USE OF DIFFUSIVE OPTICAL FIBERS FOR PLANT LIGHTING

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INTRODUCTION

Lighting is one of the most critical aspects in plant production and environmental research with plants. Much research has been repeated on the effect of light intensity, spectral distribution of light and lighting cycle, but comparatively little research done on the effect of lighting direction on the growth, development and morphology of plants (Hart, 1988).

When plants are grown with lamps above, light is directed downward to the plants. Downward or overhead lighting is utilized in almost all cases. However, downward lighting does not always give the best result in terms of lighting efficiency, growth, development and morphology of plants.

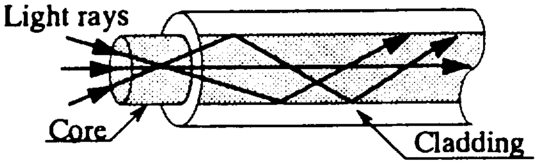
Kitaya et al. (1988) developed a lighting system in which two rooting beds were arranged; one above and the other under fluorescent lamps. Lettuce plants grew normally in the lower bed and suspended upside-down under the upper bed. The lettuce plants suspended upside-down were given the light in upward direction (upward lighting). No significant difference in growth, development and morphology was found between the lettuce plants grown by the downward and upward lighting. Combining upward and downward lighting, improved spacing efficiency and reduced electricity cost per plant compared with conventional, downward lighting. From the above example, when designing a lighting system for plants with lamps more lighting direction should be considered.

In the present study, a sideward lighting system was developed using diffusive optical fiber belts. More higher quality tissue-cultured transplants could be produced in reduced space with sideward lighting system than with a downward lighting system. An application of the sideward lighting system using diffusive optical fiber belts is described and advantages and disadvantages are discussed.

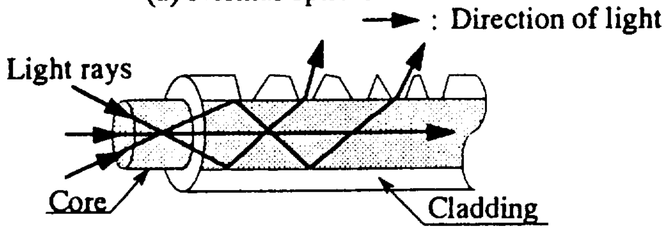
'Normal' and 'Diffusive' Optical Fibers and Diffusive Optical Fiber 'Belts'

Normal optical fibers. A 'normal' optical fiber is a filament-shaped photon (light) guide, made of dielectric material, such as glass or plastic. The fibers usually consists of a single discrete optically transparent transmission element consisting of a cylindrical core with cladding on the outside (Figure 1a; Weik, 1989). The refractive index of the core has to be higher than the cladding for photons to remain within and propagate in the fiber. 'Normal' optical fibers are used to transmit photons as signals or energy carrier for a long distance with minimum attenuation and disturbance.

Diffusive optical fibers. On the other hand, a 'diffusive' optical fiber is used as a thin line light source. For this purpose, the cladding of a 'normal' optical fiber is chemically eroded (scratched) to some degree so photons come out through the cladding gradually along the fiber (Figure 1b) Photons are sent through either or both ends (cross section of the core) of the fiber. The diffusive optical fiber used in the present experiment is made of acrylic and the refractive indices of the core and cladding are, respectively, 1.496 and 1.402. Thus, the fibers are considered to be an apparent light source and the lamp a true light source.



(a) Normal optical fiber



(b) Diffusive optical fiber

Fig. 1 Schematic diagram showing light transmission pathways in 'normal' and 'diffusive' optical fibers.

Diffusive Optical Fiber Belts

A diffusive optical fiber belt used in the present experiment is basically a flat belt (90 mm wide and 1.3 mm thick) composed of ninety diffusive optical fibers (each 1 mm in diameter) attached and fixed with a white (and opaque) reflective film on one side, with both ends of all the fibers bunched tightly together to make a circular cross-section (Kozai, 1991). When the light emitted from lamps is sent through both ends of the belt, this array of optical fibers functions as an area (surface) light source. The diffusive optical fiber belt is physically flexible.

SIDEWARD LIGHTING

Sideward Lighting System Using Fluorescent Lamps

A sideward lighting system using fluorescent lamps was developed. Quality tissue-cultured (micropropagated) transplants were produced with reduced shoot length and enhanced leaf and root growth in limited space at lower costs (Hayashi et al., 1992; Hayashi et al., 1994: Kitaya et al., 1994). Figure 2 shows schematic diagrams of the sideward lighting system using fluorescent lamps and a conventional, downward lighting system using fluorescent lamps.

When both systems supplied with the same amount of electricity for lighting, dry weight, fresh weight, leaf area and stem diameter of potato (Solanum tuberosum L., cv. Benimaru) plantlets in vitro in the sideward lighting treatment were 80% greater than those in the downward lighting treatment. On the other hand, the shoot length of the plantlets in the sideward lighting treatment was only one half of the downward lighting treatment (Hayashi et al., 1992; Kozai and Ito, 1993). Tissue-cultured transplants tend to have elongated, thin stems with small leaves and few roots, which are undesirable characteristics of transplants. Higher quality potato transplants were produced in the sideward lighting treatment than in the downward lighting treatment.

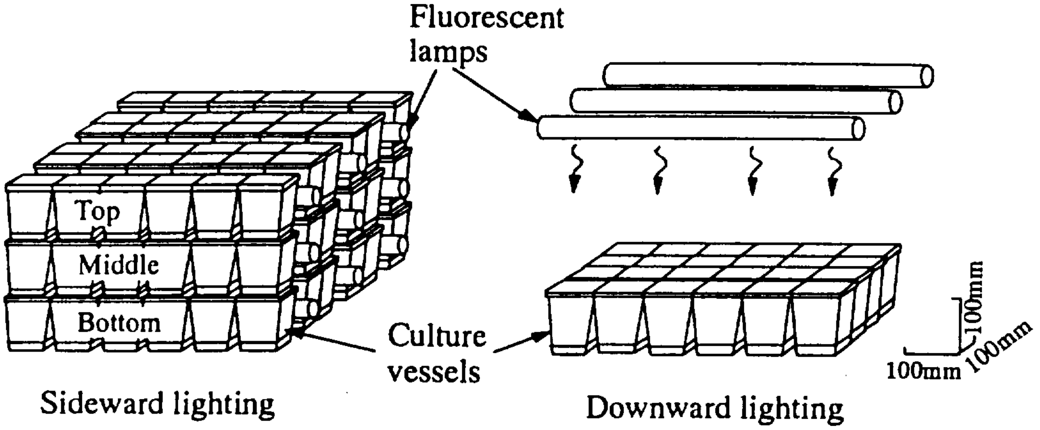


Fig. 2 Schematic diagram of the sideward lighting system using fluorescent lamps and the conventional, downward (overhead) lighting system using fluorescent lamps (Hayashi et al., 1992).

Sideward Lighting System Using Diffusive Optical Fiber Belts

A prototype of a sideward lighting system using diffusive optical fiber belts was developed for lighting plant tissue culture vessels (Figures 3 and 4). The main assembly of the system consists of two metal halide lamps, each with a reflector and a thermal filter and a pair of diffusive optical fiber belts (90 mm wide, 1.3 mm thick and 2.3 m long each). In this system, a 'true' light source is the metal halide lamps, but an 'apparent' light source is the belt. With this system, the space for the 'apparent' light source (between the rows of culture vessels) can be greatly reduced compared with the sideward lighting system, using fluorescent lamps.

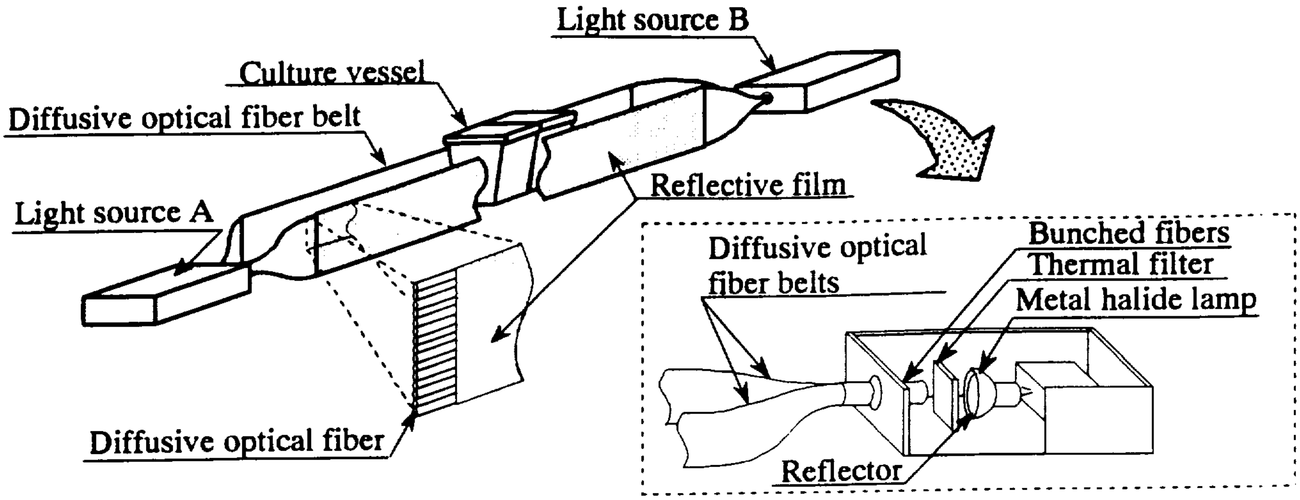


Fig. 3 Schematic diagram of the sideward lighting system using a pair of diffusive optical fiber belts for plant tissue culture (Kozai et al., 1992).

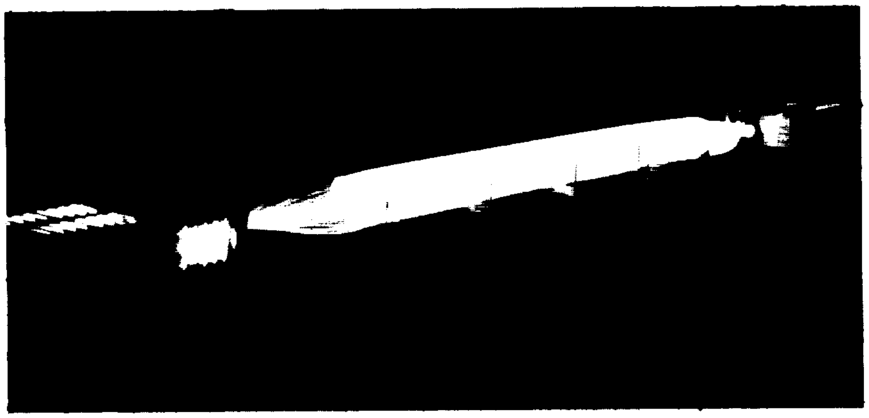


Fig. 4 Photograph of the sideward lighting system using a pair of diffusive optical fiber belts for plant tissue culture.

Light emitted from the lamps and transmitted through the thermal filters is focused, using the reflector, at the ends of the bunched optical fibers. The transmitted light passes into the bunched optical fibers and is released from the entire inner surface of the belts. The outer surface with the white reflective film is faced out. A pair of diffusive optical belts, 8 cm apart, are placed vertically in parallel on the culture shelf. Plant tissue culture vessels are placed in the space between the belts and plantlets in vitro receive light through the side walls.

Thermal radiation emitted by the lamp is removed by thermal filter before it enters the bunched optical fibers, and only photosynthetically active radiation (wavelength: 400 - 700 nm) passes into the belts. 'Actual' spectral distribution of light entering the belts is determined by the spectral distribution of light emitted from the lamp and the spectral transmissivity of thermal filter. The light emitted from the belts and transmitted through one of sidewalls of the vessel, but not received by the plantlets in vitro passes through the opposite side wall of the vessel. Thus, increase in air temperature in the culture vessel due to the radiation from the light source was less than 0.5 °C (Kino, 1993).

In application of this system, the lamps are placed outside the culture room, so not only thermal radiation, but also convective heat produced from the lamps can be removed outside the culture room, which results in a significant reduction in the cooling load of the culture room.

Figure 5 shows longitudinal PPF (photosynthetic photon flux) distributed along the diffusive optical fiber belts as measured on the vertical surface, at the center of the plant tissue culture vessels (75 mm x 75 mm x 98 mm each), when either lamp A or lamp B or both were turned on. The PPF was more or less evenly distributed along the belts when both lamps A and B were turned on. The longitudinal PPF distribution along the belts is mainly determined by the degree of erotion along the fibers.

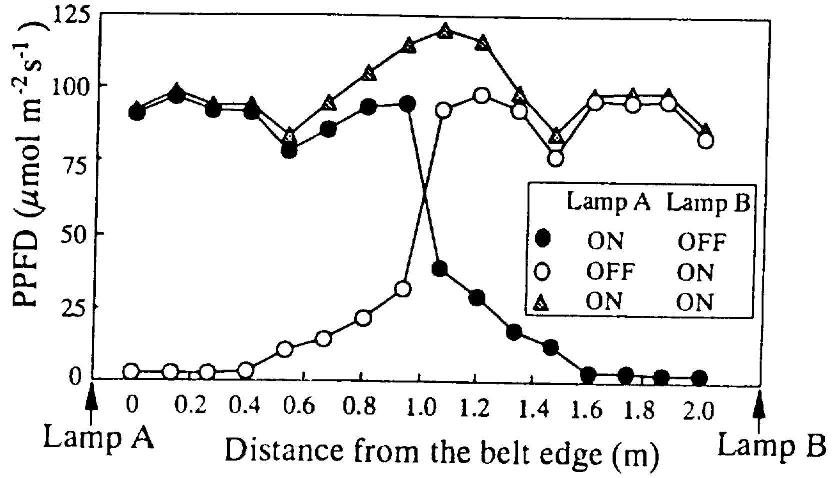


Fig. 5 Longitudinal PPF (photosynthetic photon flux) distribution along the diffusive optical fiber belts measured on the vertical surfaces at the central points of the plant tissue culture vessels shown in Figure 3.

Growth of potato (Solanum tuberosum L., cv. Benimaru) plantlets in vitro was compared using sideward and downward lighting systems. Leafy single node cuttings were used as explants without sugar in the medium. CO_2 was available in the plant space through gas permeable filters in the culture vessel. Plantlets cultured in vitro for 28 days had significantly reduced shoot length and increased stem diameter in the sideward lighting treatment than in the downward lighting treatment. There were no significant differences in dry weight, leaf area, number of unfolded leaves and net photosynthetic rate per plantlet between the two treatments (Kozai et al., 1992). Reduced shoot length and increased stem diameter are preferred characteristics of tissue-cultured plantlets for acclimatization and transplanting to ex vitro conditions.

PLANT GROWTH CHAMBER WITH DIFFUSIVE OPTICAL FIBERS

A prototype of a plant growth chamber with diffusive optical fibers was developed for plant tissue culture and transplant production (Figures 6, 7 and 8). Eight 150 W metal halide lamps were installed in the lamp house and thermally isolated from the culture room to reduce the cooling load of the culture room.

The culture room consisted of 12 (= 4 × 3) compartments , which are 20 cm wide, 30 cm high and 450 cm deep each. Thus, each compartment contained 36 (= 2 × 3 × 6) Magenta GA7 culture vessels (75 mm × 75 mm × 95 mm), totaling 432 (= 36 × 12) Magenta GA7 culture vessels in the culture room. Vertical PPF measured at the center of empty compartments averaged approximately 60 μmol m^{-2}s^{-1}. This PPF value was too low for plant tissue culture and transplant production when applied on the horizontal surface. However, a PPF of 60 μmol m^{-2}s^{-1} at the vertical surface was high enough for plant tissue culture in the present experiment.

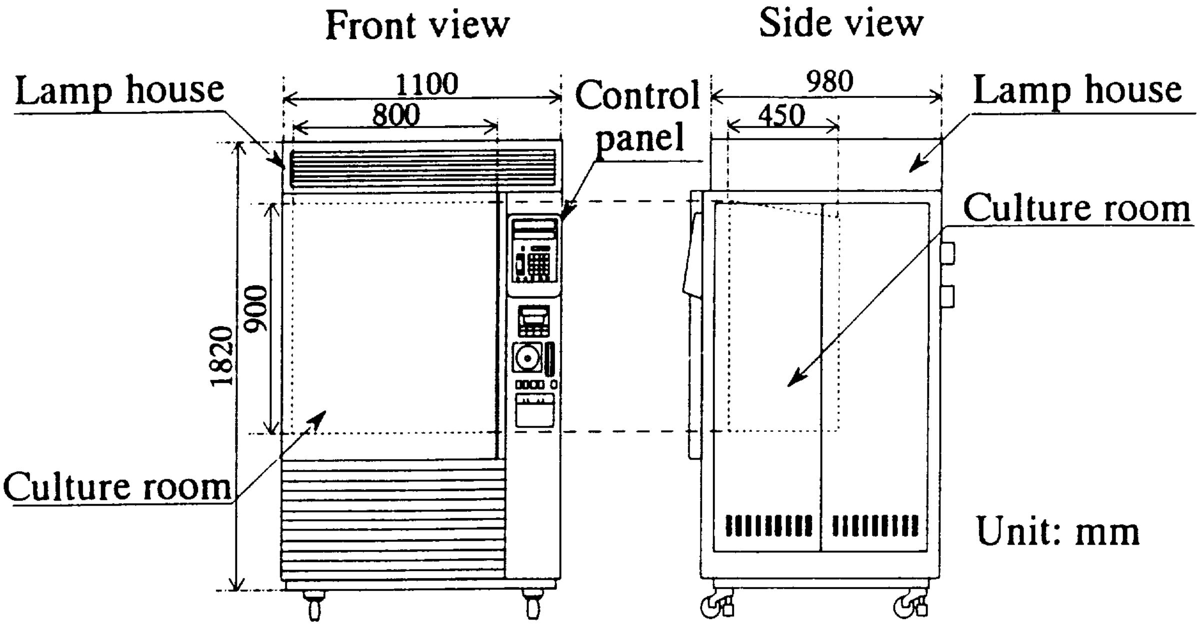


Fig. 6 Front and side views of a plant growth chamber with diffusive optical fibers developed for plant tissue culture and transplant production.

Using the plant growth chamber, quality potato (<u>Solanum tuberosum</u> L. cv. Benimaru) plantlets were successfully cultured in vitro (Kino, 1993; Kozai et al., unpublished). Further details are under study using the plant growth chamber

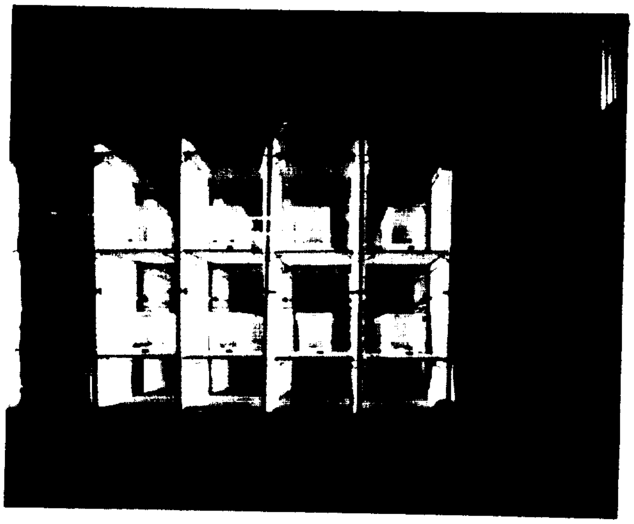


Fig. 7 Photograph of a plant growth chamber using diffusive optical fibers with the front door open, developed for plant tissue culture and transplant production.

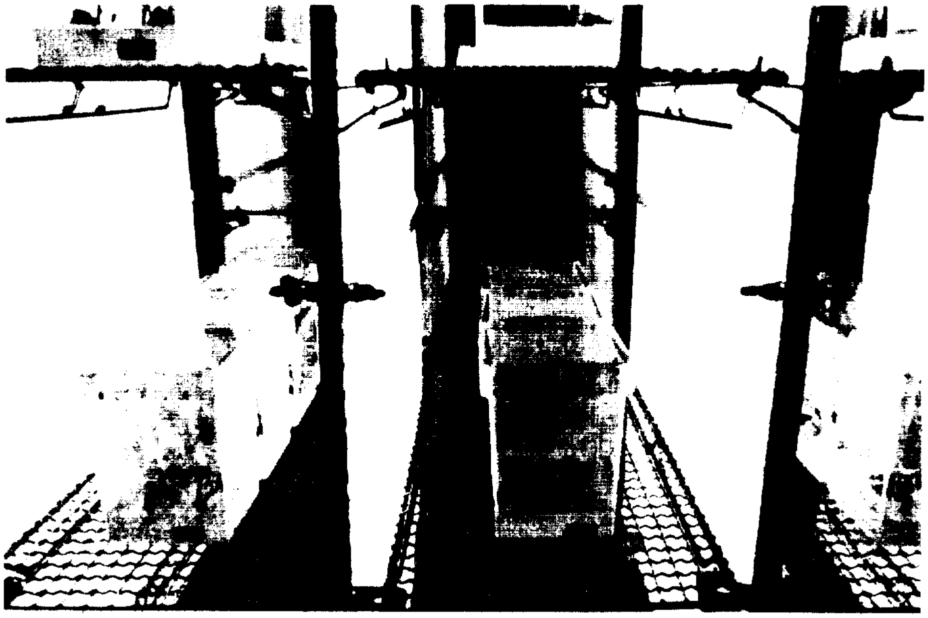


Fig. 8 Inside view of a plant growth chamber using diffusive optical fibers developed for plant tissue culture and transplant production.

ADVANTAGES AND DISADVANTAGES

Advantages of Sideward Lighting

Advantages of the sideward lighting system over the downward lighting system for plant tissue culture and transplant production include: 1) enhanced space utilization by vertically stacking culture vessels without a significant reduction in the amount of light energy received by the plantlets, 2) increased ratio of light energy received by the plantlets to the light energy released from the light source, since culture vessels or plantlets are placed next to the light source, 3) increased leaf area exposure to light, especially lower leaves of plants. Since the light is applied from the sides, the lower leaves remain photosynthetically active (Kitaya et al., 1994), and 4) sides of vessels are often more transparent to light than lids.

Advantages of Diffusive Optical Fiber Belts

Advantages of the sideward lighting system given above are further enhanced when diffusive optical fiber belts are used instead of fluorescent lamps. Additional advantages of the sideward lighting system with diffusive optical fiber belts for plant tissue culture and transplant production include: 1) reduced culture room cooling load since only photosynthetically active radiation is released in the culture room, and 2) an optical filter or an optimal light source such as light emitting diodes (LED) could be easily used with a thermal filter to obtain an improved light spectral distribution. The diffusive optical fiber belts could be used, as an area light source for downward or upward lighting systems as well as sideward lighting system. This light distribution system (diffusive optical fibers) could be used as an effective lighting system for algae culture in a tank, mushroom culture, supplementary lighting in the greenhouse, etc.

Disadvantages and Their Possible Solutions

In the present sideward lighting system, using diffusive optical fibers, the ratio of PAR (photosynthetically active radiation) energy emitted by the lamp to the PAR energy entering into the cross section of bunched optical fibers was low (approximately 0.2). This is mainly because the metal halide lamp is not a point light source and the light energy emitted by the lamp could not be effectively focused to the cross section of bunched fibers. Using a lamp reflector. This ratio should be higher than 0.8.

However, using a microwave-powered lamp (Fusion Systems Inc., MD U.S.A.; Dolan et. al., 1992; Krizek et. al., 1993) a point light source (9.5 mm in diameter for 500 W lamp and 30 mm in diameter for 3.4 kW lamp), this problem would be largely solved (Kozai and Kitaya, 1993).

Methods of designing the lighting system using the diffusive optical fibers have not been adequately developed. There are many possible geometrical layouts of lamps, reflectors, thermal filters and the fibers. There are many design problems to be solved for further development.

CONCLUSIONS

A plant growth chamber with a sideward lighting system was developed using diffusive optical fiber belts as an 'apparent' light source. High quality tissue-cultured transplants with reduced shoot length and increased stem diameter could be produced with this growth chamber. Advantages of this lighting system include: 1) enhanced space utilization, 2) increased ratio of light energy received by the plants to the light energy released from the light source, 3) increased leaf area exposure to light, 4) reduced cooling load, and 5) reduced air and leaf temperature rise. A disadvantage of this lighting system is the low ratio of light energy emitted from the lamp to the light energy entering the diffusive optical fiber belts.

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