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Research Report

Development of Planting-density Growth Harvest (PGH) Charts for Quinoa (*Chenopodium quinoa* Willd.) and Sowthistle (*Ixeris dentata* Nakai) Grown Hydroponically in Closed-type Plant Production Systems

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Abstract. When designing a plant production system, it is crucial to perform advanced estimation of growth and productivity in relation to cultivation factors. In this study, we developed Planting-density Growth Harvest (PGH) charts to facilitate the estimation of crop growth and harvest factors such as growth rate, relative growth rate, shoot fresh weight, harvesting time, marketable rate, and marketable yield for quinoa (*Chenopodium quinoa* Willd.) and sowthistle (*Ixeris dentata* Nakai). The plants were grown in a nutrient film technique (NFT) system in a closed-type plant factory under fluorescent lamps with three-band radiation under a light intensity of 140 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with a 12-h/12-h (day/night) photoperiod. We analyzed the growth and yield of quinoa and sowthistle grown in nutrient solution at EC 2.0 $dS \cdot m^{-1}$ under four planting densities: 15 cm between rows with a within-row distance of 15 × 10 cm (67 plants/m^2), 15 × 15 cm (44 plants/m^2), 15 × 20 cm (33 plants/m^2), and 15 × 25 cm (27 plants/m^2). Crop growth rate, relative growth rate, and lost time were closely correlated with planting density. We constructed PGH charts based on the growth data and existing models. Using these charts, growth factors could easily be determined, including growth rate, relative growth rate, and lost time, as well as harvest factors such as shoot fresh weight, marketable yield per area, and harvesting time, based on at least two parameters, for instance, planting density and shoot fresh weight.

Additional key words: expolinear, harvesting time, marketable yield, nutrient film technique, plant factory, within-row spacing

Introduction

Planting density is an important factor that markedly affects the growth and yield of vegetables, thereby affecting productivity (Kahn et al., 1997; Maynard and Scott, 1998; Reiners and Riggs, 1999; Schultheis et al., 1999; Leskovar et al., 2000). Crop yield per area increases at higher planting densities, whereas marketable yield per plant decreases (Locascio and Stall, 1994; Motsenbocker, 1996; Kulter et al., 2001). When designing a plant production system, it is important to estimate how plant growth and productivity change in response to cultivation factors, such as planting density. For instance, crop productivity and marketable rates can be determined in relation to planting density. Crop growth models can be useful tools for making such determinations, as they integrate knowledge about crop physiology and the control of crop growth (Huevelink, 1995; Marcelis et al., 1998; Lee et al., 2003).

Of the currently available growth models, the expolinear growth model has been applied to many crops (Goudriaan and Monteith, 1990; Dennett and Ishag, 1998; Ishag and Dennett, 1998; Lee et al., 2003). Parameters of the expolinear growth model include crop growth rate (CGR), relative growth rate (RGR), and time. Lee et al. (2003) reported that the expolinear growth model as a function of radiation requires knowledge about light use efficiency (LUE), leaf area index (LAI), and RGR per radiation. Furthermore, LAI and LUE are affected by planting density (Goudriaan and Monteith, 1990; Papadopoulos and Pararajasingham, 1997; Lee et al., 2003). Therefore, using existing models, crop growth can be estimated in relation to planting density.

Quinoa (*Chenopodium quinoa* Willd.) seeds have high nutritional value. The leaves and sprouts of quinoa also have high nutritional value, as well as high antioxidant and anticancer activities (Gawlik-Dzik et al., 2013). Sowthistle (*Ixeris dentata* Nakai) is a perennial herb with antioxidant activity (Kim et al., 2002; Lee, 2011) that is used to treat adult diseases such as diabetes (Choi et al., 1990; Hong et al., 2010) and cancer (Kim et al., 2002). This bitter, flavorful vegetable represents a good source of β-carotene, and it has been selected as a candidate crop for CELSS (Controlled Ecological Life Support System) (Qin et al., 2008). The aim of the current study was to develop a Planting-density Growth Harvest (PGH) chart in order to easily estimate the growth and productivity of hydroponically grown quinoa and sowthistle in relation to planting density in a closed-type plant production system.

Materials and Methods

Plant Materials

Seeds of quinoa (home seed production) and sowthistle (Aram seed, Korea) were sown in polyurethane sponges (2.5 × 2.5 × 2.5 cm). The experiments were conducted from December 2, 2014 to January 14, 2014 for quinoa and from March 12, 2013 to April 30, 2013 for sowthistle. The plants were grown in a closed-type plant production system (770 × 500 × 300 cm, L × W × H) at Jeju National University, Korea.

Closed-type Plant Production System

Fluorescent lamps with three-band radiation (55W, Philips Co. Ltd., Amsterdam, the Netherlands) were used. Light in-

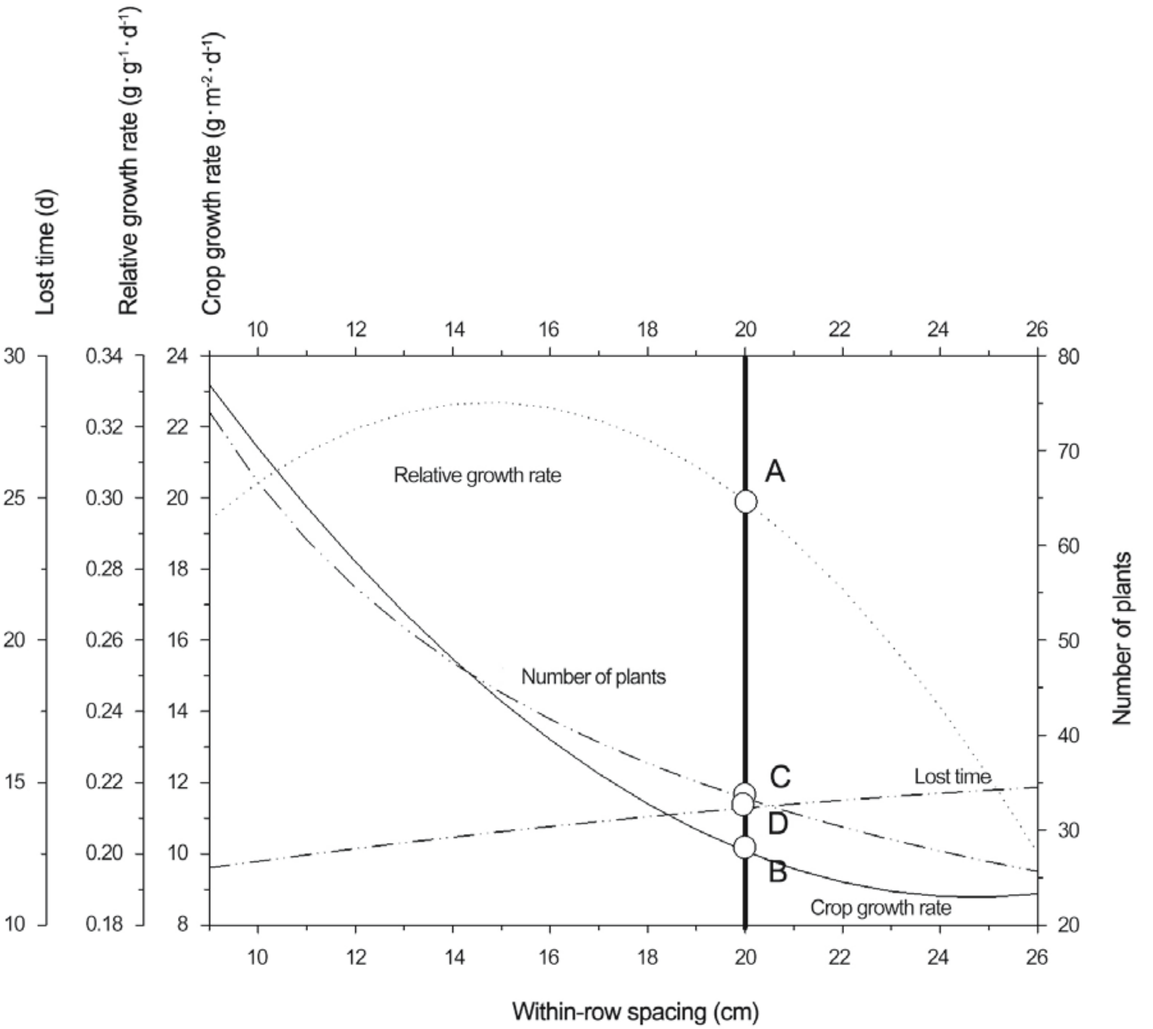

Fig. 1. Estimation of changes in growth factors with planting density for quinoa. A, B, C, and D indicate the relative growth rate, crop growth rate, number of plants, and lost time at within-row spacing = 20 cm, respectively.

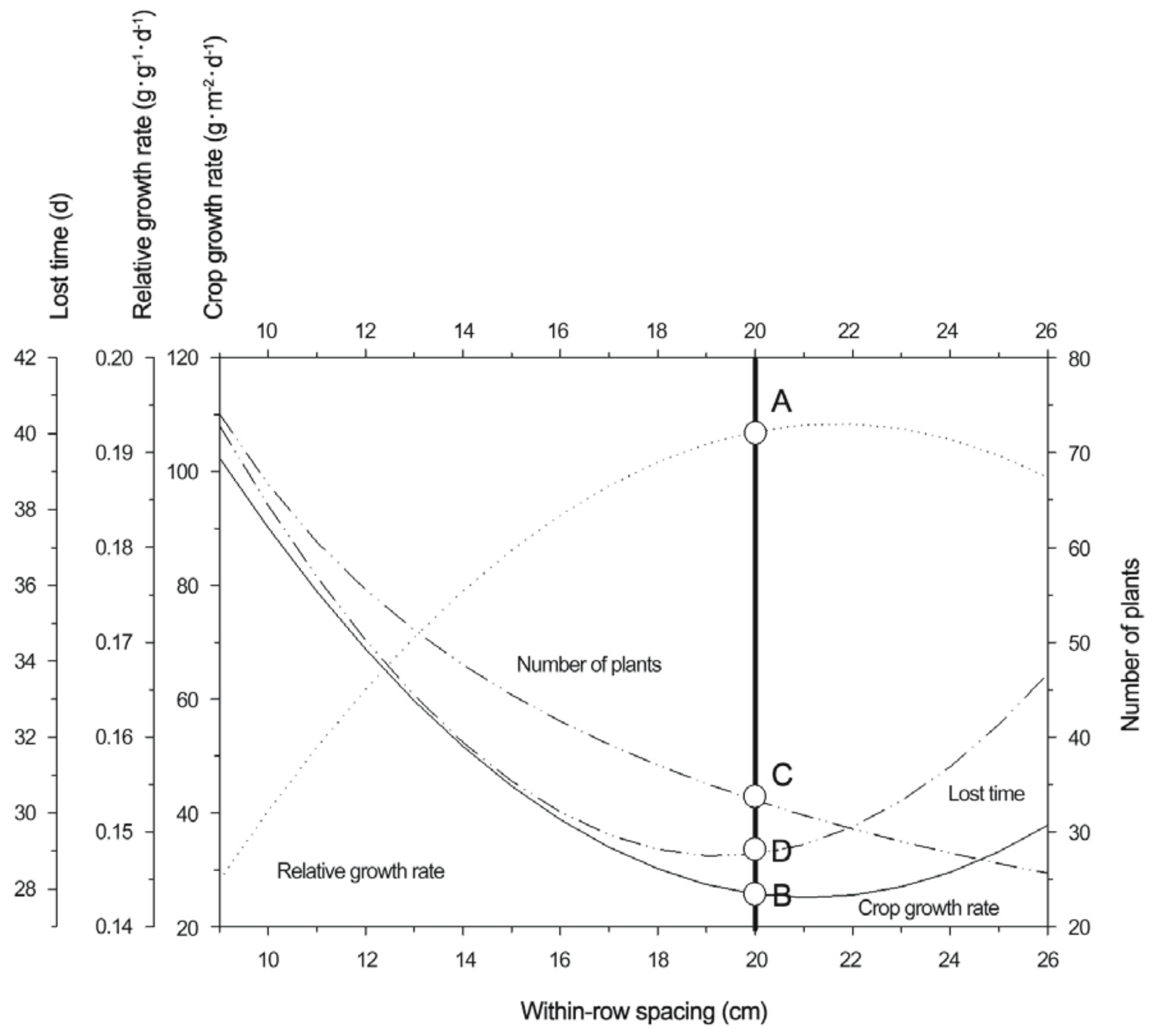

Fig. 2. Estimation of changes in growth factors with planting density for sowthistle. A, B, C, and D indicate the relative growth rate, crop growth rate, number of plants, and lost time at within-row spacing = 20 cm, respectively.

tensity (photosynthetic photon flux, PPF), temperature and relative humidity, and CO_2 concentration were measured with a quantum sensor (LI-190, LI-COR, Lincoln, NB, USA), a temperature/humidity sensor (HMP45AC, Campbell Scientific, Logan UT, USA), and a CO_2 sensor (GMP222, Vaisala, Helsinki, Finland), respectively. For quinoa and sowthistle, the light intensity was set to 140 μmol·m^{-2}·s^{-1} with a photoperiod of 12 h. The inside air temperature, relative humidity, and CO_2 concentration were maintained at 20 to 25°C, 65 to 75%, and 800 to 1,000 μmol·mol^{-1}, respectively. All data were collected every 10 min using a data logger (CR-1000, Campbell Scientific, Logan, UT, USA).

Nutrient film technique (NFT) systems (240 × 60 × 200 cm, L × W × H) were used for plant growth, with the circulation of nutrient solution set to 10-min ON and 10-min OFF. The nutrient solution was supplied when the first true leaf appeared. The ECs of the nutrient solution were adjusted to 2.0 dS·m^{-1} every two days for both quinoa and sowthistle. The pH of the nutrient solution was 5.5-6.5.

Growth and Yield at Different Planting Densities

Growth and yield were analyzed at four planting densities: a 15-cm between-row spacing with within-row spacing of 15 × 10 cm (67 plants/m^2), 15 × 15 cm (44 plants/m^2), 15 × 20 cm (33 plants/m^2), and 15 × 25 cm (27 plants/m^2) (Cha et al., 2014). Shoot dry weight was measured after drying the plants for 72 h at 70°C in an oven (Vision Sci., Korea).

The experiments were conducted with a completely randomized block design. Statistical analyses were carried out using the SAS system (Release 9.01, SAS institute Inc., Cary, NC, USA). Parameters for the model equations were obtained with SAS software using the Gauss-Newton method.

Model Construction

The number of plants (plants/m^2) according to planting density was calculated as follows:

$$\text{Number of plants} = 100/(\text{BRS}\cdot\text{WRS}) \quad (1)$$

where BRS and WRS are between-row spacing (m) and within-row spacing (m), respectively. BRS was fixed at 0.15 m in this system.

An expolinear growth function was used to quantify plant growth. The following model was used to express dry weight according to time (Goudriaan and Monteith, 1990):

$$W = C_m / R_m \cdot \ln\{1 + \exp[R_m \cdot (t - t_b)]\} \quad (2)$$

where W is shoot dry weight (g·m^{-2}) at t (days after transplanting), C_m is CGR (g·m^{-2}·d^{-1}), R_m is RGR (g·g^{-1}·d^{-1}), and t_b is the time at which the crop effectively reaches linear growth phase (lost time, d). Parameters according to planting density were obtained with SAS software using the Gauss-Newton method (SAS Institute, Cary, NC, USA).

CGR, RGR, and lost time in the expolinear function (Eq. 1) were fitted to the following quadratic function:

$$Y = a + b \cdot \text{WRS} + c \cdot \text{WRS}^2 \quad (3)$$

where Y is CGR (g·m^{-2}·d^{-1}), RGR (g·g^{-1}·d^{-1}), or lost time (day).

Shoot fresh weight was fitted to the following linear function, since fresh weight is closely related to dry weight (Heuvelink and Marcelis, 1989).

$$Y = a + b \cdot \text{SDW} \quad (4)$$

where Y is shoot fresh weight (g/plant) and SDW is shoot dry weight (g/plant).

Harvesting time and yield were calculated using the expolinear growth function.

Results and Discussion

We analyzed the relationship between growth factors and planting density. Crop growth rate (CGR), relative growth rate (RGR), and lost time differed under different planting densities. The CGR of quinoa was the lowest at within-row spacing (WRS) = 22, and RGR was the highest at WRS = 19 (Fig. 1). For sowthistle, the CGR and lost time were the lowest at WRS = 21 and 19, respectively, and RGR was the highest at WRS = 22 (Fig. 2).

Considering the shoot fresh weight per plant and shoot fresh weight per area, there are optimum planting density for both plants (Figs. 3, 4, 5, and 6). Shoot dry weight exhibited a tendency similar to shoot fresh weight for both plants. The marketable rate for both plants was 100% at planting densities of 27 to 67 plants/m^2 (Figs. 5 and 6).

Based on the growth data and existing models, PGH charts were constructed for quinoa and sowthistle. Using these charts, we could easily determine CGR, RGR, lost time, marketable rate, marketable yield per area, and harvesting time based on at least two factors. For instance, based on WRS (= 20 cm) and fresh weight per plant at harvest (= 50 g), we estimated all growth and harvest factors for quinoa shown in Figs. 1, 3, and 5; the results are shown in Table 1. The planting density, crop growth rate, relative growth rate, lost time, shoot dry weight per plant, harvesting time, mar-

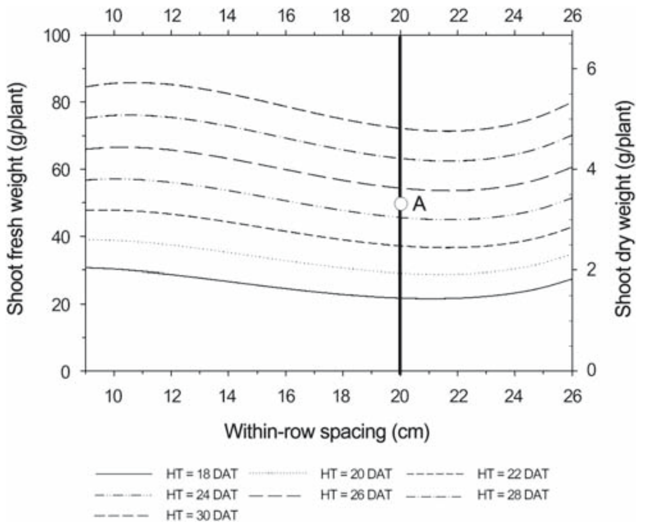

Fig. 3. Relationship among shoot fresh weight per plant, shoot dry weight per plant, harvesting time (HT), and planting density in quinoa. A indicates harvesting time = 25 DAT, shoot dry weight per plant = 3.4 g at within-row spacing (WRS) = 20 cm, and shoot fresh weight per plant at harvest = 50 g. DAT indicates days after transplanting.

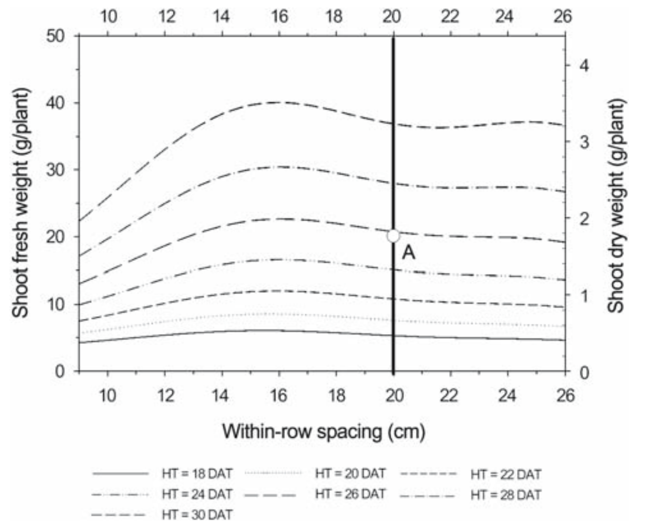

Fig. 4. Relationship among shoot fresh weight per plant, shoot dry weight per plant, harvesting time (HT), and planting density in sowthistle. A indicates harvesting time = 26 DAT, shoot dry weight per plant = 1.8 g at within-row spacing (WRS) = 20 cm, and shoot fresh weight per plant at harvest = 20 g. DAT indicates days after transplanting.

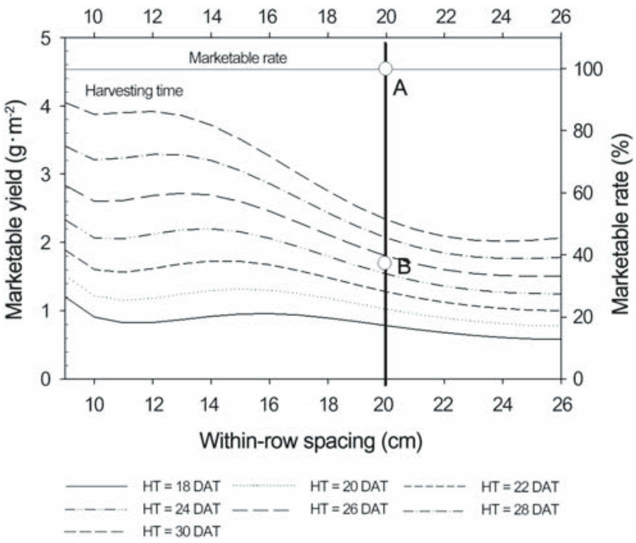

Fig. 5. Relationship among marketable yield, marketable rate, harvesting time (HT), and planting density in quinoa. A indicates marketable yield = 1.7 kg·m^{-2}, B indicates marketable rate = 100%, harvesting time = 25 DAT at within-row spacing (WRS) = 20 cm, and shoot fresh weight per plant at harvest = 50 g. DAT indicates days after transplanting.

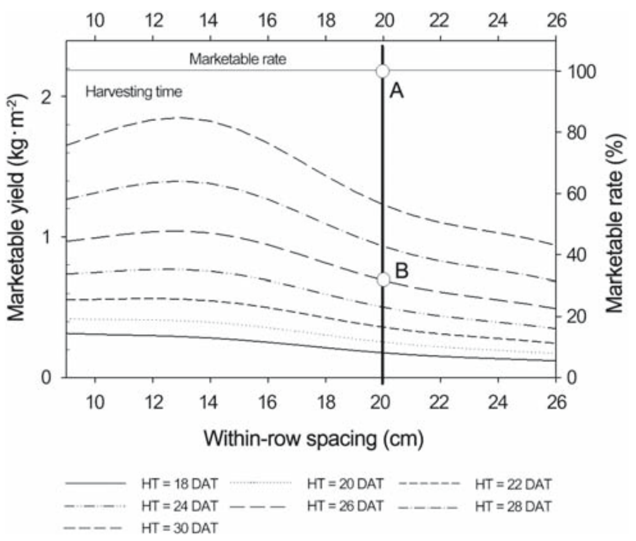

Fig. 6. Relationship among marketable yield, marketable rate, harvesting time (HT), and planting density in sowthistle. A indicates marketable yield = 0.7 kg·m^{-2}, B indicates marketable rate = 100%, harvesting time = 26 DAT at within-row spacing (WRS) = 20 cm, and shoot fresh weight per plant at harvest = 20 g. DAT indicates days after transplanting.

Table 1. Growth and harvest factors of quinoa at within-row spacing = 20 cm and fresh weight per plant at harvest = 50 g (See Figs. 1, 3, and 5)

Growth factor		Harvest factor	
Within-row spacing	20 cm	Shoot fresh weight	50 g/plant
Planting density	33 plants/m^2	Shoot dry weight	3.4 g/plant
Crop growth rate	10.1 g·m^{-2}·d^{-1}	Harvesting time	25 days after transplanting
Relative growth rate	0.30 g·g^{-1}·d^{-1}	Marketable rate	100%
Lost time	14 days	Marketable yield	1.7 kg·m^{-2}

Table 2. Growth and harvest factors of sowthistle at within-row spacing = 20 cm and fresh weight per plant at harvest = 20 g (See Figs. 2, 4, and 6)

Growth factor		Harvest factor	
Within-row spacing	20 cm	Shoot fresh weight	20 g/plant
Planting density	33 plants/m^2	Shoot dry weight	1.75 g/plant
Crop growth rate	25.8 g·m^{-2}·d^{-1}	Harvesting time	26 days after transplanting
Relative growth rate	0.19 g·g^{-1}·d^{-1}	Marketable rate	100%
Lost time	29 days	Marketable yield	0.7 kg·m^{-2}

ketable rate, and marketable yield were 33 plants/m^2, 10.1 g·m^{-2}·d^{-1}, 0.3 g·g^{-1}·d^{-1}, 14 days, 3.4 g/plant, 25 days after transplanting, 100%, and 1.7 kg·m^{-2}, respectively. Also, based on WRS (= 20 cm) and fresh weight per plant at harvest (= 20 g), we estimated all growth and harvest factors for sowthistle shown in Figs. 2, 4, and 6; the results are shown in Table 2. The planting density, crop growth rate, relative growth rate, lost time, shoot dry weight per plant, harvesting time, marketable rate and marketable yield were 33 plants/m^2, 25.8 g·m^{-2}·d^{-1}, 0.19 g·g^{-1}·d^{-1}, 29 days, 1.75 g/plant, 26 days after transplanting, 100%, and 0.7 kg·m^{-2}, respectively.

Planting density is one of the most important factors affecting plant growth and yield (Maynard and Scott, 1998; Leskovar et al., 2000). In order to determine optimum planting density, various factors such as solar radiation, the growth system, and cultivar traits should be considered (Sanders et al., 1999; Cavero et al., 2001). Although quinoa and sowthistle were selected for our case study, the charts can be extended to various plants for estimating growth and harvest factors, which will be useful for designing closed-type plant production systems.

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