设施园艺创新与进展

——2011第二届中国·寿光国际设施园艺高层学术论坛论文集

Protected Horticulture Advances and Innovations

—— Proceedings of 2011 the 2nd High-level International Forum on Protected Horticulture（Shouguang·China）

杨其长　Toyoki Kozai（日本）　Gerard P.A. Bot（荷兰）　主编
Edited by　Qichang Yang　Toyoki Kozai（Japan）　Gerard P.A. Bot（the Netherlands）

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前　言

2009年4月20~22日，在第十届中国（寿光）国际蔬菜科技博览会期间，中国农业科学院和寿光市人民政府共同举办了"设施园艺与现代科技"为主题的首届"中国·寿光国际设施园艺高层学术论坛"（2009 High - level International Forum on Protected Horticulture, HIFPH2009），邀请了数十位国内外知名设施园艺专家和150余位参会代表，就设施园艺科技进展、节能与新能源利用、环境优化控制、高效栽培、新材料及新技术等内容进行了深入研讨，取得了圆满成功。会后多位代表认为，论坛的专家层次高、报告精彩有深度、对行业发展影响力大，希望能形成一定的机制，定期举办下去。经中国农业科学院和寿光市人民政府商定，"中国·寿光国际设施园艺高层学术论坛"每两年举办一届，时间与菜博会同期。2011年第二届论坛在有关领导、专家的大力支持下，在寿光市如期举办。

近年来，设施园艺产业发展迅速，仅中国的设施栽培面积就已达350万公顷。设施园艺的快速发展为改善城乡居民的生活质量、增加农民收入，做出了巨大贡献。但随着人口的不断增长、耕地的不断减少、淡水资源的日趋匮乏以及化石能源的日益枯竭，设施园艺产业也面临着诸多亟待解决的难题。如何利用现代科技成果解决设施园艺生产中面临的资源、环境和可持续发展问题，是摆在世界设施园艺专家面前的重大课题。为此，本届论坛选择以"节能高效、绿色安全"为主题，安排40位国内外专家作大会主题报告和专题报告，并围绕节能与新能源利用、设施高效栽培、绿色安全生产、数字化调控技术等内容进行交流与研讨，探讨实现设施园艺节能、高效、安全生产的技术途径，并汇集了与会专家的43篇论文，正式编辑出版。

在论坛组织过程中，得到了中国农业科学院、山东省寿光市人民政府、荷兰瓦赫宁根大学（Wageningen UR）、日本千叶大学（Chiba University）、山东农业大学、山东省农业科学院、中国园艺学会设施园艺分会、中国农业工程学会设施园艺工程专业委员会以及北京中环易达设施园艺科技有限公司等单位的大力支持，在此表示衷心感谢！

由于时间仓促，论文集中难免会有错漏之处，恳请各位同仁和读者批评指正。

编　者

2011年4月

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综 述

Improving Utilization Efficiency of Electricity, Light energy, Water and CO_2 of a Plant Factory with Artificial Light

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Key words: Closed system; COP; Electric energy utilization efficiency; Electricity consumption; Heat pump

There are two types of plant factory: one with solar light with or without supplementary light from lamps, and the other with artificial light only.

This paper deals with plant factory with artificial light only, and discusses methods of improving utilization efficiencies of the plant factory with respect to resources such as electric and light energy, water and CO_2.

It is thought by many people that electricity cost for lighting and cooling in the plant factory should be very high and that the plant factory will not be economically feasible for plant production. This paper shows that the electricity consumption and consumptions of other resources for plant production can be considerably reduced by improving the current environmental control method and cultivation systems, and by choosing plant species suitable for production in the plant factory.

This review paper is a reduced form of Kozai (2011).

1 Aims of plant factory

A simplest plant factory with artificial light is schematically shown in Figure 1, indicating that essential resources for the photosynthetic growth of a germinated seed with unfolded cotyledonary leaves or a transplant are water, CO_2, light, inorganic nutrients and a certain range of temperatures only.

Among the essential resources, light energy is the most costly resource for plant production in the plant factory with artificial light. Thus, achieving the highest light utilization efficiency, LUE, is of a primary importance in plant production in the plant factory.

Other environmental factors such as temperature, CO_2 concentration, water vapor pressure deficit, air current speed, nutrient solution composition, etc. are controlled primarily to maximize the LUE.

The second aim of environmental control in the plant factory is to utilize essential resources other than light (i. e., water, CO_2 and inorganic fertilizers) at their highest utilization efficiencies to obtain a maximum photosynthetic growth of plants with minimum consumptions of those resources and minimum emission of pollutants (Kozai *et al.*, 2000; Kozai, 2005; Kozai *et al.*, 2005). Consumptions of non-essential resources such as fossil fuel-derived plastics must be minimized.

The third aim is to obtain a highest quality and yield of produce and the fourth is to maximize the highest value of produce with minimum resource consumption and pollution.

2 Light utilization efficiency, LUE

2.1 Definitions of LUE and EUE

LUE for a certain period (hour, day or days required for one harvest), LUE_d, is expressed by Eq. (1) (Yokoi *et al.*, 2005). Electric energy utilization efficiency, EUE_d, is expressed by Eq. (2).

"Light" in this paper means "photosynthetically active radiation" or, shortly, PAR (wave band: 400 ~ 700nm) ($MJ\ m^{-2}$). PAR energy accounts for about 98% of light energy emitted by standard fluorescent lamps, although it accounts for only about 50% of solar radiation (wave band: 300 ~ 3000nm) which spectrum varies with solar altitude, cloudiness and atmospheric transmissivity.

$$LUE_d = k \times D_n / PAR_c \tag{1}$$

$$EUE_d = h \times LUE_d \tag{2}$$

where k is the conversion factor from dry mass to chemical energy fixed in dry mass of plants (ca. 20 $MJ\ kg^{-1}$). The k value is slightly affected by weight percentages of carbohydrates, proteins and lipids in dry mass, but it is considered to be constant in this paper. D_n is dry mass increase in plants, its harvested part or its product, according to purpose ($kg\ m^{-2}$). h is the conversion coefficient of lamps from electric to PAR energy. Hourly LUE_p and EUE_p can also be expressed by Eqs. (3) and (4).

$$LUE_p = b \times C_f / PAR \tag{3}$$

$$EUE_p = h \times LUE_p \tag{4}$$

where b is the conversion factor from CO_2 fixed in plants to chemical energy fixed in dry mass of plants ($MJ\ kg^{-1}$). C_f is net photosynthetic rate of plants ($kg\ CO_2\ m^{-2}$).

2.2 Representative Values of LUE

The average LUE_d over tomato seedling production in the closed system with artificial light was 0.027 (Yokoi *et al.*, 2003), compared with the average LUE_d of 0.017 over tomato seedling production in the greenhouse (Shibuya and Kozai, 2001). Namely, the LUE in the closed system was 1.7 times the LUE_d in the greenhouse. Ohyama *et al.* (2000) show similar values for LUE_d and EUE_d for the plant factory.

2.3 Process of Energy Conversion

Figure 2 shows a scheme of electric energy conversion process to light, heat, and chemical energy in the plant factory.

As shown in Figure 2, only around 36% (100 × 8.9/25) of light energy emitted by lamps is generally absorbed by leaves, the rest is absorbed by culture beds, floor, walls, etc. and converted to heat energy in vain. On the other hand, this low percentage of 36% means that there is much room to improve the LUE by improving the lighting system of the plant factory. It is noted that approximately 99% of electric energy is converted to heat energy in the plant factory during photoperiod, which must be removed to the outside.

2.4 Factors Affecting LUE

Commercial production from plant factories is currently limited to value-added plants because electricity consumption for lighting to increase dry mass of plants is significant. Factors affecting LUE is elaborated in Kozai (2011), which basically correspond to the process shown in Figure 2 showing the issues requiring further improvement in lighting system of plant factory.

By improving the factors shown in Figare 2, LUE as for D_n can be expected to increase to 3.3% as shown in Figure 4 from 0.76 in Figure 2, being 4.3 times (=3.3/0.76) .

3 Electricity consumption by components

Eqs. (5) and (6) are also relevant to consider the suitability of plant production in a plant factory. A_A is electricity consumption for air conditioning per floor area, not per cultivated area.

$$A_A = (e \times A_L + A_M + H_V) / COP \tag{5}$$

$$A_T = e \times A_L + A_A + A_M \tag{6}$$

where e is the cultivation area per floor area; $e \times A_L$) and A_M are, respectively, electricity consumption per floor area for lighting, and for air circulation fans, nutrient solution pump, etc. H_V is cooling load per floor area due to air infiltration and heat penetration through walls. COP is coefficient of performance of heat pump (or air conditioner) for cooling or ratio of heat energy absorbed by heat pump to its electricity consumption.

In Eq. (5), A_A will fall as COP of the heat pump rises. H_V increases with increasing the number of air exchanges of culture room per hour. The annual average COP for cooling in a closed system was 7.6 in Tokyo (Ohyama *et al.*, 2002, Figure 5); approximately, 4 in summer and 10 in winter. COP was over 10 when the room air temperature is 25 C and outside air temperature is 5 C (Figure 5) . On the average, ($e \times A_L$) accounts for 73% of A_T; A_A accounts for 12% of A_T; A_M accounts for 15% of A_T in Tokyo (Yokoi *et al.*, 2003; Ohyama *et al.*, 2003) (Table 1) .

4 Electricity cost per plant and its percentage in total cost

Electricity consumption per plant can be estimated by dividing A_T in Eq, (6) by the number of plants per floor area. Electricity consumption for production of one tomato transplant is about 300 ~ 400 kJ and its cost in Japan is about 1 JPY (0.008 Euro or 1 US cent as of 2011) (Table 2).

In seedling or transplant production, the cost of electric power charges to the cost of producing seedlings in plant factories is only about 2%, but 25% for leafy vegetable production (Kozai 2007). This difference in cost is mainly due to much higher planting density in seedling production than in leafy vegetable production (around 500 ~ 1 000 and 50 ~ 100 plants per m^2, respectively).

Price of electricity per kWh differs from country to country. It is about 0.2 Euro in Japan but is 0.01 Euro in most Middle East countries.

By way of contrast, depreciation of the initial equipment/structure and labor costs account for approximately 30% each of production costs (Takatsuji and Mori, 2011). It follows that not only electric power charges and labor costs should be reduced, but also depreciation of the initial equipment/structure costs is essential because over-sized and inefficient equipment and structure are common at present.

5 Plants suited to production in plant factories

Electricity consumption for lighting per plant is proportional to E in Eq. (7).

$$E \propto PAR_C \times T \times P/J \tag{7}$$

where PAR_C is PAR flux received at culture bed; T is photoperiod per day; P is days required for cultivationt; J is the number of plants per cultivated area. Eq. (7) makes it clear that plants that can be produced with low light intensities, short (15 to 30 day) harvest cycles and high cropping densities will be suited to plant factory production. These include various types of grafted and rooted cuttings and seedlings, leafy vegetables, herbs and aromatic grasses and plants for herbal medicines (e.g., St. John' s wort or *Hypericum perforatum*), small-rooted vegetables (*hatsuka daikon*, Japanese dwarf turnip and *wasabi* etc) and small high-end flowers (miniature roses and orchids).

On the other hand, plants suited to growing in greenhouses using sunlight rather than plant factories for improved quality and yields include fruit-type vegetables such as tomatoes, green peppers and cucumbers, leafy vegetables and herbs that contain large amounts of functional components, berries such as strawberries and blueberries, high-end flowers such as phalaenopsis, dwarf loquats, mangoes and grapes etc for growing in containers with trickle irrigation, and non-woody or annual medicinal plants such as angelica, medicinal dwarf dendrobium, Asian ginseng, saffron and *Swertia japonica.*

Plants that do not lend themselves to plant factory production are plants used primarily as sources of calories (carbohydrates, protein and fats) for people and livestock such as rice, wheat, corn and potatoes, plants such as sugarcane and rapeseed used primarily as fuel (energy) sources, larger fruit trees and trees used for timber such as cedar and pine and others including daikon, burdock and lotus. These plants require large areas for growth and have harvest cycles of several months to ten or more years, but they have relatively low value (prices) to mass.

6 Towards integrative environmental control

Set points of environmental factors need to be determined considering, in addition to LUE: (1) status of plant growth and development; (2) predicted yield, quality and value; (3) total costs of environmental control and resource inputs; (4) price of produce in the market; (5) weather forecast; (6) spread of pest insects and disease; (7) emission of pollutants including CO_2 gas;

(8) utilization efficiencies of water and CO_2. Thus, integrative environmental control of plant factory with use of a multi-purpose objective function is a challenging subject (Figare 6). For efficient integrative environmental control, use of heat pumps for cooling, air circulation and dehumidification is essential (Kozai *et al.*, 2011).

7 Water and CO_2 utilization efficiencies

Water utilization efficiency, WUE, can be defined similarly to LUE, as shown in Eq. (8).

$$WUE = W_f/W_s = (W_s - W_c - W_r)/W_s \quad (8)$$

Where W_f is the water absorbed and kept in plants and substrate; W_s is water supplied or irrigated to the plant factory; W_c is water condensed at the cooling panel of heat pump for cooling and collected for its recycling use; W_r is the water vapor released to the outside through air gaps of the plant factory. In the plant factory with N of about 0.01 h^{-1}, over 90% of W_s is condensed and collected as W_c. Thus, *WUE* is greater than 0.9. While *WUE* is lower than 0.02 in the greenhouse because W_c is zero and over 95% of W_s is released to the outside as W_r. This means that *WUE* is about 45 times greater in the plant factory than in the greenhouse (Water consumption in the plant factory is $1/45^{th}$ compared with that in the greenhouse).

CUE is defined by Eq. (9).

$$CUE = C_f/S_s = (C_s - C_r)/C_s \quad (9)$$

Where C_f is CO_2 fixed by plants or net photosynthetic rate; C_s is CO_2 supplied to the plant factory; C_r is CO_2 released to the outside through air gaps of the plant factory. W_r and C_r are, respectively, given in Eqs. (10) and (11).

$$W_r = d \times N \times V_a \times (AH_i - AH_o) \quad (10)$$

$$C_r = c \times N \times V_a \times (C_i - C_o) \quad (11)$$

Where *d* is specific weight of water vapor; *N* is the number of air exchanges per hour of the culture room; V_a is the air volume of the culture room; AH_i and AH_o are, respectively, absolute humidity inside and outside the culture room; *c* is specific weight of CO_2; C_i and C_o are, respectively, CO_2 concentration inside and outside the culture room.

Eqs. (10) and (11) show that reduction of *N* (increase in air tightness) is primarily important to reduce W_r and C_r and thus improve *WUE* and *CUE* (Figs. 7 and 8). *N* of the culture room in the plant factory should be preferably around 0.01 ~ 0.02 h^{-1}. *CUE* is low at low *LAI* or low C_p (net photosynthetic rate) because C_r is constant and C_s increases with increasing *LAI* or C_p. Similarly, *WAU* is low at low *LAI*.

It should be noted that C_f in Eq. (3) can be estimated by Eq. (12). The C_p is an important variable for optimizing the set points of environmental factors. A method of continuous monitoring of N will be described elsewhere. In an integrative environmental control, monitoring and control of state variables such as C_p, C_r, W_s, A_T and maximizing LUE, *WUE* and *CUE*, in combination of monitoring and control of state variables such as temperature and humidity are essential.

$$C_p = C_s - C_r \quad (12)$$

8 Closed system

Understanding and introducing the concept of closed system with minimum *N* is essential in the design, construction and operation of plant factory. Its concept is schematically shown in Figure 8. In the "ideal" closed system, all resources inputted to the system are converted to produce with minimum generation of heat energy, resulting in no emission of pollutants to the outside and highest resource utilization efficiencies possible.

The closed system with minimum *N* is important not only for achieving maximum *WAU* and CUE, but also for preventing pest insects or pathogenic microorganisms from entering the closed system and for minimizing the environmental disturbance by weather outside. In order to minimize the thermal disturbance, the walls of the closed system need to be thermally well insulated (Kozai *et al.*, 2000).

This closed system for plant production is schematically shown in Figure 8. This closed system was commercialized in 2005 in Japan (Kozai *et al.*, 2006; Kozai 2007) and has been used for commercial plant production of transplants, leafy vegetables and herbs at about 150 locations in Japan.

Conclusion

Factors affecting utilization efficiencies of plant factory with artificial light are analyzed and methods to improve those efficiencies are discussed. It is suggested that current light energy utilization efficiency can be doubled or even tripled in the future. Electricity consumptions for lighting and cooling account for, respectively, about 73% and about 12% of total electricity consumption, in case that the plant factory is thermally well insulated. It is also indicated that the closed system is an important concept to design the plant factory having high utilization efficiencies of light, water, CO_2 and inorganic fertilizers. Plant factory technology will contribute to producing horticultural crops with minimum resource consumption and minimum emission of pollutants. Discussion is given in more detail in Kozai (2011).

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