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Effects of Concrete Block Flooring on Greenhouse Microclimate and Floor Surface Heat Balance

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Abstract

Greenhouse floor management is essential for effectively utilizing solar energy in horticultural production. Covering soil floors with concrete is one method of greenhouse floor management. This paper assesses the effects of this method on greenhouse microclimate and floor surface heat balance by comparing two adjacent single-span greenhouses, namely, an "interlocking concrete block floor" greenhouse (ICFG) and an "uncovered soil floor" greenhouse (SFG). During days with high solar radiation in 2019 winter, the maximum air temperature was 10.0°C lower, and the average vapor pressure was 0.5 kPa lower in the ICFG than in the SFG. On clear nights, the average air temperature was 1.6°C higher in the ICFG than in the SFG. The concrete floor had a higher albedo than the soil floor. This contributed to the lower daytime temperatures in the ICFG. The lower heat absorption by the concrete during the day was more than compensated for by a larger total transmission of heat from the ground to the greenhouse air at night due to the greater thermal conductivity of concrete. These results indicate that replacing soil floors with concrete floors could help farmers avoid temperature extremes and high daytime humidity without requiring external energy derived from fossil fuels or other sources.

Discipline: Agricultural Engineering

Additional key words: greenhouse horticulture, energy saving, environment monitoring, floor material, heat transfer

Introduction

Greenhouses are used in horticultural production to control the internal environment, thereby promoting healthy crop growth. Greenhouse technologies that efficiently utilize solar energy are needed to reduce consumption of fossil fuels. Solar energy transmitted through the greenhouse cover is absorbed by the floor and is partially redistributed to the greenhouse air as sensible and latent heat. Solar energy stored underground during the day is supplied to the greenhouse air at night, providing a heat source that is valuable for low-heated or passive greenhouses (Baille et al. 2006, Bonachela et al. 2012). When using a heat pump to cool greenhouses at night, soil heat flux is among the largest cooling loads. In one study, soil heat flux represented 38% of the total cooling load (Kozai et al. 1985). Thus, heat transfer between the floor surface and greenhouse air is an important factor in optimizing the use of solar energy to control the internal environment.

Various approaches have been used to improve heat transfer at the greenhouse floor surface. In greenhouses with soil floors, increasing the soil moisture content promotes solar energy storage (Al-Kayssi et al. 1990). Covering a soil floor with gravel mulch increases soil heat storage and root zone temperature, reduces evaporation from the soil, and moderates the greenhouse internal climate (Bonachela et al. 2020). Soil heat storage systems such as ground-coupled heat exchangers can be used to accelerate heat exchange between the greenhouse air and the ground (Kurata & Takakura 1991, Miyoshi et al. 2013). Greenhouse floor heating systems that use

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concrete as the floor material have been developed (Reiss et al. 2007, Roberts & Mears 1989).

Though concrete-floored greenhouses are not special globally, they are not common in Japan because they were not treated as farmland in the Agricultural Land Law, and higher tax had been levied on them than other types of greenhouses. However, as the advantages of concrete flooring in greenhouse become more widely known, the law was changed to treat concrete-floored greenhouses as other types of greenhouses in 2018, so that farmers can easily install concrete floor greenhouses today (National Chamber of Agriculture 2020).

The advantages of concrete floors include (1) making the greenhouse floor surface smoother, which is helpful for introducing robotic technology (Ota et al. 2019) and for supplying plant-nourishing solutions; (2) making it easier to maintain a clean greenhouse environment to protect crops from disease; (3) providing insulation; and (4) enabling greenhouse management practices such as floor heating and ebb-and-flood irrigation (Reiss et al. 2007, Uva et al. 2001). Guidelines for constructing concrete floors for greenhouses have been proposed (American Society of Agricultural Engineers 1993, Hart & Vanweel 1988, Okushima & Nakajima, 2017). Furthermore, several reports described the microclimate and floor heat balance of greenhouses with concrete floors (e.g., Reiss et al. 2007, Roberts & Mears 1989). However, as floor heating systems were used in these studies, the effect of the concrete floor itself on greenhouse thermal environment was not evaluated.

This study assesses the effects of introducing a concrete floor on greenhouse microclimate by monitoring the internal climate and floor surface heat transfer of two adjacent greenhouses, one with an uncovered soil floor and the other with an interlocking concrete block floor.

Materials and methods

1. Experimental greenhouses

The uncovered soil floor greenhouse (SFG) and interlocking concrete block floor greenhouse (ICFG) were built in Tsukuba, Ibaraki, Japan (36°2′N 140°5′37″ E). Figure 1 illustrates the structure of the interlocking concrete block floor. The periphery of the ICFG floor was left uncovered. Uncovered widths of the periphery were 20 cm along the side vents and 30 cm along the gable surfaces, respectively. The small joint spaces between the interlocking blocks were filled with quartz sand. Table 1 presents the physical characteristics of the floor materials. The floor area of each greenhouse was 59.4 m^2 (6.0 m wide by 9.9 m long). The frames of the greenhouses were made of steel pipes (Fig. 2); such pipe-framed greenhouses occupy 80% of the total greenhouse area in Japan (Moriyama et al. 2015). Both of the greenhouses were north–south oriented. The experiment was conducted from February 7 to 13, 2019, with all ventilators closed and without plants in the greenhouses.

2. Monitoring greenhouse climate

To evaluate the microclimate and heat balance at the greenhouse floor surfaces, air temperature, relative humidity, global solar radiation, reflection of solar radiation, floor surface heat flux, net radiation, and floor surface temperature were monitored in this study (Fig. 3). Table 2 lists the sensing systems used in this research. The sensors for net radiation and floor surface temperature were installed at a height of 1 m above the

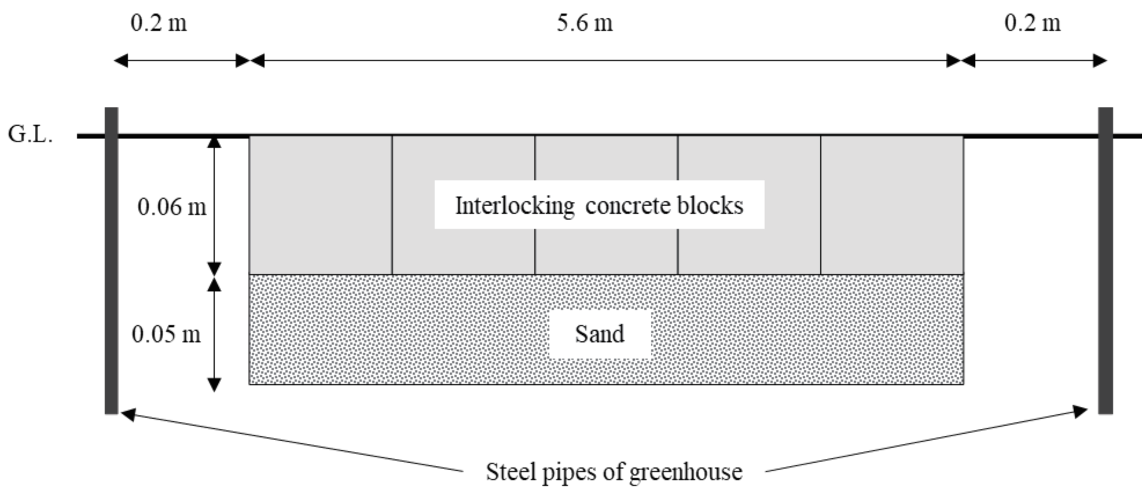

Fig. 1. Cross section of interlocking block concrete floor
G.L. represents the ground level.

Table 1. Physical parameters of floor materials

Parameter	Concrete	Soil
Dry density (kg m^{-3})	2,400	872
Thermal conductivity (W m^{-1} K^{-1})	1.2	0.252
Volumetric heat capacity (MJ K^{-1} m^{-3})	2.2	1.488

The values for concrete are typical values (The Japan Society of Mechanical Engineers 2009). Andosol is the typical soil type of the study area, but sandy soil is brought to the place where the greenhouses are built. Therefore, the soil in the research field is a mixture of them. Thus, the values for soil were measured on site in April and May of 2018 by core sampling for dry density and by using a thermal property sensor (KD2 Pro; Decagon Devices, Inc.) to measure thermal conductivity and volumetric heat capacity.

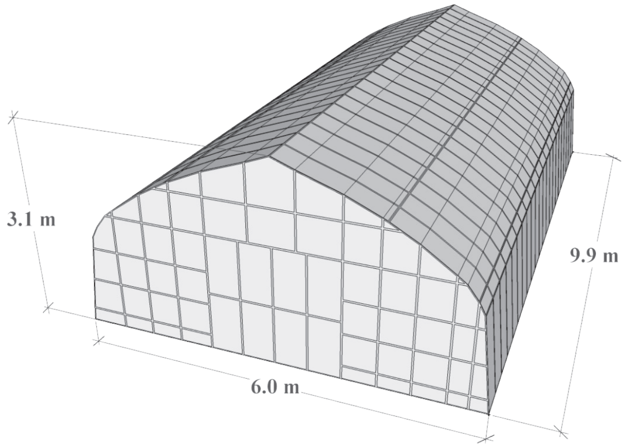

Fig. 2. Schematic of a greenhouse

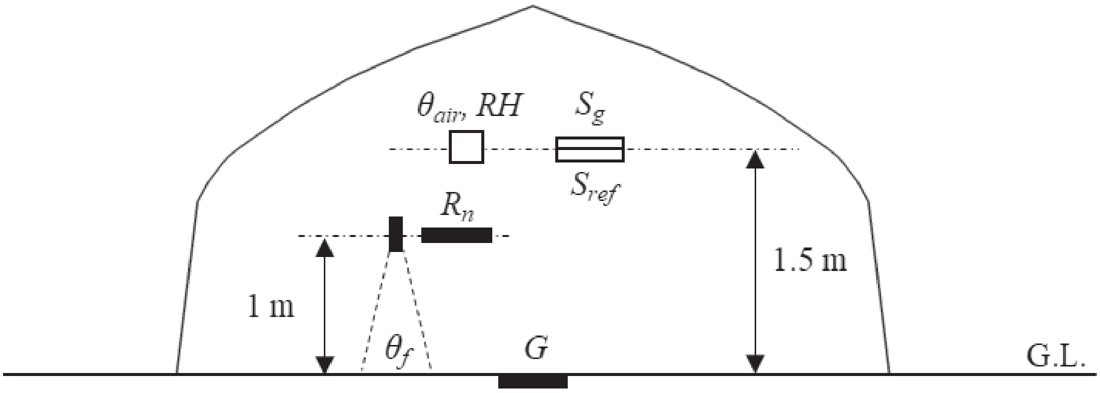

Fig. 3. Arrangement of sensors in the greenhouses

The locations of the sensors used to measure air temperature (θ_{air}, °C), relative humidity (RH, %), global solar radiation (S_g, W m^{-2}), reflection of solar radiation (S_{ref}, W m^{-2}), net radiation (R_n, W m^{-2}), floor surface temperature (θ_f, °C), and floor surface heat flux (G, W m^{-2}) are shown. G.L represents the ground level.

Table 2. Sensors and data logger used for greenhouse environment monitoring

No.	Factor	Units	Sensor
1	Air temperature	°C	Wireless thermo-recorder RTR-503L (T&D Corporation, Japan)
2	Air relative humidity	%	Wireless thermo-recorder RTR-503L (T&D Corporation, Japan)
3	Global solar radiation	W m^{-2}	Thin-film pyranometer ML-02 (EKO Instruments B.V., Japan)
4	Reflection of solar radiation	W m^{-2}	Thin-film pyranometer ML-02 (EKO Instruments B.V., Japan)
5	Floor surface heat flux	W m^{-2}	Heat flux meter Z2014 (Hioki E.E. Corporation, Japan)
6	Net radiation	W m^{-2}	Net radiometer NR-LITE2 (Campbell Scientific, Inc., USA)
7	Floor surface temperature	°C	Radiation thermometer TIR-12WV (Sensatec Co., Ltd., Japan)
8	Data logger (except Nos. 1 and 2)	-	LR8416 (Hioki E.E. Corporation, Japan)

floor. In the SFG, the heat flux sensors were set at a depth of less than 5 mm beneath the floor surface. In the ICFG, the heat flux sensors were set on the floor surface and were covered with quartz sand. The heat flux sensors were installed such that downward heat flux was positive. All other sensors were installed at a height of 1.5 m above the floor in the center of each greenhouse. Air temperature and relative humidity were monitored with the fan-aspirated sensors (made in-house). Parameter values were recorded at 10-min intervals. The albedo of the floor surface was calculated as the ratio of reflected solar radiation to incident solar radiation. Data obtained when global solar radiation was less than 10 W m^{-2} were not used in the albedo calculation.

Outside climate, i.e., air temperature, relative humidity, atmospheric pressure, and global solar radiation, was monitored at a weather station located in the same institute as the greenhouses (Yoshida et al. 2012). Relative humidity was converted to vapor pressure (kPa) by multiplying the relative humidity by the saturated vapor pressure (e_s, kPa), which was calculated from the air temperature θ_{air} (°C) (Murray 1967) as follows:

$$e_s = 0.61078 \exp[17.2693882\ \theta_{air} / (\theta_{air} + 237.3)] \quad (1)$$

3. Floor surface heat balance and supplied heat

The heat balance at the greenhouse floor surface in steady state is expressed as

$$R_n = G + H_f + \lambda evap_f \quad (2)$$

where R_n is net radiation (W m^{-2}), G is floor surface heat flux (W m^{-2}), H_f is the sensible heat transfer at the floor surface (W m^{-2}), λ is the latent heat of water evaporation (J kg^{-1}), and $evap_f$ is evaporation from the floor surface (kg s^{-1} m^{-2}). The product $\lambda evap_f$ is the latent heat transfer at the floor surface. The incoming direction to the ground surface is expressed as positive for R_n, and the outgoing direction from the ground surface is expressed as positive for G, H_f, and $\lambda evap_f$. The total supplied heat from the floor surface (E_{sup}, W m^{-2}) was calculated as

$$E_{sup} = H_f + \lambda evap_f = R_n - G \quad (3)$$

Results

1. Internal greenhouse environment

During the day (11:00-14:00), the average air temperature was 5.1°C lower in the ICFG than in the SFG, and the maximum was 10.0°C lower in the ICFG than in the SFG (Fig. 4, upper panel; Table 3). At night (23:00-2:00), the average air temperature was 1.6°C higher in the ICFG than in the SFG. The average relative humidity was 6% lower in the ICFG than in the SFG at night (Fig. 4, lower panel). During the day, the average vapor pressure was 0.5 kPa lower in the ICFG than in the SFG. There was no marked difference in the average vapor pressure at night (Fig. 5; Table 3). The rise in vapor pressure in the ICFG during the day was smaller than in the SFG and was likely due to evaporation from joint spaces between concrete blocks and from the uncovered periphery of the ICFG floor.

2. Temperature and radiation balance of the floor surfaces

The average floor surface temperature was 7.3°C lower during the day and 3.2°C higher at night in the ICFG than in the SFG (Fig. 6; Table 3). The average reflected solar radiation was ~90% higher in the ICFG than in the SFG (Fig. 7; Table 3). The concrete floor had a higher average albedo than the soil floor (0.32 versus 0.18; calculated from data in Table 3). As a result, the ratio of energy absorption to incident solar radiation was 17% lower in the ICFG than in the SFG. The average absorbed solar radiation during the day, calculated by subtracting reflected from incident solar radiation, was 12% lower in the ICFG than in the SFG. The maximum absorbed solar radiation was 19% lower in the ICFG than in the SFG (Table 3).

No marked difference was observed in the absolute value of floor surface heat flux during the day, though it was 14 W m^{-2} higher at night on average in the ICFG than in the SFG (Table 3; Fig. 8). The sum of negative (upward) floor surface heat flux values was 59% larger in the ICFG. No marked difference was observed between the sums of positive (downward) heat flux values in the two greenhouses. These results indicated that more heat was supplied to the greenhouse air by the concrete floor than by the soil floor (Fig. 9). As shown in Figure 9, the concrete floor supplied more heat than was stored during the day. Together, these results indicate that the concrete floor promoted the transmission of ground heat energy into the greenhouse to a greater extent than the soil floor, providing an even greater source of heat than daytime energy storage. This greater heat uptake from the ground was due to the higher thermal conductivity of concrete than soil (Table 1).

The absolute value of net radiation from the greenhouse floor was on average 11 W m^{-2} lower during the day and 9 W m^{-2} higher at night in the ICFG than in the SFG, which means that the ICFG gained less energy and lost more energy as radiative heat transfer than the

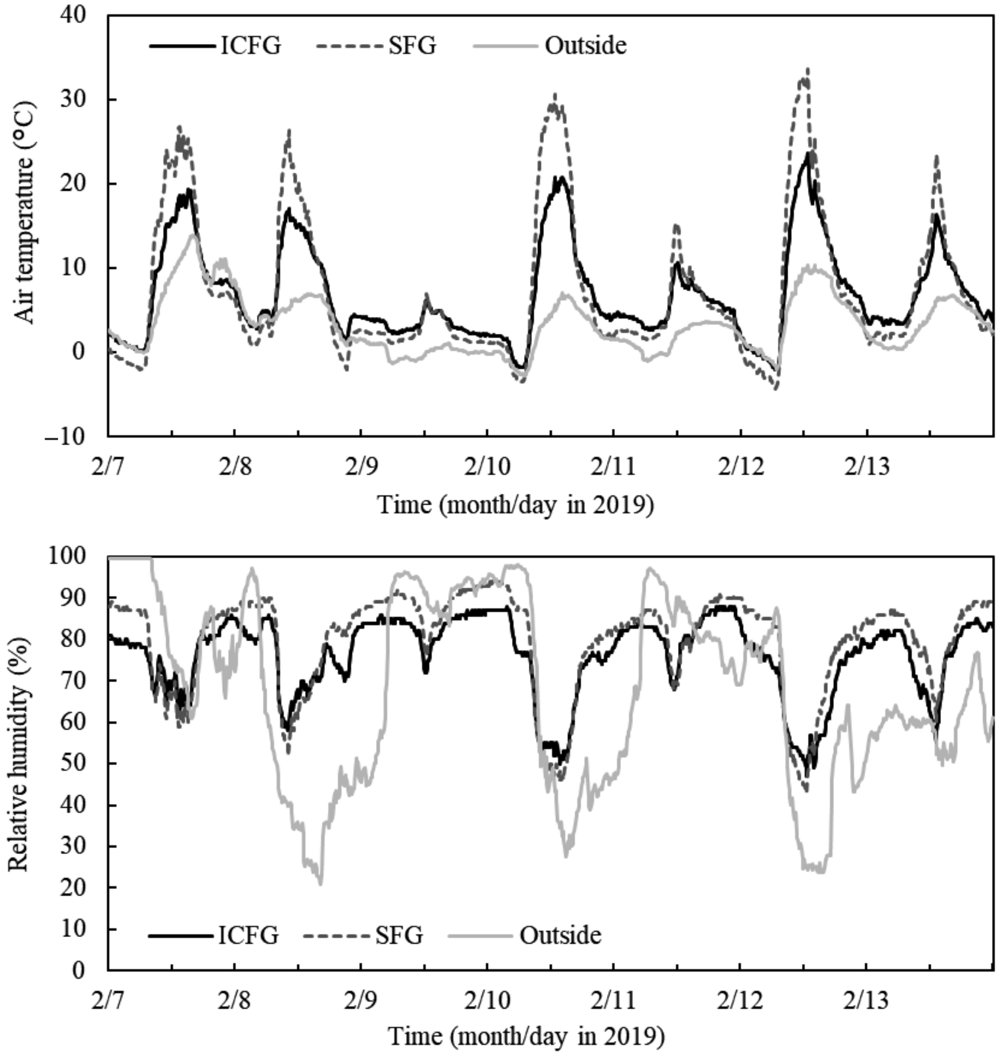

Fig. 4. Temperature (top) and relative humidity (bottom) in the interlocking concrete block floor greenhouse (ICFG), uncovered soil floor greenhouse (SFG), and outside

SFG (Table 3). From the sum of positive and negative values of net radiation, the ratio of radiative heat gain to loss was 54% in the ICFG and 31% in the SFG (Fig. 10).

3. Total heat supplied from the greenhouse floor

The total heat supply from the greenhouse floor was on average 17% lower in the ICFG than in the SFG during the day but was twice as high in the ICFG as in the SFG at night (Table 3). The total heat supplied from the floor includes latent heat; however, there was no steep rise in vapor pressure at night (Fig. 5). Thus, the heat supplied to the greenhouse air at night can be attributed mainly to sensible heat.

Discussion

1. Effects of a concrete floor on greenhouse microclimate and floor heat balance

As shown in Figures 4, 5, a concrete floor reduces greenhouse temperature fluctuations and reduces daytime vapor pressure and thus stabilizes the greenhouse climate, when compared with a greenhouse with a soil floor.

The concrete floor stored less solar energy than the soil floor and lost more energy through radiative heat transfer. However, the concrete floor transmitted more heat from the ground. In the ICFG, the supply of ground heat to the greenhouse air at night was larger than the energy storage during the day. Concrete promotes the uptake of heat from the stable heat source deep in the

Table 3. Greenhouse environmental parameters

Elements	Daytime (11:00-14:00)			Nighttime (23:00-2:00)		
	Mean	Max.	Min.	Mean	Max.	Min.
Temperature (°C)						
SFG	19.1 (± 8.6)	33.7	2.3	2.0 (± 1.8)	6.7	−1.6
ICFG	14.0 (± 5.4)	23.7	3.1	3.6 (± 1.8)	8.3	0.4
Vapor pressure (kPa)						
SFG	1.50 (± 0.48)	2.30	0.63	0.62 (± 0.08)	0.86	0.47
ICFG	1.00 (± 0.23)	1.40	0.63	0.66 (± 0.09)	0.93	0.49
Floor surface temperature (°C)						
SFG	23.6 (± 12.4)	44.0	4.1	3.6 (± 9.3)	7.8	1.1
ICFG	16.3 (± 6.8)	28.9	5.8	6.8 (± 5.2)	10.1	4.0
Incident global solar radiation (A; W m^{-2})						
SFG	250 (± 147)	685	40	-	-	-
ICFG	265 (± 161)	667	37	-	-	-
Reflected solar radiation (B; W m^{-2})						
SFG	44 (± 26)	102	7	-	-	-
ICFG	84 (± 51)	199	12	-	-	-
Absorbed solar radiation (A−B; W m^{-2})						
SFG	206 (± 122)	590	32	-	-	-
ICFG	181 (± 111)	479	25	-	-	-
Floor surface heat flux (W m^{-2})						
SFG	50 (± 42)	152	−11	−21 (± 5)	−13	−31
ICFG	53 (± 48)	168	−21	−35 (± 7)	−24	−50
Net radiation (W m^{-2})						
SFG	134 (± 102)	387	0	−17 (± 4)	−10	−26
ICFG	123 (± 86)	372	−4	−26 (± 5)	−17	−38
Heat supplied from floor surface (W m^{-2})						
SFG	84 (± 66)	305	−61	4 (± 1)	8	1
ICFG	70 (± 47)	209	−29	9 (± 2)	15	4
Specific enthalpy (kJ kg'^{-1})						
SFG	42 (± 16)	69	12	11 (± 3)	20	6
ICFG	30 (± 9)	45	12	14 (± 3)	22	8

Max: maximum, Min: minimum; the values shown in parentheses of mean values are the standard deviation.

ground at night due to its high thermal conductivity.

The daytime greenhouse air temperature was lower in the ICFG than in the SFG. Because the daytime rise in vapor pressure was smaller in the ICFG than in the SFG, latent heat generated at the floor surface should be less in the ICFG. Typically, a smaller latent heat content is accompanied by a higher sensible heat content (higher air temperature). This was not the case in this study because the total heat supplied from the floor surface in the ICFG was less than that supplied from the soil floor in the SFG, resulting in a lower daytime air temperature in the ICFG.

Together, the results indicate that the thermal properties of the floor material and its reflectivity are important in greenhouse floor management to control the greenhouse environment and to effectively use solar energy.

2. Benefits of introducing a concrete greenhouse floor

The results demonstrate that introducing a concrete floor in greenhouses is an effective method for stabilizing greenhouse microclimate. By avoiding temperature extremes, a concrete floor will help create a microclimate that is beneficial for crop growth without requiring additional external energy sources or equipment.

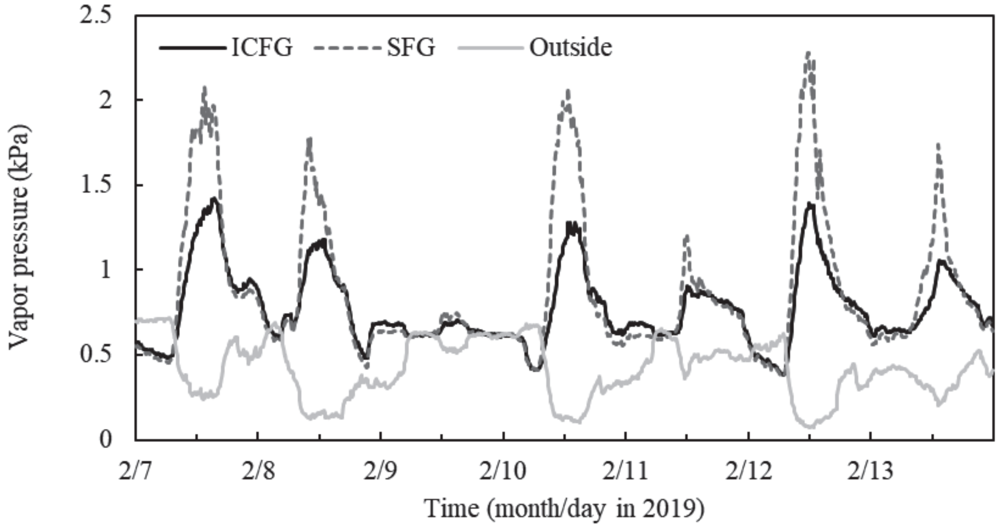

Fig. 5. Vapor pressure in the interlocking concrete block floor greenhouse (ICFG), uncovered soil floor greenhouse (SFG), and outside

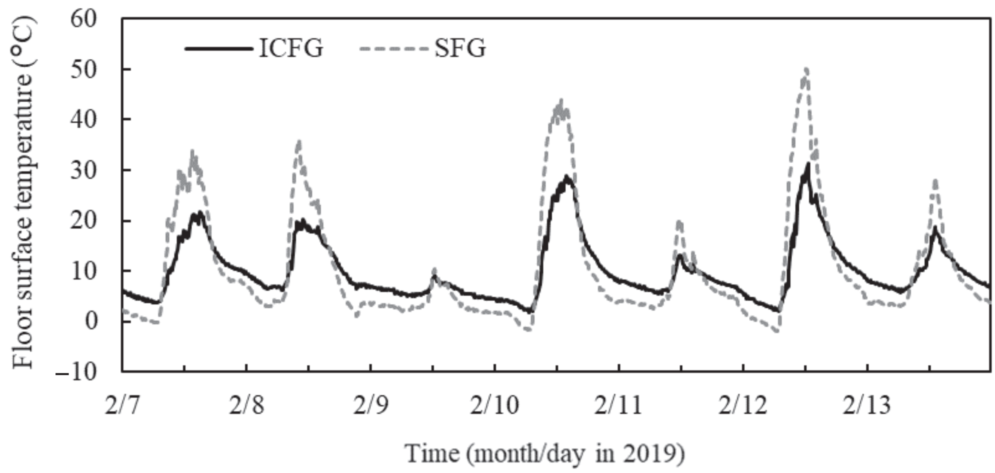

Fig. 6. Floor surface temperatures of the interlocking concrete block floor greenhouse (ICFG) and uncovered soil floor greenhouse (SFG)

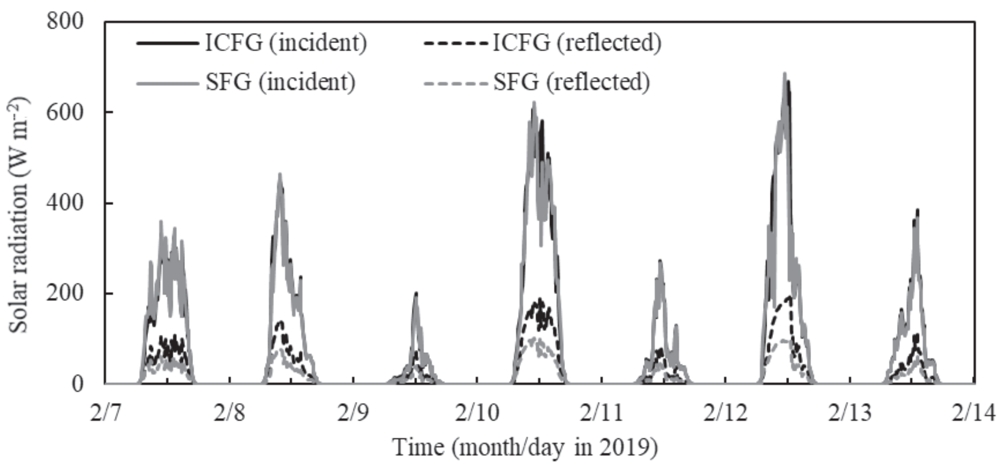

Fig. 7. Incident and reflected solar radiation in the interlocking concrete block floor greenhouse (ICFG) and uncovered soil floor greenhouse (SFG)

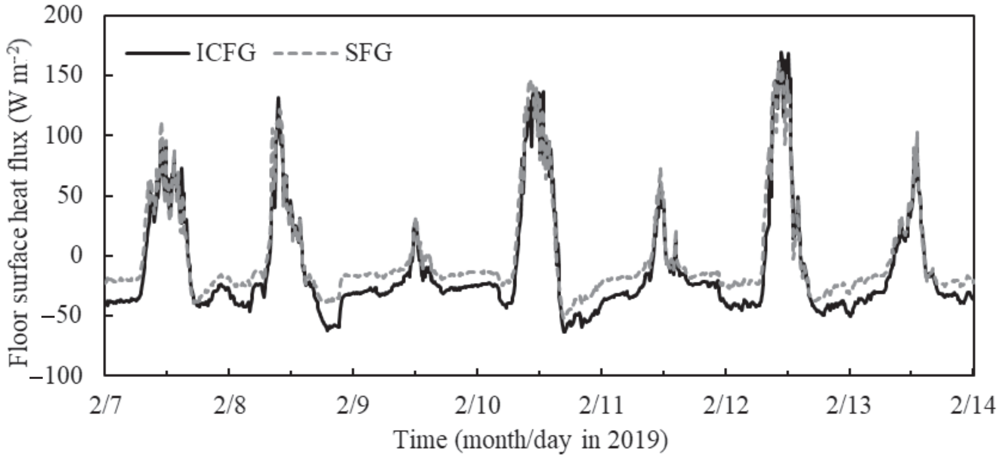

Fig. 8. Floor surface heat flux in the interlocking concrete block floor greenhouse (ICFG) and uncovered soil floor greenhouse (SFG)

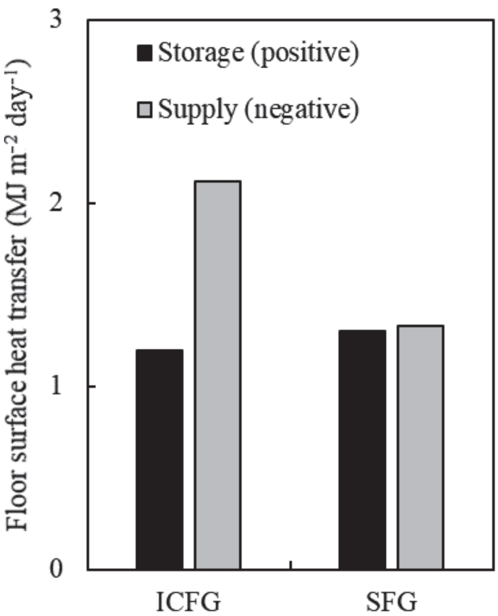

Fig. 9. Heat storage at and heat supply to the greenhouse floor surface
Storage is the periodic average of the daily sum of positive floor surface heat flux. Supply is the periodic average of the daily sum of negative floor surface heat flux expressed as an absolute value.

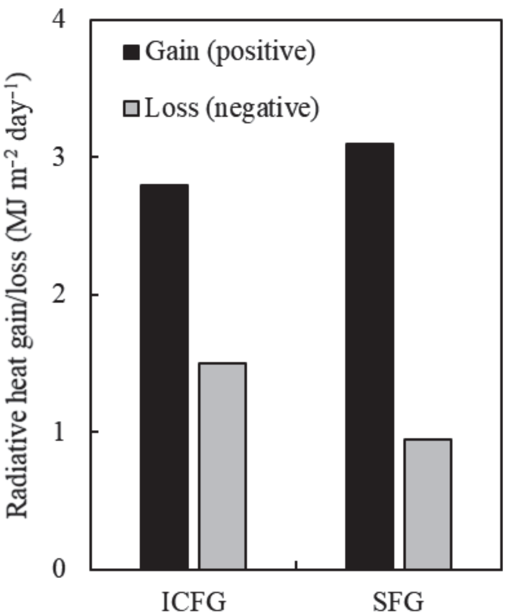

Fig. 10. Comparison of radiative heat gain and loss of the greenhouse floor calculated as the average of the daily sum of positive (gain) and negative (loss) values, expressed as an absolute value

Concrete floors are also beneficial for using robotic technology for greenhouse automation (Ota et al. 2019) and for introducing irrigation technology such as flood floor irrigation (Uva et al. 2001). Further research focused on the optimal construction of concrete floors for greenhouses, including new methods for integrating concrete floors with agricultural robotics, irrigation systems, and environmental control systems, is required to establish a more efficient concrete-floor-based greenhouse system.

Conclusions

This study reveals the effects of introducing interlocking concrete blocks as the floor material in a single-span pipe-framed greenhouse. On the basis of a comparison of two adjacent greenhouses, one with a concrete floor and the other with a soil floor, the following conclusions are drawn:

- Introducing a concrete floor reduces fluctuations in greenhouse air temperature and vapor pressure and thus is expected to improve greenhouse productivity without consuming energy from external sources, for example, fossil fuels or solar panels.
- Concrete has a higher thermal conductivity than soil and therefore allows greater uptake of ground heat at night, stabilizing the nighttime air temperature of greenhouses.
- The increase in vapor pressure during the day was smaller when using a concrete floor, indicating that the concrete floor reduces evaporation from the soil.
- The higher reflectivity of concrete than soil reduces the daytime heat absorption at the floor surface and prevents the rise in temperature during the day.

References

Al-Kayssi, A. W. et al. (1990) Influence of soil moisture content on soil temperature and heat storage under greenhouse conditions. *J. Agric. Eng. Res.*, **45**, 241-252.

American Society of Agricultural Engineers (1993) EP460: Commercial greenhouse design and layout. https://elibrary.asabe.org/abstract.asp?aid=45686. Accessed on 1 September 2021.

Baille, A. et al. (2006) Night energy balance in a heated low-cost plastic greenhouse. *Agric. For. Meteorol.*, **137**, 107-118.

Bonachela, S. et al. (2012) How plastic mulches affect the thermal and radiative microclimate in an unheated low-cost greenhouse. *Agric. For. Meteorol.*, **152**, 65-72.

Bonachela, S. et al. (2020) Effects of gravel mulch on surface energy balance and soil thermal regime in an unheated plastic greenhouse. *Biosyst. Eng.*, **192**, 1-13.

Hart, C.', & van Weel, P. A. (1988) Constructional aspects of some heated concrete floors for greenhouses. *J. Agric. Eng. Res.*, **39**, 161-172.

Kozai, T. et al. (1985) Cooling load of a greenhouse:(1) characteristics of cooling load in summer nighttime. *J. Agric. Meteorol.*, **41**, 121-130 [In Japanese with English abstract].

Kurata, K. & Takakura, T. (1991) Underground-storage of solar-energy for greenhouses heating. 1. analysis of seasonal storage-system by scale and numerical-models. *Trans. ASAE*, **34**, 563-569.

Miyoshi, Y. et al. (2013). Application of the constant soil temperature layer for energy-saving control of the local environment of greenhouse crops: 1. Local control of the ambient environment of strawberry. *Environ. Control. Biol.*, **51**, 89-94.

Moriyama, H. et al. (2015) Which design constraints apply to a pipe-framed greenhouse?: From perspectives of structural engineering, meteorological conditions, and wind engineering. *JARQ*, **49**, 1-9.

Murray, F. W. (1967) On the computation of saturation vapor pressure. *J. Appl. Meteorol.*, **6**, 203-204.

National Chamber of Agriculture (2020) The new system for concrete flooring in greenhouses. AgriweB. https://www.agriweb.jp/knowledge/1411.html. Accessed on 2 February. [In Japanese].

Okushima, L. & Isamu N. (2017) Concrete flooring in greenhouses. Mail magazine of NIRE, **92**, http://www.naro.affrc.go.jp/org/nkk/m/92/05-01.pdf. Accessed on 2 February. [In Japanese].

Ota, T. et al. (2019) Development of small automatic guided vehicle by contact detection to hydroponics cultivation system. *JARQ*, **53**, 31-40.

Reiss, E. et al. (2007) Numerical modeling of greenhouse floor heating. *Trans. ASABE*, **50**, 275-284.

Roberts, W. J. & Mears, D. R. (1989). Floor heating of greenhouses. *Acta Hortic.*, **257**, 189-199.

The Japan Society of Mechanical Engineers (2009) V. Physical properties. *In* JSME Data Book: Heat Transfer 5th Edition, Maruzen Publishing Co., Ltd., Tokyo, Japan, pp. 279-332 [In Japanese].

Uva, W. L. Weiler, T. C. & Milligan, R. A. (2001) Economic analysis of adopting zero runoff subirrigation systems in greenhouse operations in the northeast and north central United States. *Hort. Sci.*, **36**, 167-173.

Yoshida, T. et al. (2012) Configuration of integrated weather observation system and quality assessment of observed data. *Tech. Rep. Natl. Inst. Rural. Eng. Japan*, **212**, 43-52 [In Japanese with English abstract].