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Full Length Research Paper

Research of plant type and light distribution of tomatoes determined by imaging technology

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In order to determine the canopy structure of tomato plants (*Lycopersicon esculentum* Mill.) that has the advantages of increasing light interception and decreasing planting area, the authors selected two representative tomato plant type strains, namely, leaf-up and leaf-down as testing materials. Plant type structure parameters, leaf area index (LAI) and light distribution (gap fraction) were measured using imaging technology. At planting spacing of 0.4, 0.5, and 0.6 m, the effective LAI of leaf-up tomatoes was all greater than that of leaf-down tomatoes. At the azimuths and zeniths, gap fractions of leaf-up tomatoes were less than those of leaf-down tomatoes. Overall, the interceptive capability of leaf-up tomatoes was superior to that of leaf-down tomatoes. The leaf-up type is a better plant type for close planting and intercepts more light.

Key words: Tomato, plant type, plant spacing, light distribution, imaging technology.

INTRODUCTION

Tomato (*Lycopersicon esculentum* Mill.) is a main kind of photophilous plant throughout the world. It is known that light is the most important factor affecting tomato growth (McAvoy et al., 1988; McCall, 1992; Demers et al., 1998). A proportion of the solar radiation falling on the canopy is accepted by the leaves and stems, whereas the remainder is either transmitted to the ground or is reflected. The radiation environment in the canopy is very complex, even if the intensity of radiation above the canopy is the same. Light distribution is influenced by canopy architecture, which is determined by the size, shape and spatial arrangement of constituent plants (Sampson et al., 1993; Gretchen, 1995; Maddonni et al., 2001; Lhotka et al., 2006). In comparison, narrow plant spacing could increase light interception in the tomato population (Papadopoulos et al., 1997). Light attenuation in the tomato canopy in the sloped field was smaller than that in the flat field (Higashide, 2009). In addition, tomato is characterized by plant types of different shapes (Feng et al., 2008), which could improve the distribution and utilization of light in the canopy.

Imaging technology is the method applied to create, preserve, process or analyze images. It has been widely used in agriculture, such as measurement, classification and management, which has the advantages of being easy, quick, and providing a permanent record (Van Gardingen et al., 1999; Fernandes et al., 2004; Neto et al., 2006; Wang et al., 2008; Boese et al., 2008). Ichnography is a horizontal section of objects, showing its true dimensions according to a geometric scale (Foley et al., 1993). Hemispherical photography is an effective tool to describe the architecture and radiation regime of plant canopies in a quantitative manner, with the zenith in the center of the image and the horizons at the edges to determine which parts of the sky are visible and which parts are obstructed by a plant canopy (Jonckheere et al., 2004; Cescatti et al., 2007).

Presently, the research of tomato plant type is just beginning. The inheritance of several plant type characters in truss tomato was studied (Feng et al., 2008). This study described the application of imaging technology of ichnography and hemispherical photography on tomato plant structure. The aims were: 1) To compare the conventional LAI (LAIcon) and the effective LAI (LAIeff) of leaf-up and leaf-down tomatoes by direct measurement and indirect measurement. 2) To confirm the relationships

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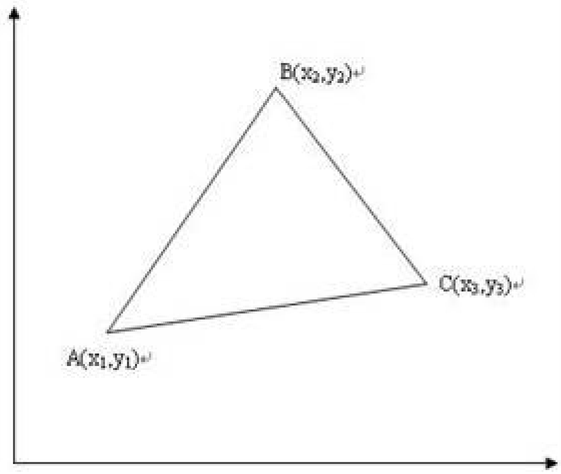

Figure 1. The coordinate plot of a trigon (ABC).

Figure 2. Shapes of the two representative tomato plant type strains, namely, leaf-up and leaf-down.

between tomato architecture and light distribution.

MATERIALS AND METHODS

Plant materials and study site

The study was conducted in the vegetable plot of Shenyang Agricultural University, Liaoning, China (123°23′E, 41°48′N, and 50 m above sea level) where the declination is 7°44′. The plant materials the authors used were truss tomatoes of erect plant type (leaf-up) and droopy plant type (leaf-down) (Figure 2), planted in the same size pots in the greenhouse , with sufficient space for growth in order not to cover each other or affect plant shape. Tomato plants at 10th leaf age were moved in the field of an open area. All of leaves were measured on 3 and 4 June 2009, when there was an evenly overcast sky with no direct sunlight and no strong wind. In both leaf-up and leaf-down tomato populations (4 × 4 plants), the plant spacing was 0.4, 0.5 and 0.6 m respectively, with random arrangement and three replications.

Software processing

Length and angle

Plant type parameters, including base angle, opening angle, drooping angle, opening length, drooping length, leaf length, leaf width, plant height, plant width, node length, and node width (Figure 4), which have a direct bearing on plant shape characteristics, were measured by tomato plant type measurement software (ToPM-1). By selecting characteristic points in the resulting image, all of these parameters can be considered as measurements of angle and line. Through scale, an unknown size was computed from a known size in the software (Feng et al., 2009).

Point A (x1, y1), Point B (x2, y2), Point C (x3, y3) (Figure 1)

a =#BC#= $\sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}$

b =#AC#= $\sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$

c =#AB#= $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$

BAC= arccos $(b^2 + c^2 - a^2)/2bc$

Leaf area and the conventional LAI (LAIcon)

The conventional LAI (LAIcon) is the total one-sided area of leaf per unit ground surface area (Waston, 1947). Leaf area was measured by Photoshop software; the relative error of the method was 0.11 (Xiao et al., 2005). A pixel is one of the many tiny dots that make up the representation of a picture in a computer's memory. The color and intensity of each dot is chosen individually by the computer to represent a small area of the picture, so area can be calculated by pixels. In Photoshop, tomato outline was selected by magic wand tool, and pixel values were found from histogram. The area of reference object was known. Then through the pixel scale of leaf and reference object, the area of leaf was computed by the following formula:

Area leaf = ($Pixels_{leaf}$ / $Pixels_{refe}$) × $area_{refe}$

LAIcon = $area_{leaf} / area_{ground}$

Gap fraction and the effective LAI (LAIeff)

Gap fraction is the proportion of visible sky within a given sky sector, where a sky sector is defined by a range of zenith θ (angle relative to the zenith) and azimuth angles α (angle relative to true north) (Figure 3). Zenith divisions define a series of annuli that represent equal ranges of zenith angles. Azimuth divisions define a series of pie-shaped wedges that represent equal ranges of azimuth angles. A gap fraction of zero (0) means that the sky is completely blocked (obscured) in a given sky sector. Conversely, a gap fraction of one (1) indicates that the sky is completely visible (not obscured) in a given sky sector.

LAIeff calculated in this manner of Hemiview software is termed "effective LAI" (Chen et al., 1995; Demarez et al., 2008; Montes et

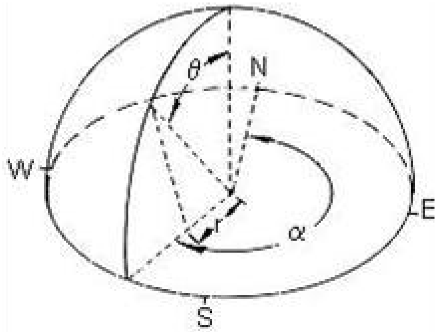

Figure 3. Diagram of the azimuth (α) and zenith (θ) angles. Zenith is the angle relative to the zenith and azimuth is the angle relative to true north.

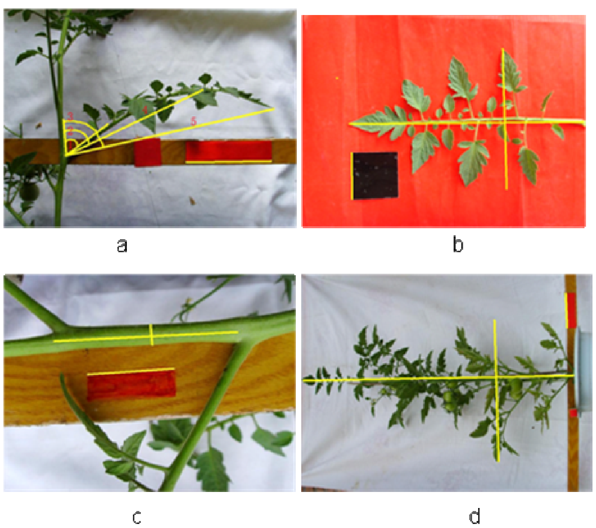

Figure 4. Measured parts of the tomato plant. Part A: base angle(1), opening angle(2), drooping angle(3), opening length(4), and drooping length(5); Part B: leaf length and leaf width; Part C: node length and node width; Part D: plant height and plant width.

al., 2007). The calculation uses Beer's Law, which can be expressed as follows:

LAIeff= $-\ln G(\theta)/K(\theta)$

Where LAIeff is the effective LAI, G is the gap fraction, K (θ) is the extinction coefficient at angle θ, and θ is the zenith angle. This method based on the measurement of light transmission through canopies has been widely applied to the estimation of LAI (Montes et al., 2007; Jonckheere et al., 2004).

Image showing

Taking photographs of leaf, stem and the whole plant are a simple process. The digital camera should be paralleled with subjects, including the geometric scale (Figure 4). When taking pictures of leaf, it was needed to spread tomato leaf flat out on the background board, since the tomato plant type measurement (ToPM-1) software could not measure curve (Feng et al., 2009), and it was necessary for measuring area (Xiao et al., 2005).

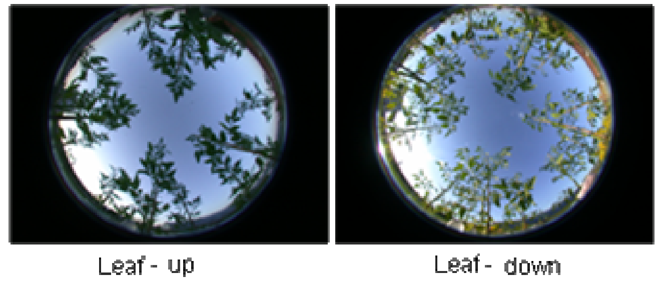

Figure 5. Canopy images of leaf-up and leaf-down tomatoes were recorded using a Nikon Coolpix 995 digital camera of a 180° fisheye.

Hemispherical images were recorded using a Nikon Coolpix 995 digital camera with a 180° fisheye lens attached on a self-leveling mount. The camera was pointed upward and oriented with magnetic north in a known direction. Operated by a self-timer, the camera took images from under the canopy. The image is an equiangular projection for a full 180° field of view (Figure 5), which has been used to calculate solar radiation regimes and plant canopy characteristics such as the effective leaf area index (LAIeff) (Chen et al., 1995; Demarez et al., 2008; Montes et al., 2007). The ideal conditions for taking photographs are an evenly overcast sky with no strong wind. In the absence of an overcast sky, photographs are best taken predawn or post sunset, when there is no direct sunlight (Hale et al., 2002). Photographs taken with direct sunlight in the field of view tend to be unevenly exposed, with a bright region around the sun and with reflections on foliage. Uneven sky lighting could make a mistake in pixel and threshold values. So the quality of pictures is very important. HemiView uses the total intensity of each pixel to determine whether it should be counted as obstructed or visible sky. Pixels which are brighter than a 'Threshold' intensity value are counted as visible. Darker pixels are counted as obstructed. The software uses a model to estimate how much solar radiation will be received, both directly from the sun and diffuse radiation from the whole sky, and over the whole period of interest. This could be a day, a month or a year.

Statistical analysis

Means and significant differences were compared by independent-samples T test of SPSS software.

RESULTS

Structural characteristics of the two representative tomato plant types

Using tomato plant type measuring software, the relative error of measuring length was 0.015 and relative error of measuring angle was 0.013 (Feng et al., 2009). Table 1 shows that the drooping angle of leaf-down was greater than its opening angle and considerably greater than the drooping angle of leaf-up which was less than 45° and similar to its opening angle. The base angle of leaf-up was smaller than that of leaf-down. Correspondingly, the

Table 1. Average base angle, opening angle, drooping angle, opening length, drooping length, leaf length, leaf width and leaf area of leaf-up and leaf-down tomatoes by independent-samples T test.

Plant type	N	Base angle (°)	Opening angle (°)	Drooping angle (°)	Opening length (cm)	Drooping length (cm)	Leaf length (cm)	Leaf width (cm)	Leaf area (cm^2)
Leaf-up	186	37.6903	42.3452	43.5206	25.2269	25.4522	26.9953	16.6065	108.8295
Leaf-down	184	50.9363	56.1612	77.2202	20.9597	25.5449	30.5583	20.9640	137.5077
Significance	-	***	***	***	***	ns	***	***	***

Significant differences by t-test, N: numbers of sample. ns: non-significant at p = 0.05; ***: significant at p = 0.0001.

Table 2. Average length and width of node and plant of leaf-up and leaf-down tomatoes by independent-samples T test.

Plant type	N	Node length (cm)	Node width (cm)	N	Plant height (cm)	Plant width (cm)
Leaf-up	235	4.5751	0.7601	16	75.6613	38.6500
Leaf-down	217	5.1418	0.8266	16	82.4944	52.0556
Significance	-	***	**	-	***	***

Significant differences by t-test, N: numbers of sample. ns: non-significant at p = 0.05; **: significant at p = 0.01. ***: significant at p = 0.0001.

opening length and drooping length of leaf-up were essentially the same. Compared with leaf-down plants, the leaves and nodes of leaf-up tomatoes were shorter and erect (Tables 1 and 2).

Leaf area index of the two representative tomato plant types

In Figure 6, LAIcon and LAIeff increased with a decrease in plant spacing. The largest LAIcon and LAIeff were those of leaf-up tomatoes at plant spacing of 0.4 m. At the plant spacing of 0.4, 0.5 and 0.6 m, LAIcon of leaf-up was lower and LAIeff of leaf-up was higher than those of leaf-down. LAIcon was computed with leaf area. But LAIeff was related with area of intercepting light, which depends on incident radiation, canopy structure and optical properties (Jonckheere et al., 2004). Since leaf-up and leaf-down tomatoes were different in their morphology, LAIcon and LAIeff were different.

Light distribution of two representative tomato plant types in different plant spacing

Light distribution in azimuths

In Figure 7, the concave parts are dense vegetation; the convex parts are spaces of light where gap fractions were higher. At the same plant spacing and with different azimuths, gap fractions of leaf-up tomato populations were less than those of leaf-down populations; consequently, the amount of light intercepted by the leaf-up tomatoes was greater than that of the leaf-down tomatoes.

At different plant spacing of 0.4, 0.5 and 0.6 m, with a decrease in plant spacing, gap fractions decreased, whether leaf-up or leaf-down. At plant spacing of 0.4 m, gap fractions of the leaf-up tomatoes were lowest. In this study, gap fractions of leaf-up tomatoes at plant spacing of 0.6 m were less than those of leaf-down at 0.4 m plant spacing.

Light distribution in zeniths

From Figure 8, the following results were obtained:

1. Plant spacing = 0.4 m

Zenith = 1.0° to 7.0°, leaf-up gap fraction = leaf-down gap fraction = 1
Zenith = 9.0° to 23.0°, leaf-up gap fraction > leaf-down gap fraction
Zenith = 25.0° to 81.0°, leaf-up gap fraction < leaf-down gap fraction

2. Plant spacing = 0.5 m

Zenith = 1.0° to 13.0°, leaf-up gap fraction = leaf-down gap fraction = 1
Zenith = 15.0° to 81.0°, leaf-up gap fraction < leaf-down

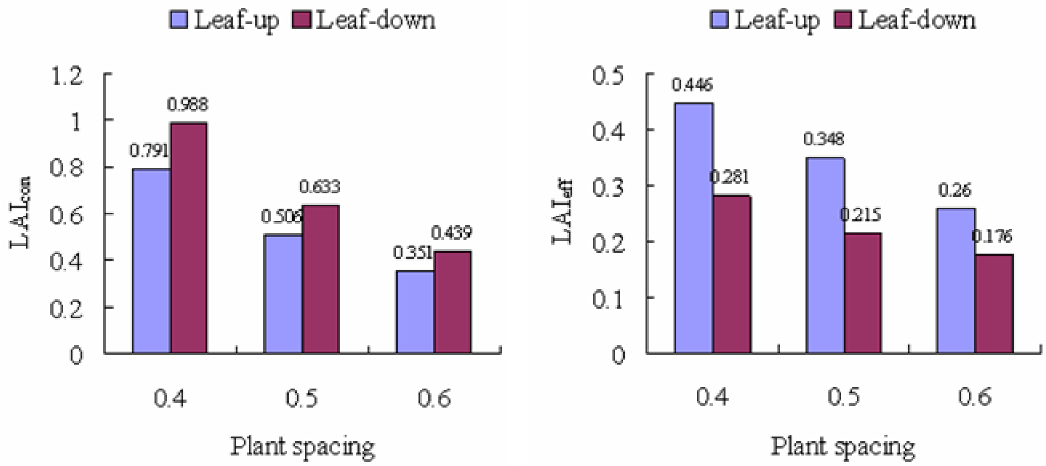

Figure 6. The conventional LAI (LAIcon) and the effective LAI (LAIeff) of leaf-up and leaf-down plant type tomatoes in the plant spacing of 0.4, 0.5 and 0.6 m.

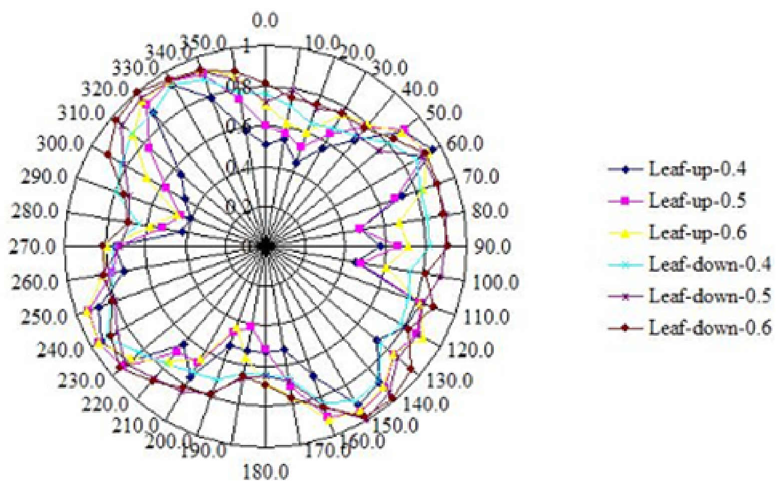

Figure 7. Gap fraction distribution of the two representative tomato plant types of leaf-up and leaf-down for different azimuths and at plant spacing of 0.4, 0.5 and 0.6 m.

gap fraction

3. Plant spacing = 0.6 m

Zenith = 1.0° to 19.0°, leaf-up gap fraction = leaf-down gap fraction = 1
Zenith = 21.0° to 39.0°, the difference between them was not significant.
Zenith = 41.0° to 81.0°, leaf-up gap fraction < leaf-down gap fraction.

When the gap fraction of the zenith was 1, there was visible sky and no leaves. Furthermore, the higher the plant spacing, the greater were the gap fraction and the range of zenith angle. The zenith angle of places was greater than 81° where closed to horizon, the gap fractions were decreased greatly and there was no significant difference between the two representative plant type tomatoes. At the plant spacing of 0.4, 0.5 and 0.6 m, with a decrease in plant spacing, gap fractions also decreased. Overall, gap fractions of leaf-up tomatoes were smaller than those of leaf-down tomatoes, and their performance was more stable and obvious in the middle and lower parts of the canopy.

DISCUSSION

Plant type parameters and light parameters were both measured using digital imaging, which has the

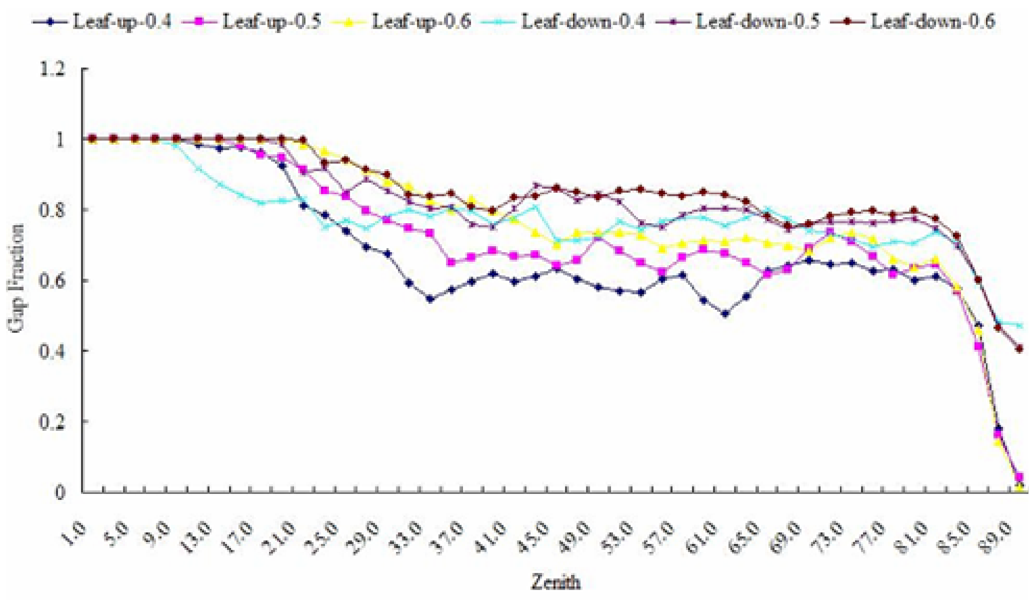

Figure 8. Gap fraction distribution of the two representative tomato plant types of leaf-up and leaf-down for different zeniths and at plant spacing of 0.4, 0.5 and 0.6 m.

advantages of being easy, quick, and accurate. On the basis of tomato characteristics, the authors developed the tomato plant type measurement software (ToPM-1) (Feng et al., 2009). Considering the pinnate compound leaves of the tomato and the co-existing parameters of leaf length and width, ToPM-1 could not be used to measure curve length; however, we put leaves by using plastic transparent plates in order to measure leaf length and width.

The HemiView canopy analyzer has previously been applied in research on tree canopies (Keeling et al., 2007; Hanssen et al., 2007). In cases where the camera was very close to the ground, it was necessary to crouch or even lie down to get out of the lens' field of view. In order to adapt the device to low vegetation such as the tomato canopy, the authors successfully modified the self-leveling mount using a low stand to support the mount and using a viewfinder to avoid including the photographer in the shooting range. The method was convenient for obtaining large amounts of data. The ideal conditions for taking hemispherical canopy photographs are an evenly overcast sky with no strong wind. In the absence of an overcast sky, photographs are best taken predawn or post sunset, when there is no direct sunlight. Canopy photographs taken with direct sunlight in the field of view tend to be unevenly exposed, with a bright region around the sun and with reflections on foliage or other objects. Uneven sky lighting makes it difficult to precisely distinguish foliage from canopy openings using a threshold technique. Bright reflections on leaves could be mistaken for openings (Hale et al., 2002).

In this study, there were two definitions of LAI. The conventional LAI can be simply defined as the amount of leaf surface area per unit ground area, which was calculated by direct LAI measurement. Direct method is the most accurate; however it has the disadvantage of being extremely time-consuming. The effective LAI can be assessed from the angular distribution of gaps and the angle of incidence of the sunbeam based on the Beer-Lambert law, which measured by Hemiview canopy analyzer of indirect non-contact method (Jonckheere et al., 2004). Leaf area index (LAI) is widely used to describe the photosynthetic surface of plant canopies. Leaf area is an important photosynthetic factor, but leaf angle also affects intercepting light. So the effective LAI (LAIeff) was better on considering incident radiation and canopy structure.

Papadopoulos (1997) reviewed that greater fruit yields are possible in narrow compared with wide plant spacing in greenhouse tomato, owing to increased light interception. In our study, we compared light distribution in different plant spacing, and found that gap fractions in narrow plant spacing were smaller, whether leaf-up or leaf-down tomatoes. So manipulation of plant spacing is an important means to increase light interception and its efficient use in tomato. Higashide (2009) reported that light interception was affected by leaf angle of plants grown on sloped field. But that is not enough to illuminate that effect of plant architecture on light distribution, so the authors chose two representative tomato plant types of leaf-up and leaf-down, having significant difference in plant shape. The authors accordingly found that gap fractions of leaf-up tomatoes were lower than those of leaf-down tomatoes, a feature that is strongly related to the straight and erect properties of the leaf. The straight property indicates the extent of bending (drooping angle), whereas the erect property reflects the leaf base angle and opening angle. Compared to the leaf-down tomatoes, the straight and erect properties of the leaf-up tomatoes facilitated better light distribution and reduced light wastage.

At different zeniths, gap fractions of leaf-up tomatoes were higher than those of leaf-down tomatoes in the upper parts of the canopy, but lower than those of leaf-down tomatoes in the middle and lower parts, particularly at the plant spacing of 0.4 m. It is possible that because the leaves in these middle and lower parts were fully extended, their characteristics were more marked. At low plant spacing, the leaves covered each other to a greater extent.

Such a covering should intercept more light; however, as the light transmitted by the canopy gradually decreases and gap fractions of the top parts of leaf-down canopy were lower than those of leaf-up, particularly when grown at plant spacing of 0.4 m. Consequently, less light was intercepted by the middle and lower parts of the leaf-down tomato canopy than by leaf-up tomato canopy. On the basis of the above findings, it can be concluded that light distribution is determined by both plant type and plant spacing.

Leaf-up tomato structure is erect and straight; thus, light transmission in the top parts of the canopy is better than that of the leaf-down canopy, enabling better light interception in the middle and lower parts of the canopy. Light interception of leaf-up tomato was better than leaf-down tomato. To consider from light energy utilization, leaf-up tomato has certain potential for increasing production and needs further investigation.

Conclusions

This study had shown that it is useful to analyze canopy structure using image technology. The major conclusions of the work were as follows.

1. With a decrease in planting spacing, both LAIcon and LAIeff were increased. Considering the effect of canopy structure, LAIcon and LAIeff were different at the same plant spacing. The more leaf areas, the more was LAIcon. It was not true that areas were larger and plant could intercept more light, which was also determined by leaf angle.
2. Light distribution was affected by both plant spacing and plant structure, which was related with angular distribution and clumping of the foliage. Straight and erect leaves of tomato (Leaf-up) are favorable to light transmission and interception.

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