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Comparison of Plant Growth and Glucosinolates of Chinese Cabbage and Kale Crops under Three Cultivation Conditions

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Abstract

Purpose: The objective of this study is to evaluate the effect of cultivation conditions on the growth and glucosinolate content of Chinese cabbage and kale. **Methods:** Chinese cabbage and kale were grown in three different cultivation conditions, including a plant factory, greenhouse, and open field. Samples were collected at two harvesting times (10 d and 20 d after transplanting the seedlings). Nine growth parameters (plant height, plant width, number of leaves, petiole diameter, SPAD readout, leaf length, leaf width, stem diameter, and plant weight) were measured immediately after harvesting, and the samples were freeze-dried and stored until the glucosinolate content was analyzed. Mean values of the growth parameters and glucosinolate contents were evaluated using Duncan's multiple range tests. **Results:** The results indicated that the plant parameters of the Chinese cabbage and kale were greater for plants grown in the plant factory and greenhouse. The plant height, width, and weight showed significant differences in the Duncan's multiple range tests at a 5% level. The plant factory also produced greater contents of most of the glucosinolates. **Conclusions:** Three different cultivation conditions significantly affected the growth and glucosinolate contents of Chinese cabbage and kale. Further study is necessary to investigate other functional components and different vegetable varieties.

Keywords: Functional component, Greenhouse, Growth parameters, Open field, Plant factory

Introduction

The growth parameters and nutritional components of vegetables are affected by a number of factors, including cultivation conditions, variety, fertilization, sampling time, and location. Recently, studies of the effects of the cultivation system on plant growth and yield have been reported, particularly for plant factories and greenhouses. Plants normally grow within a limited range of temperature, humidity, light, nutrient solution, and oxygen (Hakala et al., 2003; Bodin et al., 2007; Çakmakçi et al., 2006). The remaining factors may not compensate for poor cultivation systems having improper temperatures, inadequate light, or pest problems. A plant factory is an upgraded greenhouse cultivation system with an artificially controlled environment, which enables the stable production of crops with less material consumption. A large number of organizations and research groups have studied and developed various cultivation devices for plant factories and greenhouses (Shimizu et al., 2011; Ioslovich and Gutman, 2000; Kim, 2010; Searchinger et al., 2008). Plants are also affected by environmental changes during the development process and growth. The quality and yield of wheat grown in different cultivation environments was investigated in a study by Dong et al. (2015). Their results showed that the yields from greenhouse and field treatments were both lower than that of a plant factory treatment. At the same time, the grain protein concentration was inversely correlated

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Figure 1. Chinese cabbage in the plant factory (left), greenhouse (middle), and open field (right) after transplanting the seedlings.

with the grain yield. Different growth stages were also investigated (Dong et al., 2014), and three light intensity levels were set up according to the growth period. No significant differences in plant characteristics were observed for the low-light treatment in the seedling stage (e.g., biomass, nutritional content, components of inedible biomass, and healthy index). In another study, the growth of *Gracilaria lemaneiformis* cultivated under three different conditions in China was evaluated (Yang et al., 2006). It was concluded that *Gracilaria* has the potential to remove excess nutrients from coastal areas, and a large-scale cultivation system could be effective for controlling eutrophication in Chinese coastal waters.

In the Republic of Korea, Chinese cabbage (*Brassica rapa*, subspecies *pekinensis* and *chinensis*) and kale (*Brassica oleracea var. alboglabra Bailey*) originating in China are popular. They are leaders in the vegetable markets in China, Rep. Korea and South-East Asia. Ninety percent of domestic Chinese cabbage production in Rep. Korea is earmarked for kimchi processing (GAIN, 2010). Recently, Chinese cabbage and kale have been grown in greenhouses and indoor farm plant factories with less material consumption (Ngo et al., 2013; Chung et al., 2014). Many studies have focused on the effects of environmental factors on their growth and components (Poonguzhali et al., 2008; Liu et al., 2010; Olle and Viršilė, 2013; Chen et al., 2005; Shim et al., 2016; Lee et al., 2015). However, there are few published reports comparing the effects of different cultivation systems on glucosinolates or physical parameters of Chinese cabbage and kale. This study aims to investigate the effects of three different cultivation systems (i.e., plant factory, greenhouse, and open field) on Chinese cabbage and kale growth and their functional components (i.e., glucosinolates).

Materials and Methods

Experimental setup and sample collection

Three cultivation conditions were established: a plant factory, greenhouse, and open field. Approximately 1520 days after sowing the seeds, seedlings were transplanted to each of the cultivation locations. Chinese cabbage and kale were transplanted to the plant factory, greenhouse, and open field at the same time on April 25th, 2015, at Chungnam National University, Daejeon, Rep. Korea. Figure 1 shows Chinese cabbage seedlings in the plant factory, greenhouse, and open field after transplantation.

The environment in the plant factory was controlled and monitored automatically with a system consisting of a computer and a self-developed wireless sensor and control network. Growth conditions such as the temperature, humidity, pH, electrical conductivity (EC), photosynthetic photon flux density (PPFD), carbon dioxide concentration, and light-emitting diode (LED) color ratio were controlled based on horticultural growth considerations (Table 1). Environmental conditions in the plant factory and greenhouse were measured daily. While the environmental conditions in plant factory were controlled, the conditions in the greenhouse were not controlled and operated in normal conditions. The sensor node was composed of a temperature and humidity sensor (HT-01 DV, Mico SnP Co., Ltd., Rep. Korea), a 5 V power supply, a carbon dioxide module (SH-300-DTH, Sohatech Co., Ltd., Rep. Korea), a Zigbee module (Xbee S1, Digi International, MN, USA), and an Atmega module (mega128_xbee, www. cpuplaza.com). Software for collecting environmental data from the plant factory and greenhouse was developed using Visual Basic (version 6.0, Microsoft, Washington, USA). Environmental data in the plant factory and greenhouse were collected at 1 min intervals. More than 1400 data points were collected

Table 1. Growth conditions of the crops

		Temperature (ºC)	Humidity (%)	Light source (LED color ratio)	CO_2 (ppm)
Plant factory	Chinese cabbage	25.52 ± 1.45	56.81 ± 5.29	Red : Blue : White (11:4:3)	1118 ± 130.7
	Kale	16.37 ± 1.74	62.1 ± 3.48	Red : White (11:7)	1372 ± 178.98
Greenhouse		21.97 ± 5.29	62.1 ± 17.37	-	401.49 ± 26.17
Open field		18 – 23	55 – 68	-	-

each day for each cultivation system. The collected environmental data were analyzed and are summarized in Table 1.

Based on the growth status of Chinese cabbage and kale required for analysis, samples of Chinese cabbage and kale leaves were collected at two different harvest times: 10 and 20 d after transplanting the seedlings to the cultivation locations. A total of 96 leaves were picked from the Chinese cabbage and kale plants (48 leaves each for Chinese cabbage and kale) to satisfy the sample requirements for the laboratory measurements and functional component analyses. Initially, leaves without spots or diseases were selected by visual observation. The leaves selected for the measurement of physical parameters and chemical analysis were mature and healthy. To investigate the effects of the cultivation system on the growth of Chinese cabbage and kale, nine physical parameters of the plants were measured using calipers and a SPAD meter (SPAD 502 plus chlorophyll meter, Spectrum Technologies Inc., USA): leaf physical parameters including the leaf length, leaf width, SPAD readout, and number of leaves; and plant physical parameters including the stem diameter, plant height, plant width, plant weight, and petiole diameter. Measurement of each parameter was repeated three times for statistical analysis.

Determination of glucosinolate content

The collected leaves were freeze-dried for at least 48 h in liquid nitrogen after measurement of their physical parameters. Before being stored in a desiccator, their dry weight was then measured, and the leaves were powdered. Crude glucosinolates were extracted from 100 mg of the freeze-dried material in 4.5 mL of 70% boiling methanol for 5 min. Then, desulfation of the crude extracts was performed on a diethyl-aminoethyl (DEAE) anion exchange column (GE Healthcare, Uppsala, Sweden), eluted with 0.5 mL (x 3) of ultrapure water. The eluent was filtered through a 0.45 μm polytetrafluoroethylene (PTFE) syringe filter before high-performance liquid chromatography (HPLC) analysis. A 1200 series HPLC system (Agilent Technologies, CA, USA) was used to analyze the desulfo-glucosinolates. The HPLC system setup used a detector wavelength of 227 nm and a flow rate of 1.0 mL/min. Solvent A was ultrapure water, and solvent B was 100% acetonitrile. Sinigrin was used as an external standard. The individual glucosinolates were identified with mass spectrometry. The ion spray voltage of the mass spectrometer was 5.5 kV. The heating gas was set at 50 Pa and 550℃. The curtain gas and nebulizing gas were set at 20 Pa and 50 Pa, respectively (Kim et al., 2010; Kim and Ishii, 2006).

Statistical analysis

To investigate the effects of different cultivation systems on the growth and glucosinolate content of Chinese cabbage and kale, analysis of variance (ANOVA) and Duncan's multiple range tests at a 5% level were applied using the SAS software package (SAS Institute, Cary, NC, USA).

Results and Discussion

Results of environmental condition measurements

The collected environmental condition data are shown in Figure 2 for the greenhouse and plant factory. Data with errors and outliers were removed using Matlab software (version 7.10, The MathWorks, Natick, Massachusetts, USA). The temperature in the greenhouse was within 14.15-39.35℃, whereas the temperature in the plant factory was more stable (19-29℃). In the plant factory, the humidity was intended to be maintained at approximately 55% for the Chinese cabbage and 65% for the kale. However, the average humidity in the plant factory for Chinese cabbage was higher than the target value (62.1% 3.48%). Mean values for the carbon dioxide concentration

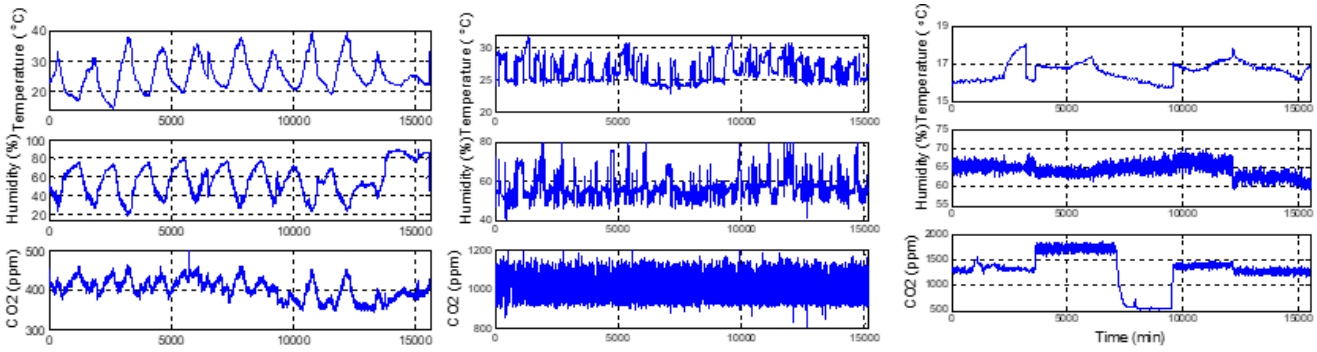

Figure 2. Environmental conditions in the greenhouse (a) and plant factory for Chinese cabbage (b) and kale (c).

in the plant factory and greenhouse were satisfactory.

Effects of cultivation conditions on plant growth

Table 2 summarizes the results of the Duncan's multiple range tests at a 5% level for the physical parameters of the Chinese cabbage. In general, the physical parameters were greater for Chinese cabbage cultivated in the plant factory than in the other cultivation locations. However, the number of leaves and petiole diameter were greater for Chinese cabbage cultivated in the greenhouse. Furthermore, the SPAD readout and plant weight of the Chinese cabbage were lower for the plant factory than the other cultivation conditions. For samples collected at 20 d after transplantation, the Chinese cabbage grew well in the greenhouse, and had the greatest plant height, plant width, number of leaves, leaf length, and stem diameter. The SPAD readout and plant weight of Chinese cabbage in the open field

Table 2. Results of Duncan's multiple range tests for physical parameters of the Chinese cabbage

Sampling time	Parameter	Cultivation system		
		Plant factory	Greenhouse	Open field
10 d	Plant height (mm)[a)]	178.33 ± 7.5^{a}	107 ± 14.7^{b}	107.66 ± 9.33^{b}
	Plant width (mm)	328.66 ± 42.1^{a}	307.33 ± 16.4^{a}	315.69 ± 14.73^{a}
	No. of leaves	17 ± 0.8^{a}	17.66 ± 0.4^{a}	16.45 ± 0.6^{a}
	Petiole diameter (mm)	4.9 ± 0.6^{a}	5.2 ± 0^{a}	4.1 ± 0.4^{b}
	SPAD readout	26.34 ± 15.8^{a}	26.7 ± 6^{a}	30.72 ± 8^{a}
	Leaf length (mm)	204.6 ± 26.8^{a}	182.3 ± 6.1^{b}	170.42 ± 9.73^{b}
	Stem diameter (mm)	67.66 ± 8.8^{a}	34.33 ± 6.8^{b}	28.05 ± 6.1^{c}
	Leaf width (mm)	104.66 ± 10.8^{b}	113.33 ± 13^{a}	94.8 ± 16^{c}
	Plant weight (g)	31.92 ± 6^{b}	35.93 ± 4.1^{a}	37.26 ± 3.3^{a}
20 d	Plant height (mm)	186 ± 3.2^{a}	178.66 ± 22.9^{b}	175 ± 12.91^{b}
	Plant width (mm)	330.66 ± 9.7^{a}	353.66 ± 21.3^{a}	321.55 ± 11.06^{a}
	No. of leaves	20.33 ± 0.4^{a}	23 ± 1.4^{a}	19 ± 0.8^{a}
	Petiole diameter (mm)	5.86 ± 0.3^{a}	5.66 ± 0.3^{a}	4.86 ± 0.4^{a}
	SPAD readout	42.1 ± 0.4^{a}	42.13 ± 1.7^{a}	48.28 ± 4.9^{a}
	Leaf length (mm)	203 ± 7.2^{b}	246 ± 9.2^{a}	220 ± 9.44^{a}
	Stem diameter (mm)	44 ± 4.3^{b}	89.33 ± 7.7^{a}	87.67 ± 9.7^{a}
	Leaf width (mm)	120 ± 2.8^{a}	106.66 ± 5.4^{a}	101.26 ± 8.5^{a}
	Plant weight (g)	47.8 ± 0.4^{b}	47.98 ± 4.2^{b}	58.05 ± 5.6^{a}

[a)] Mean values with different superscripts (a, b, c) in each row are significantly different at $p < 0.05$ in the Duncan's multiple range tests

were greater than those in the plant factory and greenhouse, while petiole diameter and leaf width showed good development in the plant factory. Overall, the early growth (10 d after transplanting) was better in the plant factory, while later growth (20 d after transplanting) was better in the greenhouse and open field. This may be due to space limitations in the plant factory.

To evaluate the effects of cultivation conditions on the growth of kale, a summary of the results for the physical parameters of kale grown in the plant factory, greenhouse, and open field are given in Table 3. At 10 d of plant development, the greatest plant height, plant width, petiole diameter, leaf length, stem diameter, and leaf width were observed for kale plants cultivated in the plant factory, while the number of leaves and SPAD readout were greater for the greenhouse. Similarly, the physical parameters of kale at 20 d of plant development were greater for plants cultivated in the plant factory. Results of Duncan's range tests indicated that most of the physical parameters were grouped in the 'a' group. There were no significant differences in the leaf parameters (leaf length, leaf width, number of leaves, petiole diameter) between the plant factory, greenhouse, and open field. However, significant differences were observed for the plant parameters (plant height, plant width, plant weight). Similar to the results for Chinese cabbage, the early stage growth of kale was generally better in the plant factory, but the later growth was improved in the greenhouse and open field. Further study is necessary for plant factory conditions with greater space, and also for the effects of variable environmental conditions on the growth status.

Effect of cultivation conditions on glucosinolate content

There were non-detected components in some of the Chinese cabbage samples cultivated in the open field (glucoalyssin, glucobrassicanapin, glucoerucin, gluconasturtiin). Only components detected in all cultivation systems were used for further analysis. The seven remaining components were progoitrin, sinigrin, gluconapin, 4-hydroxyglucobrassicin, glucobrassicin, 4-methoxy-glucobrassicin, and neoglucobrassicin. It should be noted that the glucosinolate content was different as a result of the different cultivation conditions of the three environmental systems. The environmental conditions in

Table 3. Results of Duncan's multiple range tests for physical parameters of the kale

Sampling time	Parameter	Cultivation system		
		Plant factory	Greenhouse	Open field
10 d	Plant height (mm)[a)]	162 ± 4.54^{a}	132.33 ± 16.2^{b}	118.85 ± 14^{c}
	Plant width (mm)	385.66 ± 22.5^{a}	259 ± 12.3^{b}	220 ± 18.2^{b}
	No. of leaves	14 ± 0.8^{a}	15.33 ± 1.2^{a}	14.67 ± 2.97^{a}
	Petiole diameter (mm)	4.91 ± 0.4^{a}	4.76 ± 0.3^{a}	4.58 ± 0.8^{a}
	SPAD readout	40.6 ± 0.8^{b}	56.03 ± 2.9^{a}	53.55 ± 1.67^{a}
	Leaf length (mm)	219.66 ± 15.4^{a}	157 ± 8.6^{b}	150 ± 8.33^{b}
	Stem diameter (mm)	86.33 ± 0.4^{a}	41.33 ± 3^{b}	43.73 ± 2.48^{b}
	Leaf width (mm)	118.33 ± 10.3^{a}	104.66 ± 6.7^{ab}	96.17 ± 7.62^{b}
	Plant weight (g)	23.75 ± 4.1^{a}	24.68 ± 4.3^{a}	22.16 ± 4.13^{a}
20 d	Plant height (mm)	252.33 ± 19.1^{b}	291.66 ± 23.7^{a}	280.15 ± 18.33^{a}
	Plant width (mm)	371 ± 19^{a}	359.33 ± 7.1^{a}	321.22 ± 9.44^{b}
	No. of leaves	20 ± 0^{a}	17.66 ± 0.4^{a}	13.73 ± 0.62^{b}
	Petiole diameter (mm)	6.38 ± 0.2^{a}	6.46 ± 0.4^{a}	6.48 ± 0.9^{a}
	SPAD readout	67.7 ± 4.7^{a}	45.36 ± 2.2^{b}	43.62 ± 3.34^{b}
	Leaf length (mm)	223 ± 5.7^{a}	259 ± 9.2^{a}	230 ± 12.88^{a}
	Stem diameter (mm)	67 ± 7.3^{b}	104.66 ± 5.5^{a}	96.16 ± 4.43^{a}
	Leaf width (mm)	148 ± 6.5^{a}	136.33 ± 2^{a}	123.39 ± 3.39^{a}
	Plant weight (g)	57.67 ± 4.2^{a}	43.86 ± 1.5^{b}	44.21 ± 1.36^{b}

[a)] Mean values with different superscripts (a, b, c) in each row are significantly different at $p < 0.05$ in the Duncan's multiple range tests

the plant factory were monitored and controlled in accordance with horticulture considerations and were more stable than those in the greenhouse and open field. The environmental conditions in the open field were not stable and depended on the weather outside. Figure 3 shows the glucosinolate content of leaves cultivated in the three environmental systems. The most abundant glucosinolate components in the Chinese cabbage were 4-methoxyglucobrassicin and glucobrassicin. The glucosinolate content of the leaves cultivated in the plant factory was greater than in the other cultivation systems, particularly for 4-methoxyglucobrassicin and glucobrassicin. Some components with low concentrations were more abundant in leaves grown in the greenhouse and open fields. Progoitrin and sinigrin concentrations were greater for the leaves cultivated in the greenhouse than in the plant factory. Only gluconapin was present at greater concentration in the leaves cultivated in the open field than in the greenhouse and plant factory.

For the kale, a total of five components were detected (progoitrin, sinigrin, glucobrassicin, 4-methoxyglucobrassicin, neoglucobrassicin). Sinigrin and glucobrassicin were the dominant glucosinolate constituents in kale (Fig. 4). The presence of neoglucobrassicin, glucobrassicin, sinigrin, and progoitrin was high for the leaves grown in the plant factory, whereas the 4-methoxyglucobrassicin content of the leaves grown in the greenhouse and the open field was greater than that of the leaves in the plant factory. The plant factory seemed to have a potential cultivation system for kale that resulted in lower standard deviations in the glucosinolate components. The glucosinolate content of the leaves grown in the greenhouse was also greater than that of the leaves in the open field. However, the standard deviations of the glucosinolates in the leaves from the open field were lower than those of the leaves in the greenhouse.

Conclusions

This study was conducted to evaluate the effects of three different cultivation conditions on the growth and glucosinolate content of Chinese cabbage and kale. The results showed that many physical parameters of the Chinese cabbage and kale were greater when they were grown in the plant factory and the greenhouse, particularly at the early growth stage, compared to those grown in the open field. Generally, there were no significant differences in the leaf parameters (leaf length, leaf width, number of leaves, petiole diameter) between the leaves grown in the plant factory, greenhouse, and open field, whereas significant differences were found for the plant parameters (plant height, plant width, plant weight). Additionally, the plant factory was shown to have the potential to produce Chinese cabbage and kale with greater glucosinolate content and lower standard deviations than those plants grown in the greenhouse and open field.

Conflict of Interest

The authors have no conflicting financial or other interests

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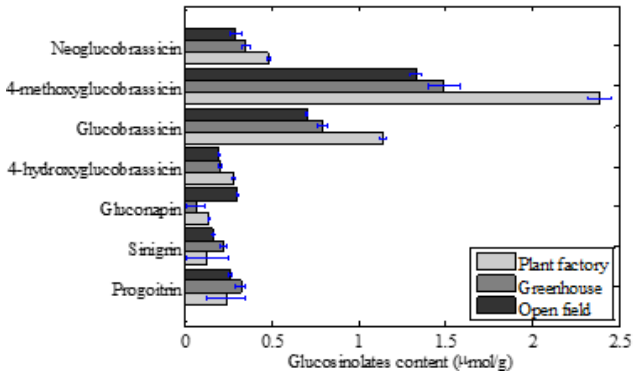

Figure 3. Glucosinolates content of Chinese cabbage grown in three cultivation conditions.

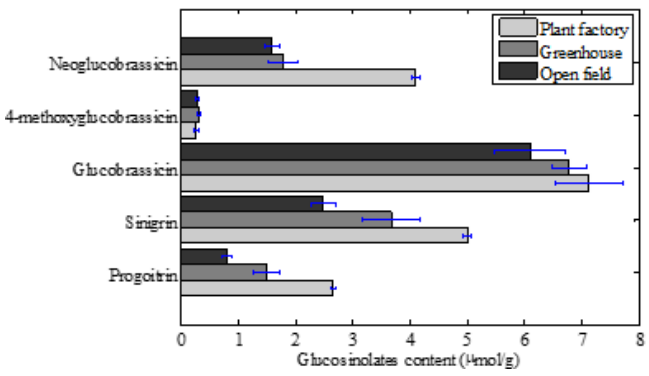

Figure 4. Glucosinolate content of kale grown in three cultivation conditions.

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