# Yield prediction of hydroponic grown lettuce base on nutrient uptake in plant factory

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## 1. Abstract

The purpose of this study was to develop a yield prediction model by measuring amount of nutrient uptake in plant factory for hydroponically grown lettuce. An automated system was developed to control pH and Electrical Conductivity (EC) of nutrient solution and measuring the amount of nutrient absorbed. The integral nutrient uptake in full day, light period and dark period were compared with fresh mass of lettuce after harvested. The result shown the integral nutrient uptake in full day had best linear relationship ($R^2$: 0.95) with the fresh mass harvested. This system can predict the fresh mass of lettuce harvested after 3 days of pure water treatment for nitrate control, and can also be used as early warning mechanism when the nutrient absorbed are low compare with normal conditions.

**Keywords:** nutrient uptake, plant factory, yield prediction, lettuce, hydroponics

## 2. Introduction

Plant factory is sustainable and environmentally sound for the growth of plants. It used much less amount of water, nutrition, and labor when compare with traditional open field and greenhouse production. A plant factory using only artificial light and enriched $CO_2$ are normally air-tight with very low air-exchange rate and no pesticides are needed during cultivation. Light, air temperature, humidity, wind speed, water, $\mathbf{CO_2}$ concentration, pH and EC of solution, etc. were controlled in order to create an artificial and efficient cultivation environment in an indoor space.

Hydroponic cultivation system is the most commonly used in plant factory. It has several advantages, such as: optimal efficiency in the use of water and nutrients, shortening life cycle of plant, fast economic return, dispensing crop rotation and with high environmental benefit (Vernieri et al., 2005). In addition, hydroponic cultivation has been reported not only to be associated to higher production yields but also to allow better control and standardization of the cultivation process, thus reducing overall production costs (Nicola et al., 2005; Fallovo et al., 2009). In hydroponic crops, nutrients play a key role in the quality and productivity of crops. The balanced application of nutrients (macro and micro elements) is vital in determining the quality of the product (Abou-Hadid et al., 1996).

An automated system was developed to control pH and concentration of nutrient solution in this study, and measured the amount of nutrient absorption to assess mass of lettuce with the assumption that the lettuce growth and nutrient uptake are directly related. Expecting this system keep abreast of the physiological state of lettuce, and help user to manage plant factory.

## 3. Materials and Methods

**Plant Material and Growth Conditions**

Lettuce (*Lactuca sativa* L. cv. Ostinata, Known-You Seed Co., Taiwan) was cultured hydroponically using the deep flow technique (DFT) in an environmental controlled confined chamber (5 $m^2$). Lettuce seeds were soaked for 5 hours then sown into plug trays, using foam/sponge cube as growth media, allow germination and growth for 14 days (stage 1: seeding stage) under cool-white florescent lamp (relative peaks at 436, 546 and 611 nm, Wellypower, Taiwan) with PPF at 250 $\mu mol\cdot m^{-2}\cdot s^{-1}$ in a growth chamber. The temperature and humidity of the chamber were kept at 20℃ and 70 ~ 80 % with a 24 hours light period (Daily Light Integral: 21.6 $mol\cdot m^{-2}\cdot day^{-1}$).

In stage 2 (day 15 to day 28; seedling stage) and 3 (day 29 to day 35; mature stage), the seedling were transplanted to another room with Day/Night temperature of 25/18 °C and humidity of 70 ~ 80 % and used light-emitting diodes (LED) as light sources with daily light integral (DLI) of 10.08 $mol\cdot m^{-2}\cdot day^{-1}$ (200 $\mu mol\cdot m^{-2}\cdot s^{-1}$, Light/Dark: 14/10 hours). In stage 4 (day 36 to day 38; harvest stage), nutrient solution was replaced with pure water for nitrate control and harvested at 38$^{th}$ days after seeding. The $CO_2$ concentration was kept at 1200 ppm in light period. Plant densities were 824 plants $m^{-2}$ from day 0 to day 14, 52 plants $m^{-2}$ from day 15 to day 28 and 17 plants $m^{-2}$ from day 29 to day 38.

Yamazaki's nutrient solution (Yamazaki, 1982) was used for experiments. The pH and electrical conductivity (EC) of nutrient solution were kept at 5.5 and 1.2 $mS\cdot cm^{-1}$, respectively with an automatic adjusting equipment.

**Planting Schedule**

As mentioned above, production is separated into 4 stages: 1. seeding, 2. seedling, 3. mature, 4. harvest stage. The seeding stage is conducted in a growth chamber and other 3 stages were in a confined environmental controlled room within the plant factory of

National Taiwan University. The crop is grown in a 3-layer bench; the top layer is the cultivation area of seedling stage anddivided into area A and B. The second and third layers are for the mature (nutrient solution for 7 days) and harvest stages (pure water for 3 days) after transplanting from top layer area Aand B, respectively. The nutrient solution used in stages 2 and 3 (15 to 35 days after seeding) were recorded by measuring amounts of stock solution A and B added into the solution tank.

The planting schedule was shown in Fig. 1. The seeds were seeded in seeding area A from day 0 today 14 (seeding stage), then transfer to seedling area Afrom day 15 today 28 (seedling stage), then moved to harvest area A from day 29 today 35 (mature stage). On day 35, the nutrient solution of harvest area A was was replaced with pure water for nitrate control and harvested after 3 days (on day 38).When seeding area A becomes empty at day 15, enter the 3rdbatch oflettuce immediately. On day 29, the seedling area becomes empty allowing 3rd batch of lettuce to move in. On day 42,harvest area A was empty allowing 3rd batch of lettuce at day 28 to move in.

The integral nutrient uptake in full day, light (08:00 am ~ 22:00 pm) and dark (22:00 pm ~ 08:00 am) periods were compared with fresh mass of lettuce after harvested.

**Nutrient Uptake Measurement Methods and Equipment**

The hydroponic nutrient control system consists of control box, EC/pH electrodes, peristaltic pumps (flow rate: 48.81 ± 1.35 mL $min^{-1}$), stock solution tanks, acid liquor storage tank (0.1 M, $H_3PO_4$) and water circulating pump. The water level of hydroponic tank was maintained by liquid level sensor and electronic valve. When the water level of hydroponic tankwas lower thanliquid level sensor, electronic valve will open to add water.After30 sec, the water level in tank will be checked using liquid level sensor until water level was equal or higher than liquid level sensor. The amount of water added was recorded.

The EC values of stock solutions A and B are 88.3 and 83.3 mS $cm^{-1}$, respectively and pH are 5 and 6.54, respectively. The amount of A or B stock solution used in nutrient supplement were equal, and were recorded by programmable logic controller (PLC) and computer. The nutrient control system was used at seedling and mature stages. The amount of nutrient absorbed was measured by recording the amount of stock solutions A and B added to the system from day 15 to day 35 after seeding.

This study compared the overall nutrient uptake in full day, light (08:00 am ~ 22:00 pm) period and dark (22:00 pm ~ 08:00 am) period with fresh mass of lettuce after harvested.

### Measurement of Basic Nutrient Uptake of Lettuce

Crops at different growth period would have different nutrient absorption rate. Figure 1 showed that at day 29 the cultivation bed has 3 lettuce crops grown at day 15, 22and 29 at the same time, thus leading to a complex situation that the amount of nutrient absorbed is not equally contributed by 3 crops. An experiment was designed to reveal the amount of nutrient uptake day after day. Totally 112 lettuces were grown at seedling stage (from day 15 to day 28), and 75 plants were selected then transplant to harvest area to begin the mature stage (from day 29 to day 35). The amount of nutrient solution absorbed was recorded from day 15 to day 35.

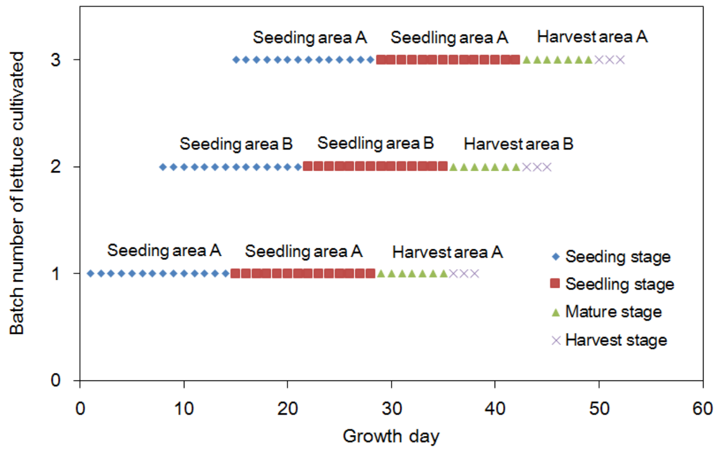


Figure 1 The planting schedule of lettuce.

### Recording Software

The parameters of air (temperature, humidity and carbon dioxide) and nutrient solution (EC, pH and absorption) were recorded (LabVIEW, National Instruments, USA) on a remote computer every ten minutes. The equipment can be controlled through AP (Access Point) with TCP / IP (Transmission Control Protocol/Internet Protocol) in a Wi-Fi environment.

## 4. Results and Discussion

### Measurement of Basic Nutrient Uptake of Lettuce

The amount of nutrient solution absorbed by lettuces in a batch at week 3, 4 and 5 was shown in table 1. The amount of nutrient solution absorbed increased along with week of growth. The fresh mass of lettuce cultivated after 28, 35 and 38 days from seeding was 37.75 ± 6.69 g, 93.24 ± 8.33 g and 111.8 ± 13.22 g, respectively. The nitrate concentration of lettuce harvested at day 38 after seeding was 2630 ± 351 ppm.

Table 1 The amount of nutrient uptake and the ratio of total nutrient uptake with lettuce each week growth.

| Growth time | Nutrient uptake | |
|---|---|---|
| | Single week (mL) | Ratio of total (%) |
| Three week (*$NS_{t-2}$*) | 68.17 | 15 |
| Four week (*$NS_{t-1}$*) | 151.47 | 34 |
| Five week (*$NS_t$*) | 230.71 | 51 |

**The Relationship between Nutrient Uptake and Fresh mass**

Values of Table 1 can be integrated as shown in Eq. [1]:

$$NA_t = NS_{t-2} \times 0.15 + NS_{t-1} \times 0.34 + NS_t \times 0.51 \tag{1}$$

The crop at different growth period would have different nutrient absorption rateTotal amount of *nutrient* solution absorbed by lettuce ($NA_t$, growth over 38 days) on week t can be considered as the 3 week total with 15%, 34% and 51% weighing factors in each week. A simplify equation was also proposed using only 2 weeks data assuming the 3rd week before harvest will be the same with the 2nd week as shown in Eq. [2], where $NS_{t-2}$ was assumed equals to $NS_{t-1}$, thus Eq. [1] could be modified as below:

$$NA_t = NS_{t-1} \times 0.49 + NS_t \times 0.51 \tag{2}$$

The total amount of nutrient solution absorbed ($NA_t$) was assumed positively correlated with the average fresh mass ($AvgFM_t$) harvested on t week plus 3 days of pure water treatment as shown in Eq. [3].

$$AvgFM_t = a_1 \cdot NA_t + b_1 \tag{3}$$

The amounts of stock solution added per week were measured continuously from 2014/05/12 to 2014/10/27. The result of relationship between nutrient solution absorbed and fresh mass of lettuce were calculated by Eq. [3] as shown in Fig. 2 ($NA_t$ estimated by Eq. [1]) and Fig. 3 ($NA_t$ estimated by Eq. [2]).

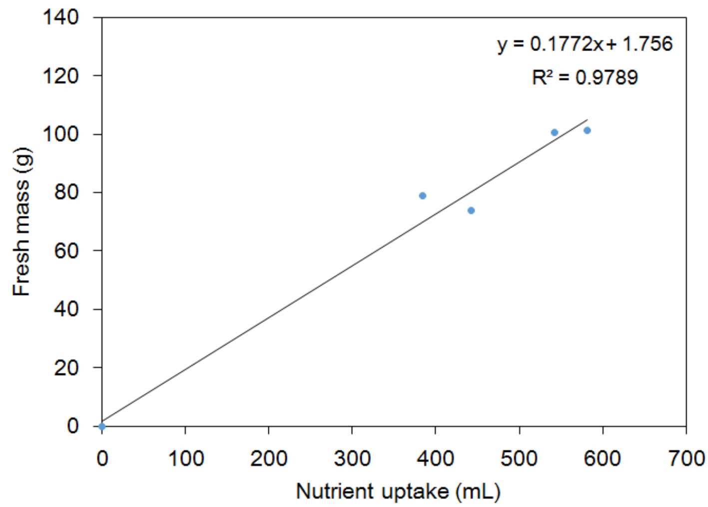


Figure 2 The relationship between fresh mass of harvested lettuce and the integral nutrient uptake through three consecutive weeks.

$NA_t$ estimated by Eq. [1] had better coefficient of determination ($R^2$: 0.9789) than estimated by Eq. [2] ($R^2$: 0.9524). It is quite reasonable that using consecutive 3 weeks of data has higher accuracy. However less dataset can be generated due to interruption of maintenance tasks conducted in a plant factory and also some other reasons. The experiment was interrupted four times due to equipment failure, and replacement of carbon dioxide tank. Only 5 sets of complete data were generated as shown in Fig. 3. Due to the difference of coefficients of determination between $NA_t$ estimated by Eq. [1] and Eq. [2] were small and also 0.95 is an acceptable value. $NA_t$ estimated by Eq. [2] was adopted due to the convenience of equipment measuring in subsequent calculations.

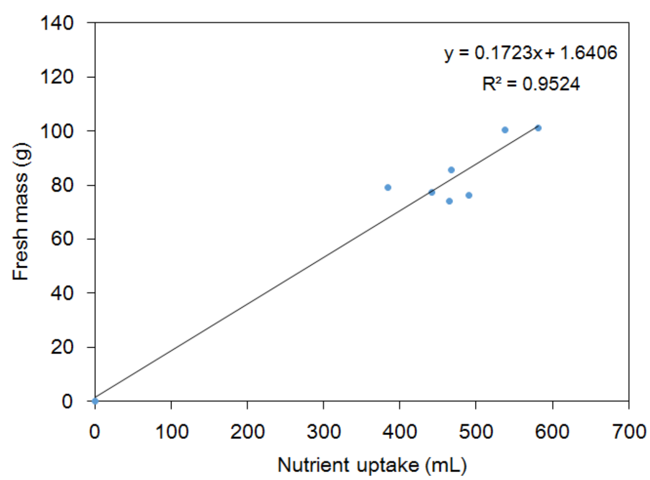


Figure 3 The relationship between fresh mass of harvested lettuce and the integral nutrient uptake through two consecutive weeks.

As shown in Fig. 4, the values of nutrient absorption integrated during full day had the better coefficient of determination ($R^2$: 0.9524) than integrated during only light ($R^2$: 0.795) or dark ($R^2$: 0.7295) period.

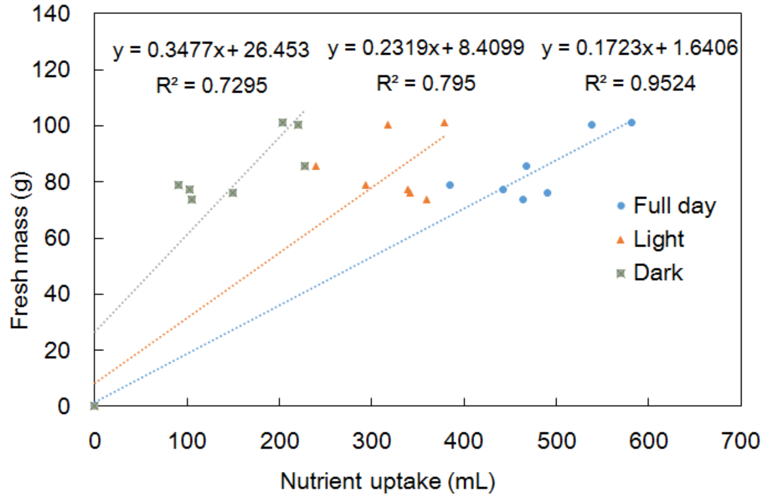


Figure 4 The relationship between fresh mass of lettuce harvested and the integral nutrient uptake in full day, light (08:00 am ~ 22:00 pm) and dark (22:00 pm ~ 08:00 am) periods.

The hydroponic system using the deep flow technique (DFT) had more water, and the time of nutrient solution adjusting was too long. So lettuce absorbing nutrient in light period might been counted to the dark period. This bias could be the reason that counting only light period is less accurate compare with counting the whole day.

In order to calculate the amount of nutrient solution absorbed per plant, the Eq. [4] was derived.

$$FM_t = a_1' \times \left(\frac{NS_{t-1} \times 0.49}{NOP_{t-1}} + \frac{NS_t \times 0.51}{NOP_t}\right) + b_1' \qquad (4)$$

$NOP_t$was the number of plants grown from day 29 to day 35 (75 plants in seedling stage), and $NOP_{t-1}$was the number of plants grown from day 15 to day 28 (112 plants in mature stage). The result of relationship between nutrient solution absorbed per plant and fresh mass of lettuce were calculated by Eq. [4] as shown in Eq. [5] ($R^2$: 0.9576).

$$FM_t = 27.077 \times \left(\frac{NS_{t-1} \times 0.49}{112} + \frac{NS_t \times 0.51}{75}\right) + 5.8875 \qquad (5)$$

Note that the Eq. [5] can be used only for the harvested fresh mass in between 73.90 and 101.19 g.

A system of nutrient absorption based yield prediction model/method of hydroponically grown lettuce was developed. The values of nutrient absorption integrated throughout the whole day had the best liner relationship with fresh mass of harvested lettuce compare with counting only the light period or dark period. It can predict the fresh mass of harvested lettuce after three days of pure water treatment to reduce nitrate concentration. In the future, more experiments will be conducted and an early warning mechanism will be included. A week by week reasonable amount of nutrient solution consumption can be predicted and compare with actual consumption and decision support tool can be developed accordingly.

## 5. Literature Cited


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