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Development of Circulating-Type Movable Bench System for Strawberry Cultivation

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Abstract
One of the direct approaches for obtaining a high yield of strawberries is high-density cultivation. Such cultivation improves the efficiency of space utilization in a greenhouse; however, it requires the movement of planting benches. The aim of this study is to develop a circulating-type movable bench system for strawberry cultivation that realizes high-density cultivation and improves work efficiency. The developed system, which is 16.0 m long and 9.2 m wide, consists mainly of two longitudinal conveying units, two lateral conveying units, two nutrient supply units, a chemical sprayer, 62 planting benches, and a control unit. The design of the longitudinal conveying mechanism combining the rotating and sliding movements of rods for pulling the benches and a method of controlling the conveying units achieves effective circulation, resulting in a cycle time of 67.0 s during which the successive bench reaches the initial position. This cycle time could be shortened by increasing the speed of lateral conveying. The planting density obtained using this approach is 16.0 to 20.0 plants m^{-2}, which is roughly 2 to 2.5 times the plant density obtained in the conventional method of cultivation. Furthermore, the four cultivars used in this study showed vigorous growth, and the cultivars Akihime and Moikko showed a marketable yield twice as high as the conventional yield.

Discipline: Agricultural machinery
Additional key words: chemical spray, high-density planting, substrate culture, longitudinal and lateral conveyors

Introduction

Although large-scale greenhouses have gained popularity in Japan for the cultivation of fruit-vegetables such as tomato and paprika[5], strawberries (*Fragaria × ananassa Duch.*) are still grown in small plastic houses. In Japan, the strawberry-growing area per farming household is a little less than 2,500 m^2, the planting density is approximately 7 to 8 plants per square meter, and the average yield is 3 to 4 kg per square meter[9]. The resulting productivity of Japan is lower than that of Europe, where the yield is more than 10 kg per square meter and the planting density is about 12 plants per square meter[3,12]. Japan's lower level of productivity is not only due to the difference in cultivars, training methods, and climate factors, but also due to the lack of a widely adopted new technology; many Japanese farmers still use traditional farming methods.

There are two direct approaches for obtaining a high yield of strawberries: increasing the yield per plant, and increasing the cultivation density. The former method involves breeding cultivars or extending the cropping season. The latter method, on the other hand, involves increasing the yield through the efficient use of greenhouse space by removing the path between each line of beds, which is about 0.9 m wide and is required for the traditional elevated substrate culture. To do so, the benches should be movable so as to provide working space for transplanting, maintaining, spraying, harvesting, etc. Many studies have been conducted on movable benches, which are already used in floriculture and the cultivation of leafy vegetables. Movable systems can be classified into four categories: rolling systems[1,2,10,13], unidirectional

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moving systems[4], circulating systems[7,11], and vertical moving systems[6,8,14]. From the standpoint of increasing land productivity and obtaining maximum solar radiation, the circulating movement is considered suitable for strawberry cultivation, because a forcing culture, which is the major type of cropping used in Japan, requires a long cropping season with low solar radiation and routine crop maintenance at least every two to three days. It was for this reason that we developed a prototype of the movable bench system for strawberry cultivation[15]. In this prototype, the lateral and longitudinal conveyors are operated independently, so the worker sometimes has to wait until the next bench comes before him/her. This indicates that the work efficiency can be increased by designing a mechanism and a method for controlling the conveyors, which would have a significant impact on its practical use.

The objectives of this study are threefold: (1) to develop a circulating-type movable bench system for strawberry cultivation that provides the effective circulation of benches, (2) to fabricated a movable planting bench suitable for this system, and (3) to evaluate the performance of the system. This study could establish a platform for an automated production system and pave the way for the high-density, year-round cultivation of strawberries.

Materials and methods

1. Basic movement of movable bench system for strawberry cultivation

Figure 1 shows the design of the movable bench system developed in this study. It is mainly comprised of two longitudinal conveying units, two lateral conveying units, two nutrient supply units, a chemical sprayer, 62 planting benches, and a control unit.

The benches are moved rotationally, as illustrated in Fig. 2, beginning their movement from an initial position shown in Fig. 2-a. Two benches that are loaded on each lateral conveying unit move simultaneously in a lateral direction and stop at the end (Fig. 2-b). They are then pulled into the longitudinal conveying unit to join the other benches in that unit, so that the farthest benches on the other side are transferred onto the lateral conveyors (Fig. 2-c). After completing a circuit, the benches return to the initial position. This cycle of movement can be repeated, resulting in the circulation of the benches all around the greenhouse. It is our expectation that the simultaneous operation of both the longitudinal and lateral conveying units constitutes an effective cycle of bench movement, that is, a short cycle time.

2. System components and functions

Table 1 presents the specifications of the movable bench system. The system is 16.0 m long and 9.2 m wide and was installed in a multi-span plastic house of a strawberry producer in Miyagi Prefecture.

(1) Planting bench

The planting bench is composed of a frame, four planters with a length of 1 m, a gutter with a length of 4.2 m, and four rollers, as shown in Fig. 3. A foam polystyrene weir is attached to the drain side of the gutter to accumulate the nutrient solution, so the surplus solution can be reused after passage though a string of nonwoven fabric by capillary action. The polyacetal roller is 50 mm in

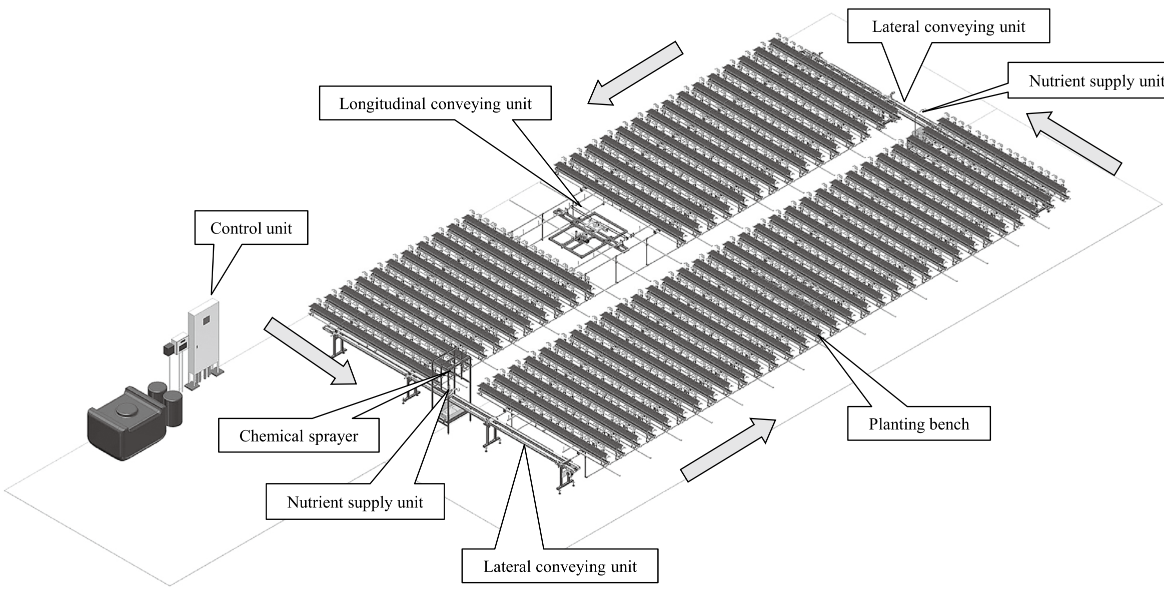


Fig. 1. Schematic diagram of movable bench system for strawberry cultivation
The arrows show the circulating direction.

diameter at the edge, with a concavity in the middle (R = 25 mm), so that it will not be derailed during longitudinal conveying.

(2) Longitudinal conveying unit

The system has two longitudinal conveying units, each of which is composed of two rails, two pull-in rods for the benches, a motor for sliding the rods, and a motor

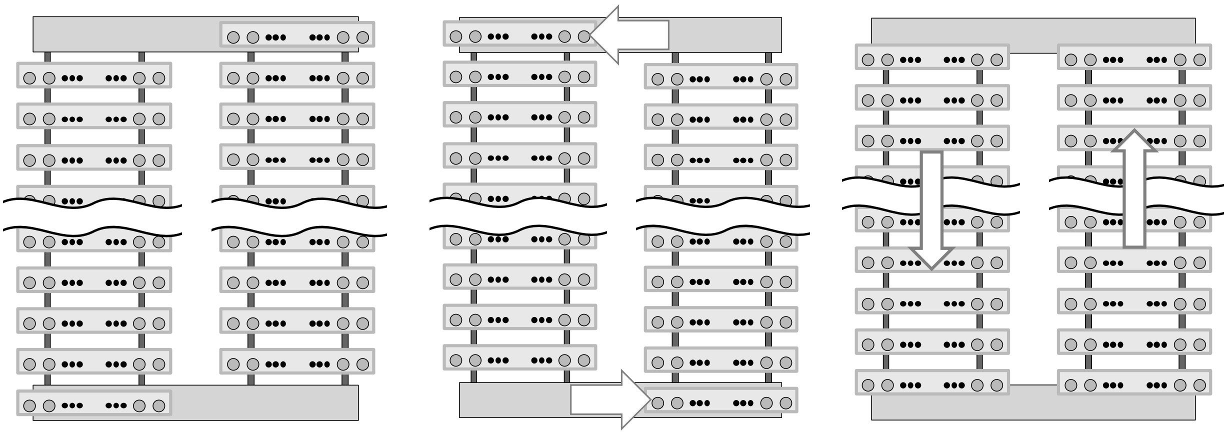


Fig. 2. Cycle movement
(a) initial position, (b) lateral conveying, and (c) longitudinal conveying.

Table 1. Specifications of the movable bench system

Size	16.0 (L) × 9.2 (W) m Number of benches: 62 (distance between benches: 500 mm)
Control unit	Sequence control by programmable logic controller (PLC) Temporary stop function with a foot switch
Longitudinal conveying unit	Number of units: 2 Pull-in rod for the bench: steel pipe (φ34.0 × 3.2 mm), hook space: 500 mm Motor for sliding the rod: 90 W Motor for rotating the rod: 30 W Conveying speed: 50 mm/s Rail:steel pipe (φ31.8), distance between two rails: 2400 mm
Lateral conveying unit	Number of units: 2 Conveying distance: 9 m Conveyor belt: 2 belts, 50-mm wide Motor: 90 W Conveying speed: max 265 mm/s (set speed: 160 mm/s)
Nutrient supply unit	Number of units: 2 Amount of supply (max): 8 L/min Electrical conductivity of solution: 0.75 dS/m
Chemical sprayer	Motor power sprayer: MS330MC-A (Maruyama MFG Co. Inc.) Motor output: 1.5 kW Maximum pressure: 3.5 MPa Spray nozzle: N-Y45-SM440 (Yamaho Industry Co., Ltd.) Number of nozzles: 3
Planting bench	Size : 4200 (L) × 240 (W) mm Number of planters:4 Volume of substrate in one planter: 13 L Outer diameter of wheel: 50 mm, wheelbase : 155 mm

for rotating the rods (Fig. 4-a). Although a unidirectional conveying mechanism for planting benches that uses a combination of a back-and-forth and up-and-down movement of the rod has been reported[4], this mechanism requires a wide clearance between the bench and the lateral conveying unit so that the rod can pass through if it is applied to a circulating-type movable bench. For this reason, we developed a mechanism that enables the rod to slide and rotate. The pull-in rod is composed of a 15-m-long steel pipe with 150-mm-long hooks at 500-mm intervals, and it allows for a 500-mm sliding motion to convey the planting beds. The mechanism is driven by a 90-W motor and a linear head, and it permits a 90° rotation in order to move the hooks up and down by means of a 30-W motor and a timing belt. To select the motor for sliding the rod, the coefficient of friction was measured when the bench moved on the rails. The resulting coefficients of static and dynamic friction were 0.063 and 0.046, respectively. Here, the required force is calculated by equation (1).

$$F = \mu_s \times m \times g \times N_b \tag{1}$$

where F is the required force (N); μ_s is the coefficient of static friction, 0.063; m is the mass of the planting bench (kg), 55 kg; g is the gravitational acceleration (m s^{-2}); and N_b is the number of planting benches being pulled simultaneously, 31 benches. Substituting the ap-

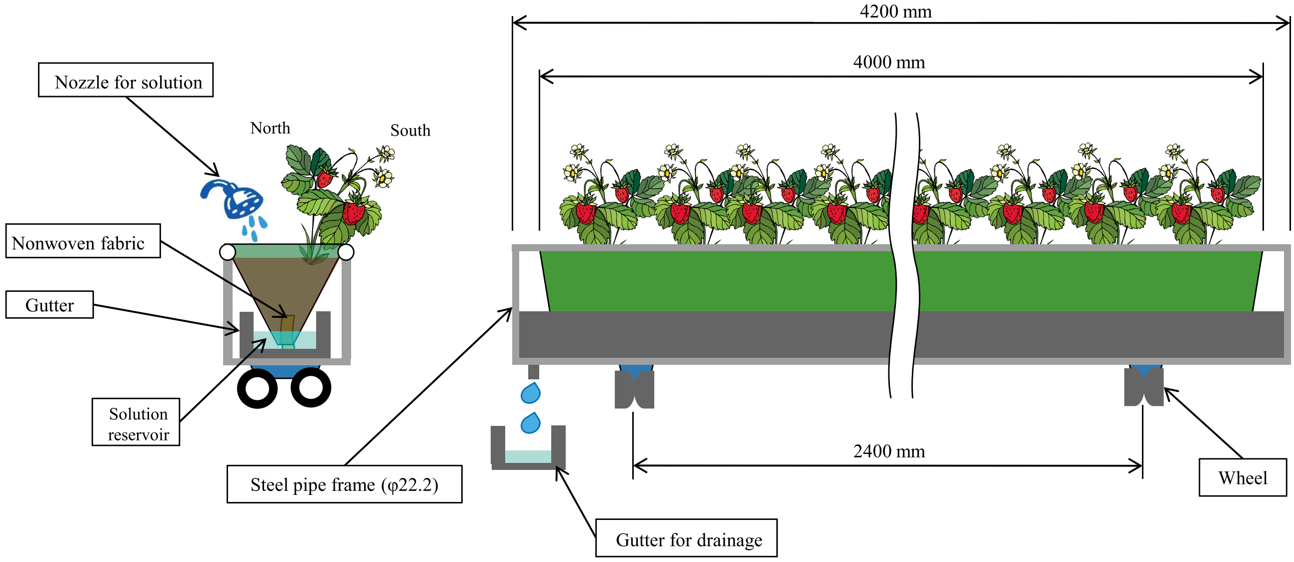
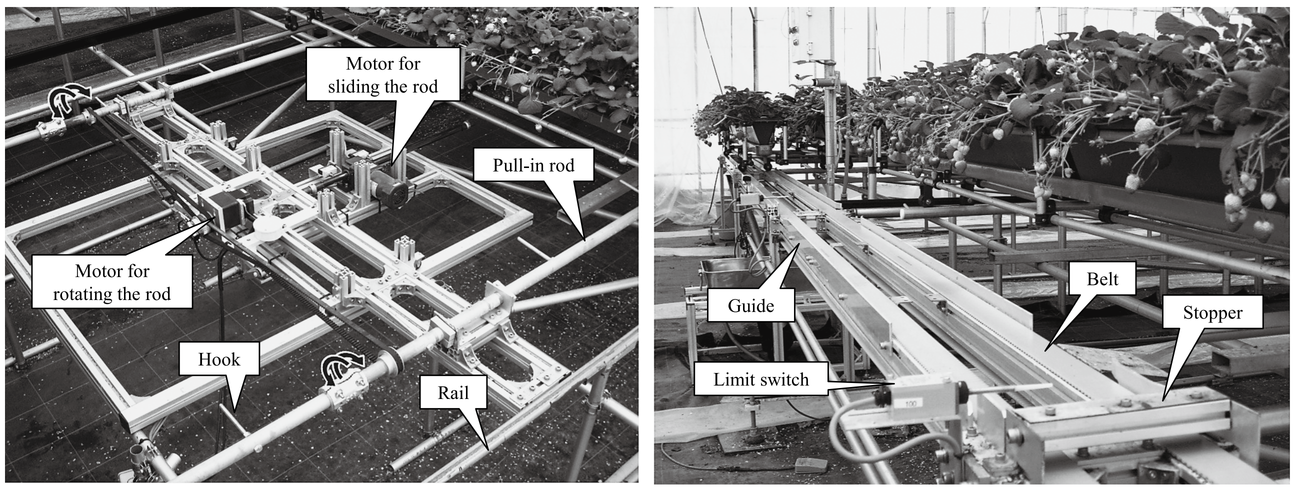


Fig. 3. Movable planting bench



(a) (b)

Fig. 4. Conveying mechanism of planting bench
(a) longitudinal conveying unit, and (b) lateral conveying unit.

plicable values into equation (1), a required force of 1053 N was obtained.

In addition, the driving force that combines the motor and the linear head selected in this study can be calculated by equation (2), as follows:

$$F' = T_m \times i \times \eta_1 \times \frac{2}{D} \times \eta_2 \qquad (2)$$

where F' is the driving force (N); T_m is the torque of the motor (mN m), 730 mN m; i is the reduction gear ratio of the linear head, 36; η_1 is the transfer coefficient by the reduction gear ratio, 0.66; D is the pitch diameter of the pinion (mm), 24 mm; and η_2 is the transfer coefficient between the rack and pinion, 0.9. Substituting the applicable values into equation (2), we obtain a driving force of 1301 N and the condition of $F' > F$ was satisfied. This demonstrates that the combination of motors in this study generates sufficient driving force to convey all the benches loaded on a single longitudinal conveying unit.

The longitudinal conveying movement of benches is illustrated in Fig. 5. The movement starts in the initial position with the hooks standing (Fig. 5-a). Next the hooks all roll down 90° to a horizontal position (Fig. 5-b). The rods slide in a leftward direction with the hook still horizontal, so that the rod ends up passing through the underside of the bench on the left-side lateral conveying unit (Fig. 5-c). In this position, the hooks roll up as the rod rotates (Fig. 5-d). Finally the rods pull all the benches, so that the bench at the right end is loaded onto the right side of the lateral conveying unit (Fig. 5-e).

(3) Lateral conveying unit

The lateral conveying units were specially designed for the planting bench used in this study. The system has two lateral conveying units, each of which is composed of an aluminium frame, two urethane timing belts, a 90-W waterproof motor, two limit switches, and a stopper (Fig. 4-b). The two belts are parallel to one another at a distance of 155 mm, which is equal to the size of the wheelbase of the planting bench. In this arrangement, the bench released from the longitudinal conveying unit is loaded on the lateral conveying unit in such a way that the bench rollers straddle just the two belts and are then moved laterally by the rotation of the belts. The two limit switches and the stopper on the other side make the

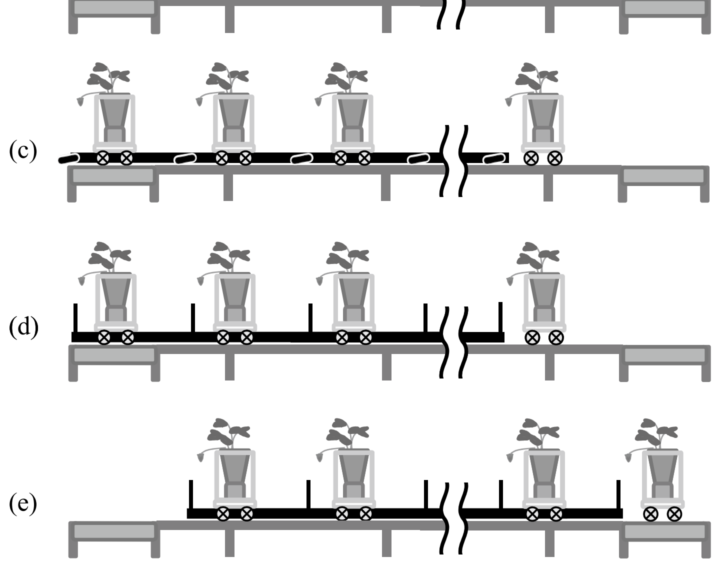


Fig. 5. Movement of longitudinal conveying

(a) initial position, (b) hook roll-down, (c) rod passing under bench on the lateral conveying unit, (d) hook roll-up, and (e) rod pulling in the bench.

bench stop at the position indicated. In addition, a guide frame is attached to both sides of the belts to prevent the derailment of the planting bench during conveying.

(4) Nutrient supply unit

Due to the way each bench circulates, as described above, it is impossible to use normal irrigation tubes to channel nutrients from a nutrient solution tank. The nutrient solution is therefore supplied by a shower nozzle installed in the middle of both lateral conveying units, as shown in Fig. 1. The position of the shower nozzle is adjustable so as to supply the nutrient solution around the side area where strawberries are not planted. Watering begins when a photoelectric sensor on the front of the shower nozzle detects the planting bench passing by. The amount of nutrients supplied per bench can be adjusted via a valve in the shower nozzle and the adjustment of the speed of lateral conveying.

(5) Chemical sprayer

The chemical sprayer is structured as a gate frame with three spray nozzles (top, left, and right side) and is installed in the middle of the lateral conveying unit through which the benches pass (Fig. 1). The spraying takes place as the planting bench passes through the gate frame, in the same manner as described for the solution supply unit.

(6) Control unit

The control program has three operational modes: working mode, watering mode, and spraying mode.

In working mode, the system performs 62 movements of the bench in the course of one complete assignment. The worker can maintain the crops or harvest the fruits at one of the two lateral conveying units, since in this study, strawberry crops were planted in clusters on one side of the bench. Foot switches near the lateral conveying units enable the worker to temporarily halt the movement of the planting bench whenever the performance of a task does not keep pace with the movement.

In watering mode, the system automatically performs 31 movements in the course of one complete assignment, and both supply units operate when the bench passes through.

In spraying mode, the system automatically performs 62 movements, again in the course of one complete assignment, and the spraying unit, which is installed on one of the lateral conveying units, goes into operation when the bench passes through.

3. System performance test

Four cultivars— Akihime, Moikko, Nyoho, and Tochiotome —were grown in a forcing culture using the developed system with a plant distance of 10 or 12.5 cm on the planting bench. The basic performance of the movable bench system was assessed in terms of cycle time, electric energy consumption, and acceleration level of the bench.

(1) Cycle time

Movements spanning 10 cycles were recorded with a digital video camera, and the execution time for each movement, such as lateral conveying, forward movement of the rod, rod rotation, and longitudinal conveying, was analysed and measured from the video data.

(2) Electric energy during one cycle

The electric energy used in the steady state and in the three operational modes (working, watering, and spraying mode) was measured for 10 cycles using a wattmeter. The wattage was sampled at 1 Hz and recorded on a PC, and the electric energy in each mode was calculated from the wattmeter data. In spraying mode, the pressure of the chemical sprayer was set at 1.5 MPa.

(3) Acceleration level of the bench

The planting benches repeatedly move and stop during circulation, and they also shake somewhat during transfer from the longitudinal conveying unit to the lateral conveying unit, and vice versa. The acceleration levels of the planting bench were measured during both lateral and longitudinal conveying. A three-axis acceleration sensor was attached to the centre of the gutter of the bench, and acceleration data were sampled at 50 Hz and recorded on a PC.

Results and discussion

1. Cycle time

The execution time for each individual cycle is shown in Table 2. The results show a cycle time of 67.0 s, which was a little faster than the 71.2 s in our previous study[15], even with a bed length that was twice as long as that in our previous study. The developed control method, in which both conveying units move simultaneously, clearly provides more effective bench circulation, which would improve work efficiency.

The lateral conveying, however, accounted for a little less than half of the cycle time, 31.3 s, which suggests that it has the potential to be accelerated further. As the speed of the lateral conveying increases, the work time involved in a single cycle, such as crop maintenance or harvesting, becomes correspondingly shorter. Thus, the selection of a lateral conveying speed suited to a given kind of work would be an important factor in providing such efficiency. For example, a high speed could be selected for the watering, spraying, or harvesting of a smaller crop, and a low speed could be selected when harvesting a larger crop.

2. Electric energy

Figure 6 shows the change in electric power during one cycle in the steady state, in which no mechanical device was in operation, and in the three operational modes. The electric power in the steady state was a constant of 167 W, and a maximum wattage of approximately 500 W was recorded during the longitudinal conveying of the benches. The average power energy used in one cycle (67 s) was calculated as 1.80 Wh in the steady state, 4.24 Wh in working mode, 4.80 Wh in watering mode, and 11.83 Wh in spraying mode.

In terms of practical cultivation, the benches require at least one complete circulation per day for watering, thus the electric energy used per day was approximated as 2.51 kWh day^{-1}.

Table 2. Execution time for each movement in a cycle

Movement	Time, s
1. Lateral conveying including hook roll-down	31.3
2. Rod passing under the benches	10.9
3. Rod rotation (hook roll-up)	8.3
4. Longitudinal conveying (rod pulling the bench)	16.5
Total	67.0

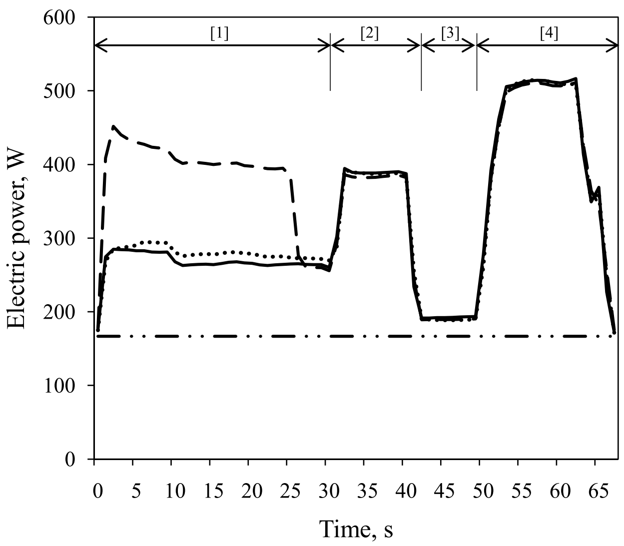


Fig. 6. Electric power during one cycle of movement in harvesting mode, watering mode, spraying mode, and steady state

The numbers in square brackets correspond to each movement in Table 2.

: Working mode, : Watering mode,
: Spraying mode, : Steady state.

3. Acceleration level of the bench

During longitudinal conveying the peak acceleration level of the bench averaged 2.6 m s^{-2} in a longitudinal direction and 3.1 m s^{-2} in a vertical direction. The peak values were almost the same, indicating that the benches shook somewhat while being pulled by the rods. During lateral conveying, on the other hand, the peak acceleration level occurred when the lateral conveying unit started. The peak values averaged 5.0 m s^{-2} in a lateral direction and 1.4 m s^{-2} in a vertical direction. At these acceleration levels, no damage to the pericarp of the fruit was observed due to contact between neighbouring plants.

4. Planting density and cultivation experiment

Photographs of the actual movable bench system and fruit settings are presented in Fig. 7. In this study, although the strawberry plants were set at distances of 10 and 12.5 cm, no obvious difference could be observed in regard to their growth or health. Moreover, the distance between benches was set at 50 cm; consequently, the planting density was calculated as 16.0 to 20.0 plants m^{-2}. This is estimated to be roughly 2 to 2.5 times higher than in the conventional method of cultivation, so a high level of productivity could quite reasonably be expected.

In the cultivation experiment, the four cultivars used in this study showed vigorous growth. In the area with a density of 16.0 plants m^{-2}, the marketable yield for Akihime, Moikko, Nyoho, and Tochiotome were 7.7, 8.3, 4.9, and 5.2 kg m^{-2}, respectively. Although the marketable yield scattered with cultivars, Akihime and Moikko showed a yield that was twice as high as the conventional yield of 3 to 4 kg per square meter[9]. This result agrees with former experimental data that the yield increases in proportion to the cultivation density[10]. However, the reason for the lower-than-expected yield in Nyoho and Tochiotome was not clear, so further study on the adaptability of cultivars to high-density cultivation is necessary.

The movable bench system allows the work space to be clearly delineated, so some form of automation or a precision sensing system, such as robotic harvesting, detection of stress reaction, measurement of crop growth, etc., could easily be incorporated.

Conclusion

A circulating-type movable bench system for strawberry cultivation was developed, which allows for high-density cultivation and improves work efficiency. The system is 16.0 m long and 9.2 m wide and consists mainly of two longitudinal conveying units, two lateral conveying units, two nutrient supply units, a chemical sprayer,

(a) (b)

Fig. 7. Photographs of strawberry cultivation using movable bench system
(a) general view, and (b) close-up of fruit.

62 planting benches, and a control unit.

The design of the longitudinal conveying mechanism combines the rotating and sliding movements of rods for pulling the benches, and a method of controlling the conveying units could allow for effective circulation, resulting in a cycle time of 67.0 s, during which the successive bench reaches the initial position. A further shortening of the cycle time might be achieved by increasing the lateral conveying speed. The system has 62 beds and needs at least 4,154 s, which is more than 1 h, to perform one complete circulation. In terms of overall system performance, this circulating-type movable bench system would be limited in terms of scaling-up in a longitudinal direction, because certain tasks such as harvesting have to be completed in limited time.

The electric energy consumed during one cycle in the steady state, working mode, watering mode, and spraying mode averaged 1.80, 4.24, 4.80, and 11.83 Wh, respectively. The planting density using the developed system was from 16.0 to 20.0 plants m^{-2}, which is roughly 2 to 2.5 times that obtained using the conventional method of cultivation. In addition, the four cultivars used in this study showed vigorous growth, and the cultivars Akihime and Moikko showed a marketable yield twice as high as the conventional yield.

Acknowledgments

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