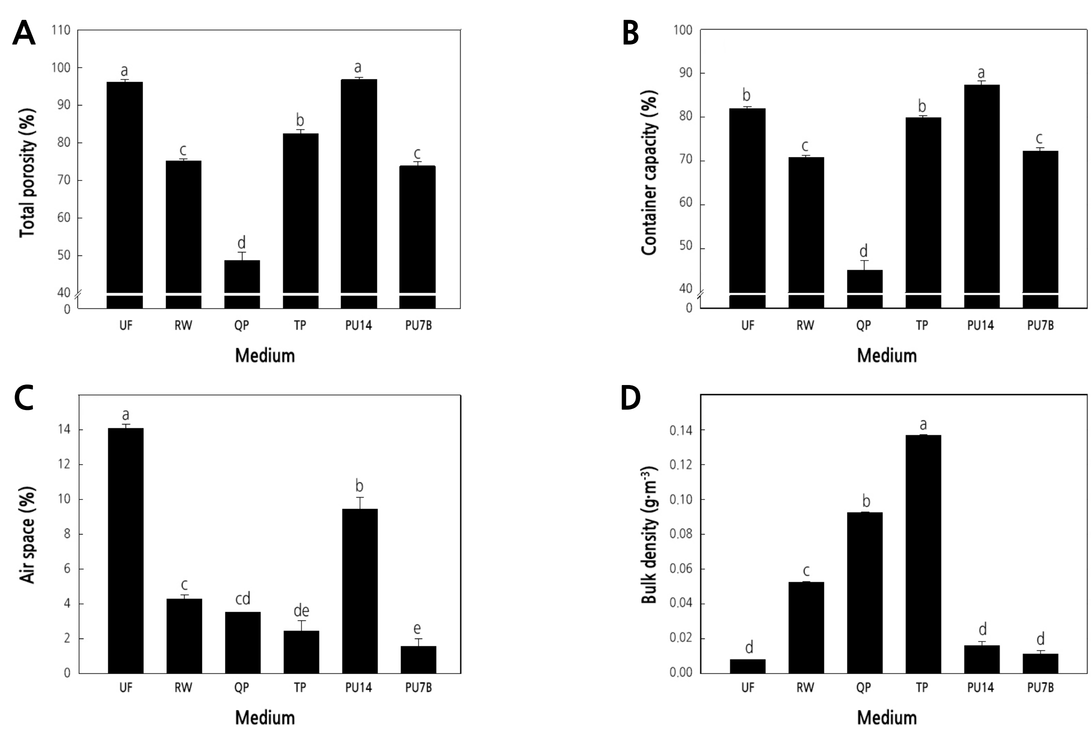

Fig. 2. Total porosity (A), container capacity (B), air space (C), and bulk density (D) of the six media used in the experiment for growth of lettuce in a closed-type plant production system. Refer to Table 2 for abbreviations of the media. Vertical bars indicate ± standard errors (n = 3). Different lower-case letters above each bar indicate that the means are significantly difference according to Duncan's multiple range test at $p \leq 0.05$.

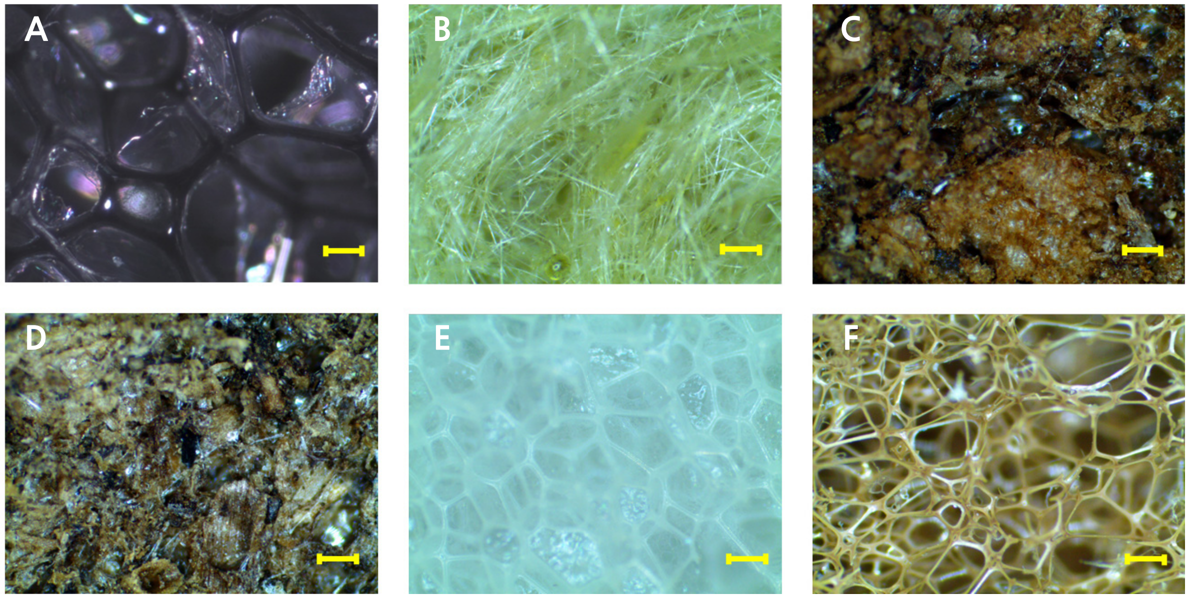

Fig. 3. Microscopic view of the six media used in the experiment (scale bar = 10 μm). A, UF; B, RW; C, QP; D, TP; E, PU14; and F, PU7B. Refer to Table 2 for abbreviations of the media.

nutrients and moisture to the crops. Air space refers to the amount of air the medium can hold after natural drainage. Air space was greatest in the UF medium at 14.1%, followed by the PU14 medium at 9.5%, and the lowest in the TP and PU7B media at 2.4 and 1.5%, respectively. The TP, QP, and RW media had the highest bulk density at 0.14, 0.09, and 0.05 $g \cdot m^{-3}$, respectively, and the UF, PU7B, and PU14 media had the lowest bulk density at 0.008, 0.011, and 0.016 $g \cdot m^{-3}$, respectively. When the bulk density of a medium is too high, the transportation costs increase, and total porosity and air space will be reduced (Corti et al., 1998). On the other hand, when the bulk density is low, the medium will lose its ability to support and hold the plant. In this study, we placed all media in the plug tray cells and therefore, we did not have a problem with low bulk density. de Boodt and Verdonck (1972) suggested that a substrate with a minimum of 85% total porosity, a container capacity between 55 and 75%, and air space between 20 and 30% is ideal for plant growth. However, these values differ in medium used for germination and seedling growth because it has a very small volume. Therefore, further studies are needed to examine the ideal physical properties of medium for germination and seedling growth.

The chemical properties of the media, which are pH and EC, are shown in Table 3. The pH is a measure of the acidity of the medium, taking a log of the reciprocal of the hydrogen ion (H^+) concentration (Beeson, 1996; Kim et al., 1997). The pH of the media used in this study ranged from 5.17 - 6.50. The pH was the highest in the PU7B medium at 6.50, and the lowest in the QP medium at 5.17. The proper pH range of the nutrient solution for lettuce is as 5.5 - 6.5 (Domingues et al., 2012). All the media used in this study had a pH within the range of 5.5 - 6.5. Therefore, pH should not negatively affect plant growth with these media. The EC is the concentration of the total amount of ions dissolved in the water (Brady and Weil, 2008). The EC of the medium used in this study ranged from 0.01 - 0.31 $dS \cdot m^{-1}$. The EC was the highest in the QP medium at 0.31 $dS \cdot m^{-1}$, which is probably because the QP medium is made of organic materials. And the EC was lowest in UF and PU14 media at 0.01 $dS \cdot m^{-1}$. The EC of all inorganic media was about half or less than that of the QP medium. The EC of the medium used for the experiment is included in a stable range of 1.50 $dS \cdot m^{-1}$ or less (Nelson, 1991).

Table 3. The chemical properties of the six media used in this study

Medium[z]	pH	EC ($dS \cdot m^{-1}$)
UF	5.38 d[y]	0.01 d
RW	6.34 b	0.15 bc
QP	5.17 e	0.31 a
TP	5.96 c	0.17 b
PU14	5.49 d	0.01 d
PU7B	6.50 a	0.06 cd

[z]Refer to Table 2.
[y]Mean separation within columns by Duncan's multiple range test at $p \leq 0.05$.

Germination Properties

Germination properties affected by the different media, such as initial and final germination percentages, and MDG, in a closed-type plant production system are shown in Table 4. The highest initial germination rate was observed in TP and PU14 media at 78.3 and 72.5%, respectively, on the 3rd day after sowing, and the highest final germination rate was observed in QP medium at 99.2% on the 10th day after sowing. The lowest initial germination rate was observed in UF and RW media at 8.3 and 13.3%, respectively, and the lowest final germination rate was observed in UF medium at 70.8%. The highest average number of germinated seeds in a day was observed for QP medium at 4.0 seeds, and the lowest average number was observed in UF medium at 2.8 seeds. The initial and final germination rate and MDG was lowest in the UF medium. Seo et al. (2007) and Lee et al. (2011) reported that spinach (*Spinacia oleracea*) seeds showed the lowest germination rate in UF medium. And seeds of lettuce and pak-choi (*Brassica campestris*) had only 5.1 and 6.9% germination, respectively, in UF medium (Choi et al., 2011). This result is attributed to the physical properties of the medium. UF medium had the highest total porosity and air space. Usually, UF medium loses moisture more rapidly than other media (Choi et al., 2011; Lee et al., 2011). UF medium is thought to have insufficient moisture holding capacity. Similar to the UF medium, the total porosity was low in both TP and PU14 media, which had low final germination percentages and MDG, although the initial germination rate was high. In the QP medium, germination properties were the greatest except for initial germination percentage, followed by the RW and PU7B media. Seed germination is affected by

Table 4. Germination characteristics of lettuce 'Seonhongjeockchukmyeon' seeds as affected by media

Medium[z]	Initial germination[y] (%)	Final germination[x] (%)	MDG[w]
UF	8.3 d[v]	70.8 c	2.8 c
RW	13.3 d	94.2 ab	3.8 ab
QP	55.0 b	99.2 a	4.0 a
TP	78.3 a	88.3 b	3.5 b
PU14	72.5 a	90.8 b	3.6 b
PU7B	37.5 c	92.5 ab	3.7 ab

[z]Refer to Table 2.
[y]Initial germination: germination percentage at the 3rd day after the sowing.
[x]Final germination: germination percentage at the 10th day after the sowing.
[w]MDG: mean daily germination (number of total germinated seeds/total measuring days).
[v]Mean separation within columns by Duncan's multiple range test at $p \leq 0.05$.

environmental factors such as moisture, oxygen, and temperature after sowing (Bewley and Black, 1982; Dennis, 1995). Total porosity, container capacity, and air space were a lower in RW, QP, and PU7B media. It was considered that these media characteristics are more appropriate for lettuce seed germination because they can provide continuous moisture and air with proper pore and water retention capabilities. In a similar result, germination rates of lettuce and pak-choi were significantly higher in RW than that of UF media, which had 61.6 and 77.7% air space, respectively (Choi et al., 2011).

Growth of Lettuce

The growth of lettuce as affected by the different media at 11 days after sowing is shown in Table 5 and Fig. 4A. Leaf length and width were the longest in the QP medium, followed by the TP medium, and the shortest in the PU14 and PU7B media. The number of leaves was highest in the UF, RW, QP, and TP media at 3 leaves, and the lowest in the PU7B

Table 5. Size and number of leaves of 'Seonhongjeockchukmyeon' lettuce measured at 11 days after sowing as affected by media

Medium^z	Leaf length (cm)	Leaf width (cm)	No. of leaves
UF	1.1 ab^y	0.6 b	3.0 a
RW	1.0 ab	0.5 c	3.0 a
QP	1.2 a	0.8 a	3.0 a
TP	1.1 ab	0.7 ab	3.0 a
PU14	0.6 c	0.4 c	2.8 b
PU7B	0.7 c	0.4 c	2.0 c

^{z}Refer to Table 2.

^{y}Mean separation within columns by Duncan's multiple range test at $p \leq 0.05$.

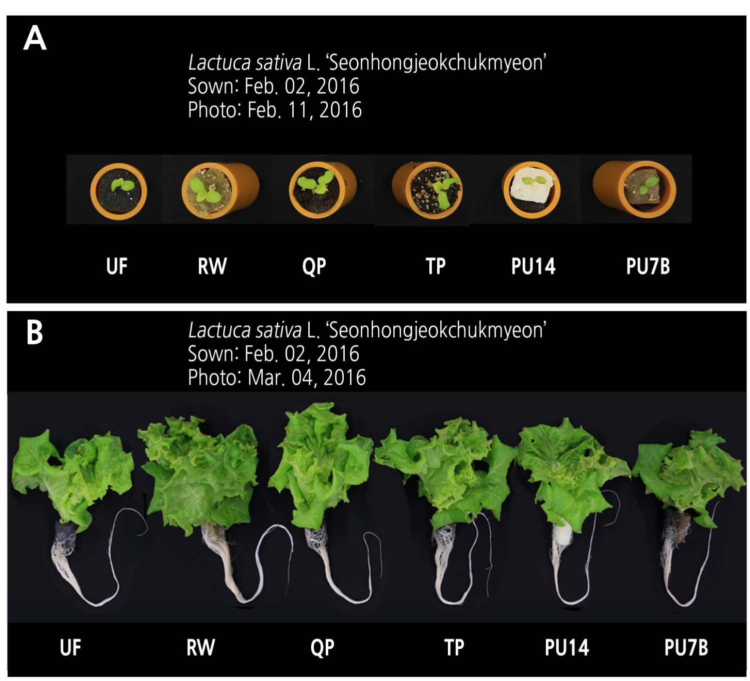

Fig. 4. Growth of 'Seonhongjeockchukmyeon' lettuce as affected by the medium measured at 11 days (A) and 32 days (B) after sowing. Refer to Table 2 for abbreviations of the media.

medium. The initial growth of lettuce was best in the QP medium, followed by the RW and TP media. The initial growth of lettuce was the lowest in the PU14 and PU7B media. This result appears to be related to the EC of the medium. The EC of QP medium was 0.31 $dS \cdot m^{-1}$, followed by the RW and TP media at 0.15 and 0.17 $dS \cdot m^{-1}$, respectively, and the others were 0.06 $dS \cdot m^{-1}$ or less (Table 3). Ions eluted from the medium affect the EC of the water in the medium, and plant growth is affected by the EC level (Handreck, 1993; Ao et al., 2008; Choi et al., 2012). The higher the EC of the nutrient solution for cucumber seedlings, the greater their growth, which was reported by Hwang et al. (2006). Therefore, this result suggests that the initial growth of lettuce seedlings in the QP medium was increased due to the relatively high EC of the medium.

The growth of lettuce as affected by the different media at 32 days after sowing is shown in Tables 6, 7 and Fig. 4B. Leaf length and width, number of leaves, leaf area, chlorophyll value, and fresh and dry weights of shoots and roots were highest in the RW, QP, and TP media. Root length was significantly the longest in the RW and PU7B media. There was no significant difference in the dry weight of roots among the media. The final growth of lettuce was similar to that of the initial growth. After the lettuce was transplanted, the same nutrient solution was used in all treatments via a deep floating technique system with nutrient recycling, so it is considered that the growth after the transplanting was influenced by the growth before transplanting. Therefore, it is important to adjust the EC of the medium. When using the newly developed medium, it is expected that the growth of lettuce will be better to that in the QP medium if nutrients are added at the time of manufacturing the medium and if a similar EC of the nutrient solution to that of QP medium is supplied.

Table 6. Growth characteristics of leaf and root, and chlorophyll of 'Seonhongjeockchukmyeon' lettuce measured at 32 days after sowing as affected by medium

Medium^z	Leaf length (cm)	Leaf width (cm)	No. of leaves	Leaf area (cm^2)	Root length (cm)	Chlorophyll (SPAD)
UF	13.3 ab^y	10.9 bc	6.7 c	223.8 cd	29.6 b	20.8 ab
RW	13.8 a	12.5 a	7.8 b	338.6 a	38.6 a	21.4 ab
QP	13.8 a	12.4 a	9.3 a	256.6 bc	33.2 b	22.4 a
TP	13.8 a	11.8 ab	8.8 a	297.6 ab	31.9 b	21.4 ab
PU14	12.9 b	11.5 abc	7.7 b	258.4 bc	32.8 b	20.3 b
PU7B	11.6 c	10.6 c	7.4 b	256.6 d	38.8 a	20.5 b

^{z}Refer to Table 2.

^{y}Mean separation within columns by Duncan's multiple range test at $p \leq 0.05$.

Table 7. Fresh and dry weights of shoots and roots of 'Seonhongjeockchukmyeon' lettuce measured at 32 days after sowing as affected by medium

Medium^z	Shoot		Root	
	Fresh weight (g)	Dry weight (g)	Fresh weight (g)	Dry weight (g)
UF	7.9 c^y	0.3 c	1.1 b	0.12 a
RW	13.1 ab	0.5 b	1.5 a	0.11 a
QP	15.1 a	0.7 a	1.6 a	0.09 a
TP	12.5 b	0.5 b	0.9 b	0.04 a
PU14	8.3 c	0.4 bc	1.0 b	0.08 a
PU7B	7.7 c	0.4 bc	0.9 b	0.07 a

^{z}Refer to Table 2.

^{y}Mean separation within columns by Duncan's multiple range test at $p = 0.05$.

As a result, germination properties were best in the RW, QP, and PU7B media, which had a range of total porosity of 48.6 - 75.1%, container capacity of 45.1 - 72.2%, and air space of 1.5 - 4.3%. The initial and final growth of lettuce at 11 and 32 days after sowing, respectively, was best in the QP medium, followed by the RW and TP media in a closed-type plant production system. This was likely related to the EC of the medium at the initial period. Finally, this study confirmed the applicability of newly developed media. We suggest that the newly developed medium PU-7B is ideal for germination and growth of lettuce in a closed-type plant production system. Also, if the EC of PU-7B is adjusted to be similar to that of the Q plug medium, it may be a better medium for lettuce cultivation.

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