

Characteristics of the Light Reception Systems Concerning a Kenaf Individual Model*

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Abstract

It is thought that plants have evolved to modulate the amount of light received by the leaves in order to raise the photosynthetic rate. By investigating a plant condensing system, it is small and a directive low condensing system may be able to develop. A compact condensing system with low directivity may be able to be developed by investigating the condensing method by a plant. This paper presents the results of an investigation into light reception characteristics using the numerical-analysis program (LAPS), with emphasis on a kenaf plant (*Hibiscus cannabinus*) with division leaf of diversity. From this analysis, the relationship between the range of movement for the light source (sun) and the shoot configuration of a kenaf plant were clarified. There is a suitable shoot configuration, and the shoot configuration has a strong influence over the efficiency of light reception. The summer season is characterized by wide oscillations of the light source, and it is therefore necessary for the kenaf plant to adjust its shoot configuration in order to improve light reception.

Key words: Light Condensing System, Solar Energy, Plant Shoot, Leaf Arrangement Analysis, Genetic Algorithm, Solar Cell Module, Kenaf

1. Introduction

Because a plant's biomass is produced by photosynthesis, changes in the amount of the light received by a plant greatly influence plant's survival. Therefore, various mechanisms have evolved to increase the amount of the light received and to increase the rate of photosynthesis. In other words, plants have evolved light reception systems through various methods throughout their evolutionary history. By examining the evolutionary process leading to the light reception system of one such plant, this paper discusses the development of the compact condensing equipment with low directivity. To examine the relationship between the shoot configuration and photosynthetic rate of the leaves of a plant, we developed an analysis algorithm, LAPS (Light-Receiving Analysis Algorithm of a Plant Shoot), based on the Monte Carlo method and a Genetic Algorithm¹⁾. The directivity of light reception is investigated by observing the light from the definite light source.

To reduce shading of photosynthetic surfaces, plants evolved phototropism and the ability to modify shoot configurations (the shape and area of the leaf, leaf orientation, the lengths of branches and leaves, distribution of leaves, etc.). The shape of a leaf changes over time. Addition and reduction of biomass is not needed for this change (in this case, division of a simple leaf) in phototropism and leaf type. The shape of a leaf develops from a simple leaf to a divided leaf, and then develops from a divided leaf to a compound leaf. A plant with a

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shallow divided leaf and a deeply divided leaf is half way through its development into a compound leaf from a simple leaf. The kenaf (*Hibiscus cannabinus*) has simple leaves and divided leaves of two or more types. In this paper, the relationship between the shoot configuration of a kenaf plant and the amount of light received by the plant is examined using numerical analysis. The growth of a kenaf plant is faster than that of other plants, as an annual height of 1.5-3.5 m is reached. The growth rate of a plant is correlated with the rate of photosynthesis. It is expected that a kenaf has a highly efficient sunlight condensing characteristic compared with other plants. This paper presents the results of our investigation into the compact radiation interception system that simulated the light reception characteristics of the kenaf. The objective of our investigation was to obtain information about the development of a highly efficient biological radiation interception system for applications in devices such as solar cell modules, radiation heat exchangers, etc.

2. Characteristic of Kenaf

2.1 Sunlight condensing characteristic of a kenaf

Figure 1 shows an individual kenaf plant. Light reception efficiency is defined as the value of the light received by the system divided by the volume occupied by the system. Light reception efficiency means the value of amount of the light received by system volume. Since the growth of a kenaf plant is fast, the stalk is used for cloth, rope, and paper manufacture. The light reception efficiency of kenaf has a high value compared with other plants because it grows quickly. Therefore, this study examines a compact light reception system with high light reception efficiency by examining the relationship between the shoot configuration of kenaf and the light reception characteristic.

2.2 Divided leaves of kenaf

As shown in Fig. 1, a typical kenaf plant has one leaf in a low position, but it has leaves that are divided 3, 5, and 7 times positioned towards the top of the shoot (Fig. 2). The number of divisions of the kenaf leaf increases with the development of the individual plant. Because each divided leaf derives from the division of a simple leaf, the directions of all divided leaves are the same. The expectation is that the number of divisions of the leaf of a kenaf and the amount of light received by an individual are highly correlated.

2.3 Shoot configuration of a kenaf

It is the characteristic of a shoot of a kenaf to have leaves of the different number of divisions. As a result, the kenaf can intercept much solar radiation. Therefore, this paper discusses the development of the light reception system with the shoot configuration of the kenaf. The goal of this study is the proposal of a light reception system with highly efficient radiation interception capabilities.

3. Surface Element of Leaf and Light Source

3.1 Surface element of a leaf

This paper expresses each divided leaf of the kenaf by the surface element model shown in Fig. 3. Except for the simple leaf in Fig. 3 (d), the leaf length (l_e) associated with the standard area of these leaf models is about 10 cm. However, in the analysis presented in this paper, the calculation time of a computer was reduced as $l_e=45\text{mm}$. The model of the simple kenaf leaf, 3-division leaf, 5-division leaf, and 7-division leaf were divided into the surface element of the quadrangle of 98,162,188, and 166 in the analysis, respectively. The areas of the leaf models used in the analysis and the area ratios of each divided leaf are shown in Table 1. All the leaf models of Fig. 3 are symmetrical along the longitudinal axis in the figure.

3.2 Light source model

3.2.1 Solar position

In an individual plant, when a divided leaf is arranged ahead of the shoot, the light can reach back leaves. Figure 4 shows an example of an overlapping arrangement of kenaf leaves. The kenaf leaf has a complex shape and the position and direction of the leaves strongly influence the amount of light received. Furthermore, a kenaf plant can configure its shoot to accommodate the position of the sun (light source), and it is considered to compete

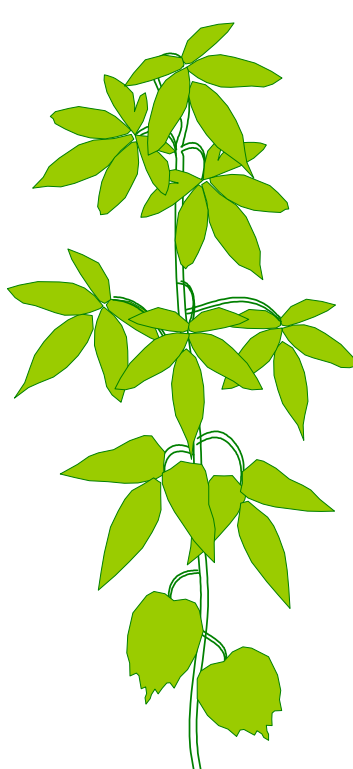


Fig. 1 Kenaf with distribution of different simple leaves

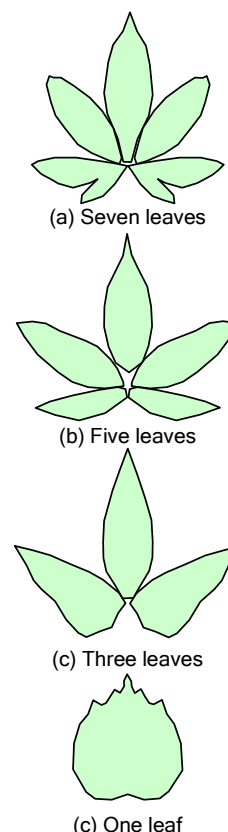
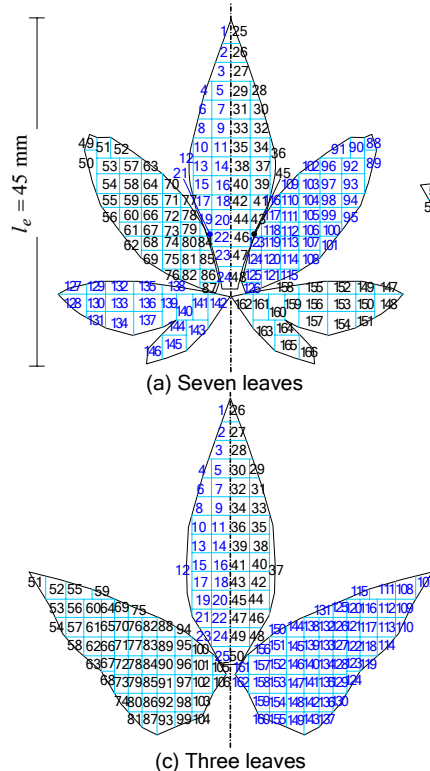
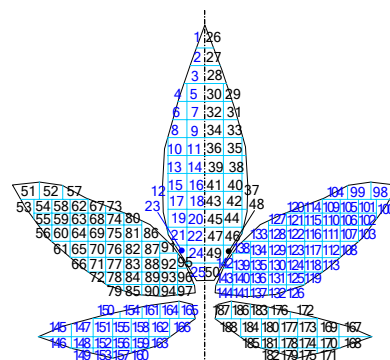


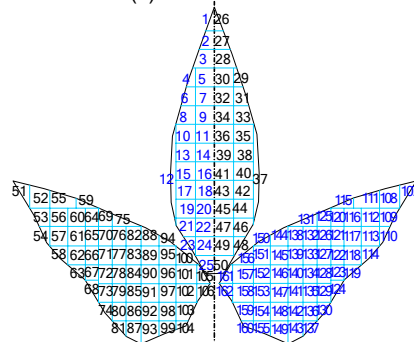
Fig. 2 Simple leaf form of a kenaf



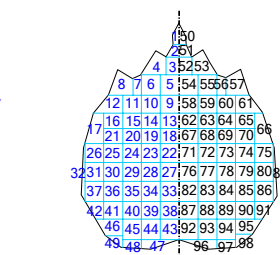
(a) Seven leaves



(b) Five leaves



(c) Three leaves



(d) One leaf

Fig. 3 Leaf model

Table 1 Area of the kenaf leaf model

The number of divided of a leaf	Area [mm ²]	Area ratio
1	479	1.0
3	709	1.48
5	753	1.57
7	794	1.66



Fig. 4 Case of the overlap of leaves

for light. The leaf at the top of the plant can take in much solar radiation, without surrounding leaves interfering. However, to maximize the amount of light received by the entire individual, the amount of light received by the leaf at the top may be controlled, so that the amount of light received by lower leaves may be increased. Furthermore, when light is too strong, the photosynthetic rate will decrease ²⁾. For this reason, the increase in the light reception efficiency of an individual plant requires that the amount of light received by the lower leaves be improved. There are many divisions of the leaves in the upper part of a kenaf, but few divisions occur in the lower leaves. Such an arrangement of the divided leaves improves the efficiency of the light received by each individual leaf of the kenaf.

3.2.2 Coordinate system

The coordinate system of an individual of a kenaf and a light source is shown in Fig. 5. A line is drawn from north to south, and south is the positive direction of the x-axis. A line is also drawn from east to west, and west is the positive direction of the y-axis. The angle of direction $\theta_{s,t}$ of the light source determines a clockwise rotation in the positive direction based on the x-axis. The origin and light sources are connected with a line segment. The angle between this line segment and the x-y flat surface is the elevation angle $\alpha_{s,t}$ of the light source.

3.2.3 Installation location of the system

The kenaf is mainly grown in warm areas, such as India and parts of Africa. The system installed in Naha in Okinawa Japan is examined in this paper. Figure 6 (a) shows the position of the sun at each time during the course of a representative day in both January and July. The trajectory of the sun in July has a wide range of directional altitude and angle compared with that in January. Therefore, to develop a radiation interception system with high light reception efficiency, and with low directivity in the summer season is important. Figure 6 (b) shows the amount of horizontal plane global solar radiation for every month and representative day in Naha ³⁾. In the winter and summer seasons, the strength of the solar radiation differs greatly. The solar position (Fig. 6 (a)) and the amount of horizontal plane global solar radiation (Fig. 6 (b)) are as symmetrical as forenoon and afternoon. Therefore, the optimal configuration of the radiation interception system in the morning and the afternoon is a symmetrical figure.

3.3 Virtual radiation plane

As shown in Fig. 5, optical particles are emitted at right angles to this plane from the random position $P_{e,q}$ of a virtual plane ($P_{v,1} - P_{v,2} - P_{v,3} - P_{v,4}$). Here, q expresses the optical particle number. In this paper, the plane of $P_{v,1} - P_{v,2} - P_{v,3} - P_{v,4}$ is described as a virtual radiation plane. The size of the virtual radiation plane was decided so that the particles of solar radiation could be emitted to the whole individual model of a kenaf. Many optical particles are emitted from the virtual radiation plane, and the amount of intercepted

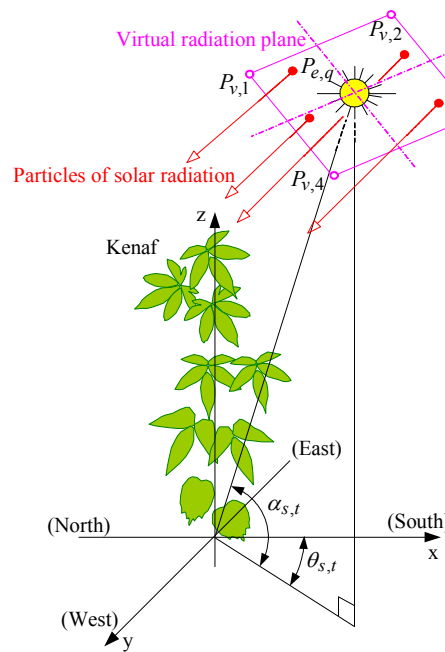
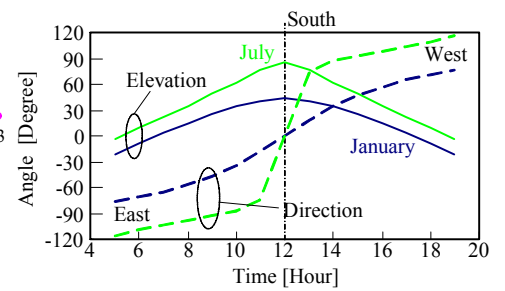
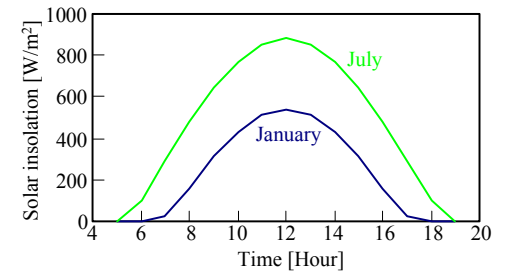


Fig. 5 Coordinate system of the sun



(a) Direction and elevation



(b) Solar insolation

Fig. 6 Insolation of the level surface in Naha

radiation is obtained from the number of optical particles that reach each leaf. The position of the central point of the virtual radiation plane is expressed by the elevation angle $\alpha_{s,t}$ and the angle of direction $\theta_{s,t}$ of the light source. The virtual radiation plane is changed for every sampling time to simulate the position of the sun, as shown in Fig. 6 (a). By the sampling time t in the representative month g , the number $nq_{g,t}$ of optical particles emitted from the virtual radiation plane is calculated using Eq. (1). However, N_a is the total number of optical particles emitted from the virtual radiation plane on a representative day, and $R_{g,t}$ is a rate of the number of optical particles emitted between $t+1$ from t . $e_{g,t}$ expresses the amount of horizontal plane global solar radiation in the time t of the representative month g (Fig. 6 (b)).

$$nq_{g,t} = N_a \cdot R_{g,t} = N_a \cdot \left(e_{g,t} / \sum_{t=0}^{Day} e_{g,t} \right) \quad (1)$$

4. Modeling Kenaf

4.1 Shoot configuration

Figure 7 shows the shoot model of a kenaf plant. In this model, the costa of a leaf and the central line of a branch of a leaf are fixed at right-angles. This paper expresses the shoot configuration of a kenaf by the elevation angle $\alpha_{n,i}$, the angle of rotation $\beta_{n,i}$, the angle of direction $\theta_{n,i}$, length of a branch of a leaf $l_{b,n,i}$, and the length of a leaf $l_{e,n,i}$. Here, n expresses the number of divisions of a leaf and i expresses the consecutive numbers of a leaf with the same number of divisions. In addition to these variables, the position of the branch supporting a leaf is also a variable of shoot configuration.

4.2 Variables of shoot configuration

The optimal shoot configuration of kenaf is examined using a Genetic Algorithm (GA) ⁴⁾. The GA can be introduced into a nonlinear problem with many variables. However, when a variable increases, many semi-optimal solutions will occur. Thus, the variables introduced into the optimization of the shoot configuration of a kenaf are set at $\beta_{n,i}$ and $\theta_{n,i}$ in Fig. 7, and variables except for these were given a priori fixed values.

4.3 Individual model of a kenaf

The components of the individual model of a kenaf are shown in Fig. 8. The direction of

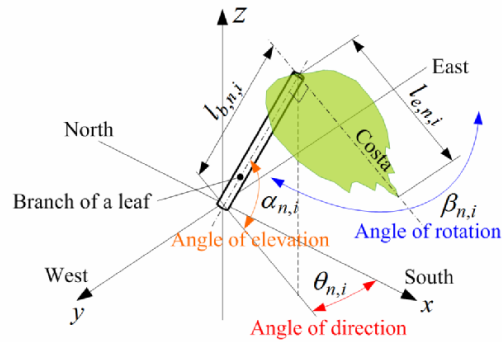


Fig. 7 Leaf and the branch of a leaf model

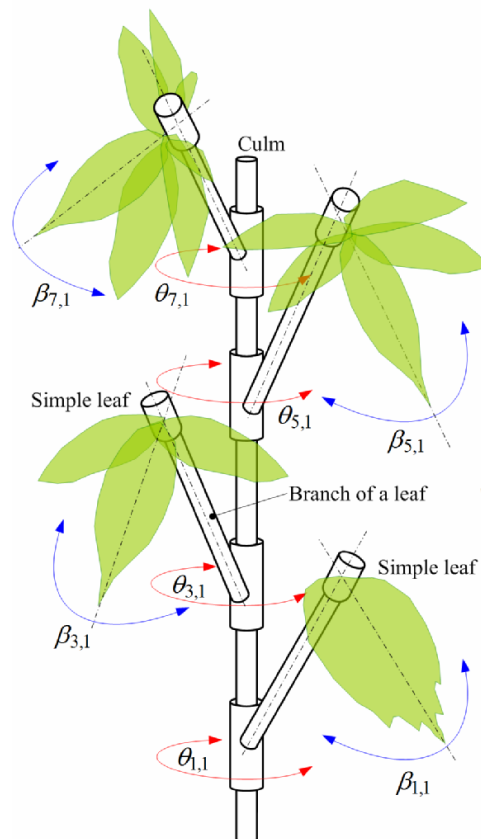


Fig. 8 Kenaf shoot model

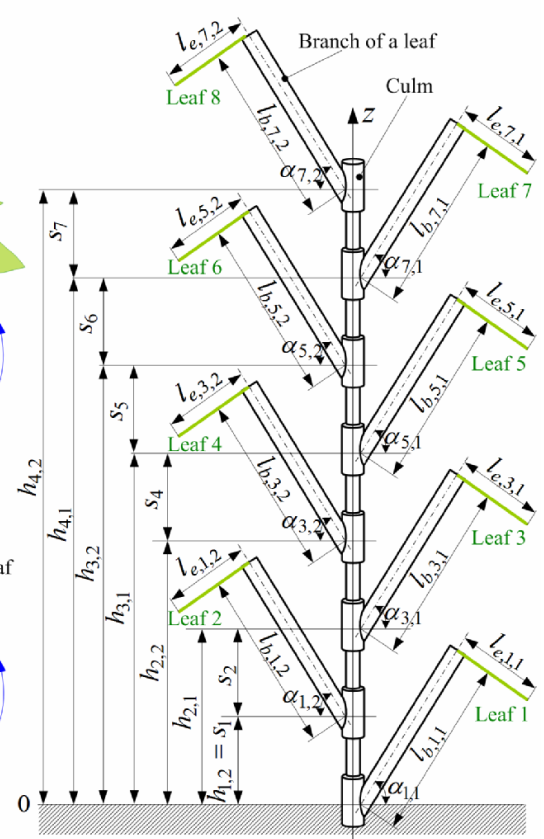


Fig. 9 Individual model of a kenaf

each leaf is expressed with the angle of direction $\theta_{n,i}$, the elevation angle $\alpha_{n,i}$, and the angle of rotation $\beta_{n,i}$. The standard of $\theta_{n,i}$ is the southern axis and the standard of $\alpha_{n,i}$ is a horizontal plane. The standard of $\beta_{n,i}$ is a perpendicular line of the central line of the branch of a leaf. In the analysis by GA, to control the appearance of multiple semi-optimal solutions, the elevation angle $\alpha_{n,i}$, the length of a branch of a leaf $l_{b,n,i}$, the length of a leaf $l_{e,n,i}$, the arrangement of the leaf of the number of divisions n , and the appearance position $h_{n,i}$ of a branch of a leaf, are given a priori fixed values.

5. Analysis Method

5.1 Kenaf model

Figure 9 shows the model of the shoot configuration of a kenaf with eight leaves. The size of each divided leaf is shown in Fig. 3. Each of the examples of a shoot model shown in Fig. 9 has the same two divided leaves. The root interval s_1 to s_7 of a branch of a leaf is set equal to 35mm or 65mm. When the root interval of a branch of a leaf is narrow, the area of light incidence on the leaves will widen. It is expected that the light incidence area changes with the arrangement of each divided leaf and the number of leaves (namely, n

Arrangement of a division leaf (See Fig. 9).

- Leaf 8 (7 leaves)-Leaf 7 (7 leaves)-Leaf 6 (5 leaves)-Leaf 5 (5 leaves)-Leaf 4 (3 leaves)-Leaf 3 (3 leaves)-Leaf 2 (One leaf)-Leaf 1 (One leaf)
- Leaf 8 (3 leaves)-Leaf 7 (3 leaves)-Leaf 6 (3 leaves)-Leaf 5 (3 leaves)-Leaf 4 (3 leaves)-Leaf 3 (3 leaves)-Leaf 2 (One leaf)-Leaf 1 (One leaf)
- Leaf 8 (5 leaves)-Leaf 7 (5 leaves)-Leaf 6 (5 leaves)-Leaf 5 (5 leaves)-Leaf 4 (5 leaves)-Leaf 3 (5 leaves)-Leaf 2 (One leaf)-Leaf 1 (One leaf)
- Leaf 8 (7 leaves)-Leaf 7 (7 leaves)-Leaf 6 (7 leaves)-Leaf 5 (7 leaves)-Leaf 4 (7 leaves)-Leaf 3 (7 leaves)-Leaf 2 (One leaf)-Leaf 1 (One leaf)

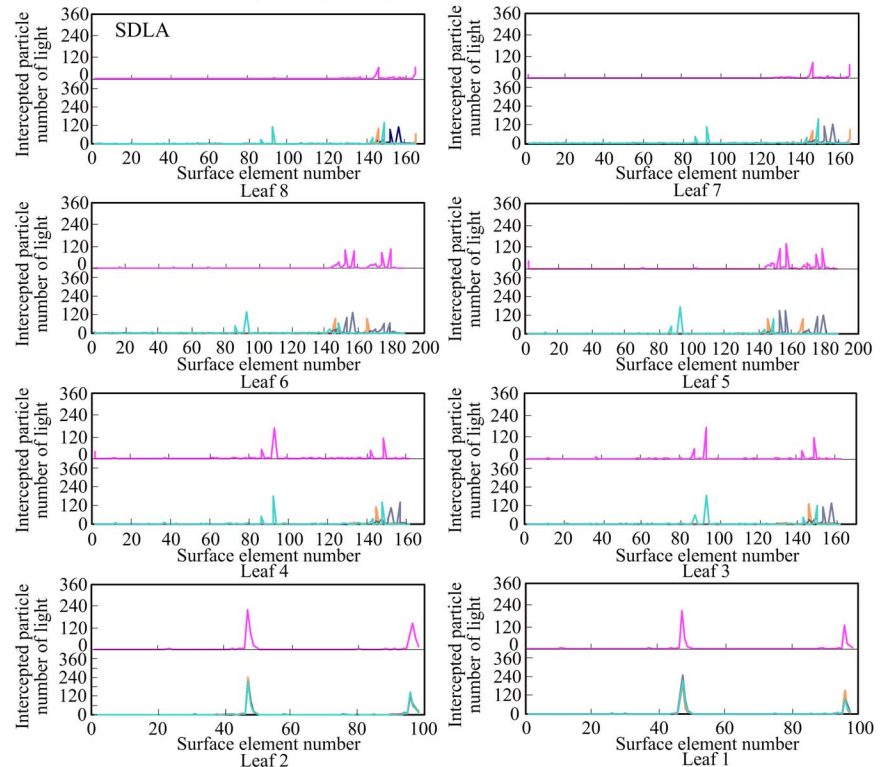


Fig. 10 Intercepted radiation characteristic of each leaf. Space of a branch of a leaf position 65 mm, January

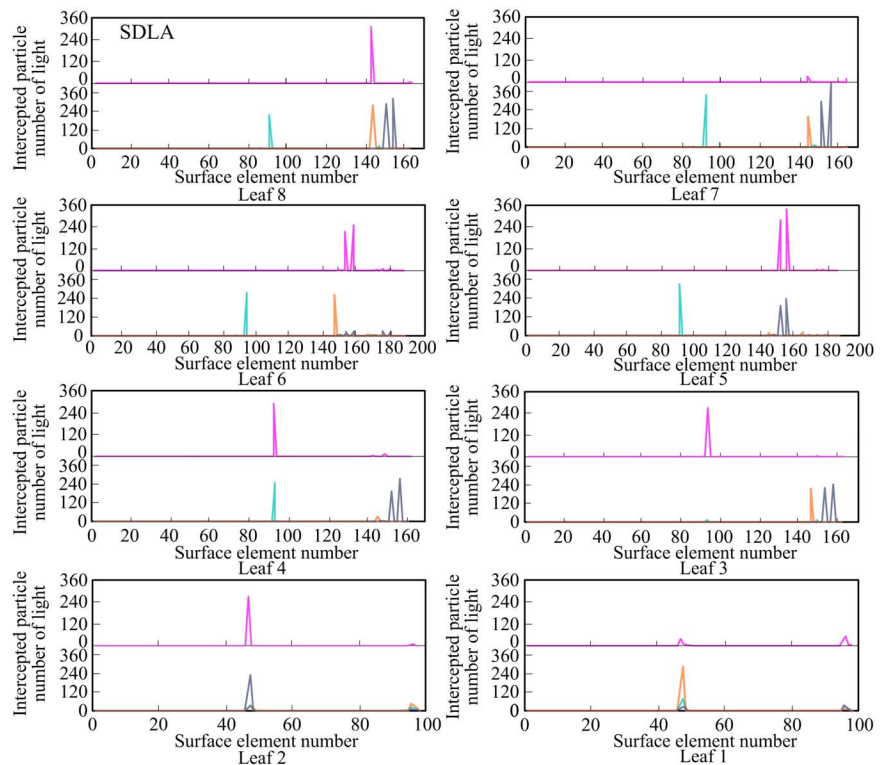


Fig. 11 Intercepted radiation characteristic of each leaf. Space of a branch of a leaf position 65 mm, July

and i) in addition to $h_{n,i}$, $l_{e,n,i}$, $l_{b,n,i}$, $\theta_{n,i}$, $\alpha_{n,i}$, and $\beta_{n,i}$. The GA searches for the

optimal values of $\theta_{n,i}$ and $\beta_{n,i}$. The optimal solution obtained in this analysis is based on a symmetrical flat surface containing the x-axis and the z-axis in Figs. 5 and 7.

5.2 Calculation of the amount of light received

The optical particles emitted from the virtual radiation plane shown in Fig. 5 are simulated using the Monte Carlo method. First, the radiation position of the optical particles on the virtual radiation plane is determined at random. Next, optical particles are emitted in the direction of a normal line of the virtual plane, and the surface element of a leaf for which the optical particle incidence is specified ¹⁾. Solar radiation is separated into reflective, absorption, and transmission components on the surface of a leaf. Although a transmission component may reach another leaf, generally, the transmissivity of visible light with a contribution of photosynthesis is very small. On the other hand, the amount of light received by the leaf from the dispersion component of solar radiation is expected to influence photosynthesis greatly. However, in considering the dispersion component of solar radiation, environmental conditions in the installation location of the system should be assumed. To simplify this, solar radiation dispersion is not considered in this paper.

5.3 Search for optimal shoot configuration

5.3.1 Chromosome model and gene

The shoot configuration of the individual kenaf leaf is expressed with a chromosome model. This chromosome model expresses $\beta_{n,i}$ and $\theta_{n,i}$ with a list (gene) with a value of 10 bits of 0 and 1, respectively. These 0 and 1 is described as a gene model. The analysis error occurred by expressing the real number with a 10-bit binary number is 1% or less. An initial generation's chromosome model is determined using random numbers. The generation of analysis is repeated, adding the genetic manipulation described in later in this paper. In this way, the GA searches for a solution with high adaptive value.

5.3.2 GA Parameters

Using trial and error, the parameters of GA are set up as follows: the N_a in Eq. (1) is 1,000,000 and the chromosome models (number of individuals of a kenaf) operated in analysis are 200. Genetic manipulation is limited to mutation and the mutation probability is 0.2. Based on mutation probability, models with genetic manipulation is selected at random among all the chromosome models, the genes in the chromosome model are determined at random, and they are reversed; the generation number of analysis is 200.

5.3.3 Adaptive value

The adaptive value of a chromosome model in the GA is high when many optical particles reach each leaf from the virtual radiation plane. The adaptive value is calculated using Eq. (2). $E_{nl,t}$ in the equation expresses the number of optical particles that reached leaf nl between sampling time $t+1$ from t . Moreover, N_l is the total number of leaves of the individual kenaf, and J expresses the number of optical particles that reach all leaves on a representative day. In the analysis in this paper, 200 chromosome models may be evolved. Among the last generation's chromosome models, an individual with the highest adaptive value is the optimal solution. The optimal shoot configuration in the individual of a kenaf is obtained by decoding the gene of this chromosome model.

$$J = \sum_{t=0}^{Day} \sum_{nl=1}^{N_l} E_{nl,t} \quad (2)$$

5.3.4 Analysis flow

The analysis flow of the optimal configuration search of the individual kenaf using LAPS¹⁾ is discussed. The shape data of a leaf model (Fig. 3), the configuration data of a kenaf individual (Fig. 9), and the parameters of the GA are first inputted into the analysis program. Next, the initial generation of the chromosome models is generated at random. The data concerning $\beta_{n,i}$ and $\theta_{n,i}$ are included in the chromosome model. Therefore, the leaf

arrangement can be known when the chromosome model is decoded. The radiation position $P_{e,q}$ of the optical particles on the virtual radiation plane shown in Fig. 5 is determined at random, and the trajectory of optical particles is determined by calculating a normal line vector. On the other hand, the position of the virtual radiation plane is changed for every sampling time so that the solar position may be simulated. Equation (2) indicates the number of arrival light particles in all the leaves. The adaptive value of a chromosome model is so high that the value of J is large. The genetic manipulation of the mutation is added to the chromosome group with a high adaptive value. Furthermore, the new chromosome determined at random is added and the chromosome group of the next generation with variety is generated. The above calculation is repeated to the last generation number. The optimal solution is an individual model with the maximum adaptive value in the last generation's chromosome model. The optimal shoot configuration of a kenaf is obtained by decoding the optimal solution.

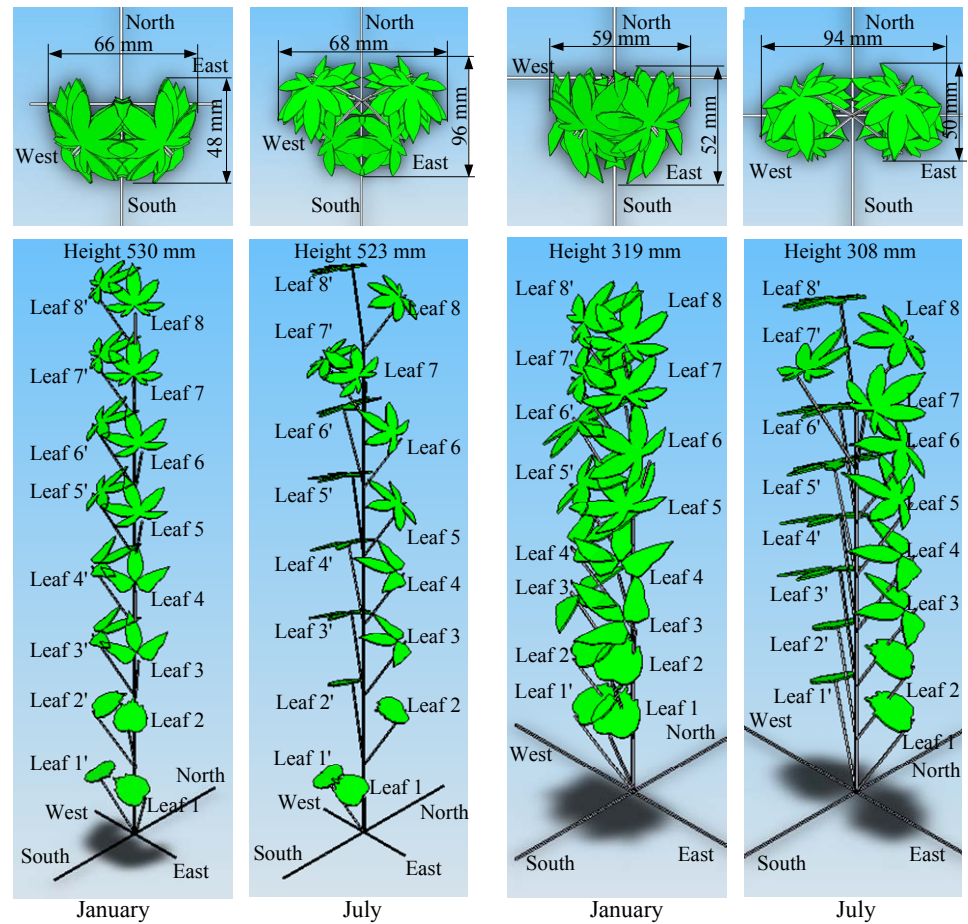
6. Analysis Results

6.1 Characteristic of the amount of light received

Figures 10 and 11 show the results of the analysis for the amount of light received by each leaf of the individual model (Fig. 9) of a kenaf in January and July. However, the space of a branch of a leaf s_1 to s_7 is 65mm, and the arrangement of the divided leaves comprise four patterns, as shown in the figures. An actual kenaf plant has a maximum of seven leaf divisions. The pattern that arranges the divided leaves of 7-7-5-5-3-3-1-1 in order from Leaf 8 to Leaf 1 in Fig. 9 is described as "standard division leaf arrangement (SDLA)." The arrangement of the division leaves is expressed in order of Leaf 8 to Leaf 1, as shown in Fig. 10 (for example, 5-5-5-5-5-5-1-1). The surface element number of each leaf is the same as in Fig. 3. The result of SDLA in January, shows that the leaves of an upper position (Leaf 7 and Leaf 8) have a low peak of light received compared with lower leaves (from Leaf 1 to Leaf 6). Moreover, there are reduced light reception amounts of Leaf 7 and Leaf 8 of 7-7-7-7-7-7-1-1 in Fig. 10 compared with other lower leaves. When the amount of light received of SDLA in January (Fig. 10) and July (Fig. 11) is compared, the distribution of the surface element that will take optical particles in the result in January is wide area. However, the peak amount of light received in July is higher than in January in many cases. As Fig. 6 (b) shows, since the amount of solar radiation at each time is strong, the peak amount of light received in July is very high. On the other hand, because the position range of the light source in July is wide zone compared with January, as Fig. 6 (a) shows, optical particles are received intensively when an amount of insolation is strong.

6.2 Shoot configuration

Figure 12 shows the results of the analysis of the optimal configuration in the SDLA of the individual model of a kenaf. The figures of the top in Fig. 12 are a figure which looked at the lower part from the top. Moreover, the figure of the bottom in Fig. 12 is the shoot of a kenaf using the optimal solution by the GA (isometrical projection). In this analysis, the individual model of 65mm constancy (Fig. 12 (a)) and 35mm constancy (Fig. 12 (b)) of the space of a branch of a leaf was calculated. The size of the maximum outside of the kenaf individual is also described in each figure. When the result of January and July in Fig. 12 (a) is compared, the sizes on the horizontal plane in January are 66 mm x 48 mm, and July is 68 mm x 96 mm. Therefore, the area on the horizontal plane of the kenaf individual with SDLA in January is a half about compared with the result of July. On the other hand, when both heights are compared, the result of January is 530 mm and July is 523 mm. When the volume of the optimal configuration of every month is compared, the result of January is 1680 cm³ and July is 3410 cm³. These volume ratios are about 2. In Fig. 12 (b), compared



(a) Space of a branch of a leaf position 65 mm (b) Space of a branch of a leaf position 35 mm

Fig. 12 Optimal configuration results of the individual model of a kenaf

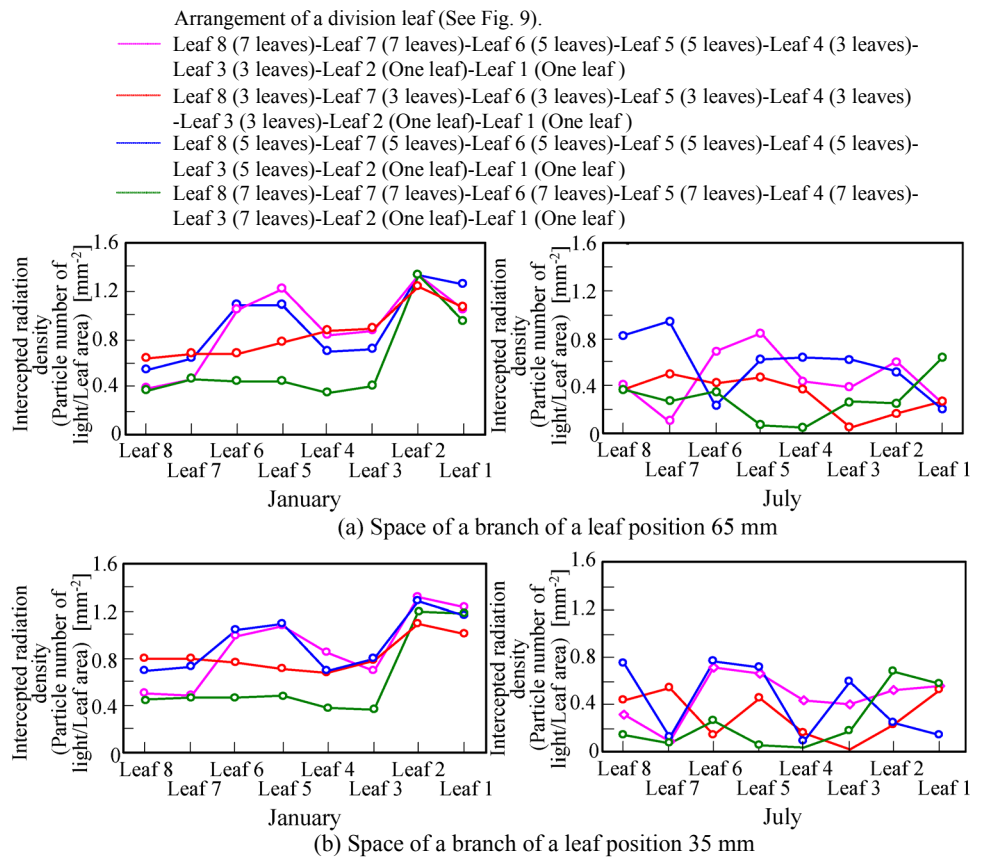


Fig. 13 Intercepted radiation density of each leaf

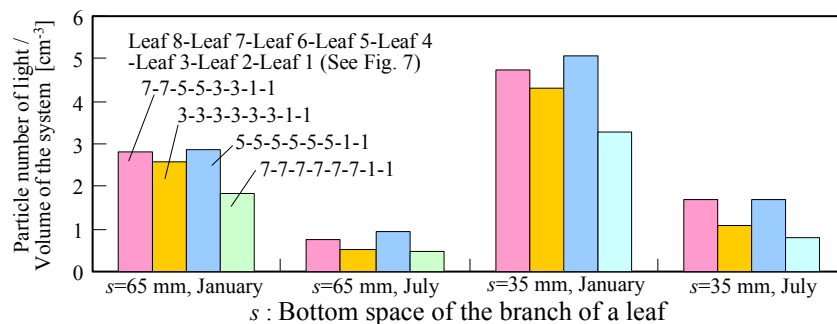


Fig. 14 Volume density of intercepted radiation

with January, the volume of the kenaf individual in July is 1.48 times. In this way, the optimal configuration in July of installation volume is larger than January. It is thinkable that the range of the light source position in July shown in Fig. 6 (a) is wider than January as this reason. Accordingly, the configuration of the individual in July is going to condense wide range solar radiation by extending the shoot. However, it is considered that the configuration of the individual model of a kenaf condenses intensively in the strong time zone of solar radiation. Therefore, the spread of the shoot in the summer season takes influence also in the strength of the solar radiation in each time other than the position of the light source.

6.3 Relation between the arrangement of divided leaves and amount of light received

The analysis result of light reception density is shown in Fig. 13. The value that divided "the number of reaching light particles of a certain leaf" by "area of the leaf" is defined as the light received density. The density of the light received in each leaf in January is larger than July, as shown in Figs. 13 (a) and 13 (b). The density of the light received in the order of a division leaf 7-7-5-5-3-3-1-1 (SDLA) and 5-5-5-5-5-5-1-1 shown in the figure is large. However, the density of the light received of the order 7-7-7-7-7-7-1-1 with maximum divisions and the order 3-3-3-3-3-3-1-1 with minimum divisions is small at each leaf in many cases. These results show that the arrangement of the divided leaves of a kenaf greatly influences the amount of intercepted radiation. Other than arrangement of divided leaves, the space of a branch of a leaf, the length of a branch of a leaf, etc. are expected to affect the amount of radiation intercepted by the individual plant of a kenaf. Since the density of the light received in January is larger than in July, when the range of movement of a light source is wide, density of the light received will fall. Realization of the system with the low directivity in the summer season is required. As Figs. 12 (a) and 12 (b) show, these simple leaves especially have contributed to the increased amount of light received in January. Similarly, it is necessary to design the arrangement plan of the leaf that contributes to the improvement of the amount of the light received in July.

6.4 Light reception efficiency

Figure 14 shows the analysis results of the light reception efficiency about arrangement of the SDLA and the other divided leaves. Although the light reception efficiency in January is large, the value in July is small. Moreover, the value of the space of a branch of a leaf 35 mm is larger than 65 mm. These ratios are the range of 1.7 times from 1.5 times. The divided leaf is designed so that light may access lower leaves. A future subject is developing the corrective strategy of a shoot configuration for making the amount of light received in the summer season increase. Accordingly, in an intercepted radiation system without phototropism, it is necessary to improve the light reception efficiency in summer or other seasons characterized by a wide range movement in the light source.

7. Conclusions

A kenaf has division leaves of two or more types, and the early growth is a characteristic. Thus, the relationship between the shoot configuration of a kenaf and the amount of light

received was examined using numerical analysis, and the development of a compact light reception system was discussed. The following conclusions were reached.

- (1) In the shoot model of a kenaf, the amount of light received in the summer season is concentrated at the time zone of strong solar radiation. A light source position and the strength of solar radiation in each time" affect the configuration of a shoot.
- (2) Because the range of movement of the light source in the summer season is wide compared with winter, the light reception systems especially needs a design with low directivity in the summer season. It is necessary to improve the individual model of a kenaf examined in this paper, and to increase the amount of intercepted radiation in the summer season.
- (3) One reason for the development to a divided leaf from a simple leaf is the increase in the overall amount of light received by the individual due to light access to lower leaves.

The shoot configuration design has a strong influence over light reception efficiency, and there is a suitable configuration in the shoot configuration.

Nomenclature

h	: Height of the bottom of the branch of a leaf (m)
J	: Total light received by individual
l	: Length (m)
l_e	: Length of a leaf (m)
N_a	: The total number of light quanta emitted in a day
N_l	: The total number of leaves of the individual
nl	: Leaf number
P_e	: Coordinates of the radiation position on the virtual radiation plane
P_v	: Apex coordinates of a virtual radiation plane
s	: Bottom space of the branch of a leaf (m)
	Roman character
α	: Angle of elevation (degree)
β	: Angle of rotation (degree)
θ	: Angle of direction (degree)
Subscript	
b	: Branch of a leaf (Figure 7)
g	: Representative month
i	: Consecutive numbers of the divided leaf
n	: The number of divisions of the leaf
q	: Simulated light-quantum number
s	: Light source
t	: Sampling time (hour)

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