Analyses of Work Efficiency of a Strawberry-Harvesting Robot in an Automated Greenhouse

Seungmin Woo 1,2, Daniel Dooyum Uyeh 1,2, Junhee Kim 2, Yeongsu Kim 2, Seokho Kang 2, Kyoung Chul Kim 3, Si Young Lee 4, Yushin Ha 2,5,* and Won Suk Lee 5,*

1 Upland-Field Machinery Research Center, Kyungpook National University, Daegu 41566, Korea; woosm7571@gmail.com (S.W.); uyehdooyum@gmail.com (D.D.U.)
2 Department of Bio-Industrial Machinery Engineering, Kyungpook National University, Daegu 41566, Korea; sda2356@naver.com (J.K.); mvio9256@naver.com (Y.K.); deshshk@naver.com (S.K.)
3 Division of Smart Farm Development, National Academy of Agricultural Science, Rural Development Administration, Jeonju-si, Jeollabuk-do 54875, Korea; kkcmole@korea.kr
4 R&D Coordination Division, National Academy of Agricultural Science, Rural Development Administration, Jeonju-si, Jeollabuk-do 54875, Korea; leesy42@korea.kr
5 Department of Agricultural & Biological Engineering, University of Florida, Gainesville, FL 32611, USA
* Correspondence: yushin72@knu.ac.kr (Y.H.); wslee@ufl.edu (W.S.L.)

Received: 14 September 2020; Accepted: 31 October 2020; Published: 11 November 2020

Abstract: Protected cultivation systems such as greenhouses are becoming increasingly popular globally and have been adopted because of unpredictable climatic conditions and their ability to easily control micro- and macroenvironments. However, limitations such as hazardous work environments and shortages in labor are major concerns for agricultural production using these structures. This has led to the development and adoption of robotic systems. For the efficient use of robots in protected cultivation systems, we formulate the work efficiency problem and model a three-dimensional standard strawberry greenhouse to analyze the effectiveness of a strawberry-harvesting robot compared to different levels of human workforce (experienced, average, and beginner). Simulations are conducted using Quest software to compare the efficiency of different scenarios of robotics to humans. Different methods of improvement from battery capacity and charge rate to harvesting speed are investigated and optimal conditions are recommended. The average hourly production of the robot is about five times lower than that of skilled workers. However, robots are more productive due to their ability to work around the clock. Comparative analyses show that a reduction in harvesting time per strawberry from 3 to 1 s would result in an increase in daily production from 347.93 to 1021.30 kg. This would lead to a five-fold increase in comparison to present daily production. A 10% improvement in battery charge time would result in the battery capacity gaining two extra hours from the current 10 h and would cut the current 2 h needed for charge to 1 h. This paper proposes an operation process and suggestions for changes needed for improving the work efficiency of robots in a greenhouse. This could be extended to other crops and greenhouses.

Keywords: protected cultivation; greenhouse; robots; work efficiency; premium crops

1. Introduction

Protected cultivation using systems such as greenhouses and, most recently, plant factories has served many purposes to communities dating back to early human civilization. The Korean Agriculture History Association recorded the use of protected cultivation systems as early as the 1450s [1]. Since that era, these structures were constructed to grow food during the freezing winters.
and were taken down at the end of the cold season. This has transformed and advanced over the centuries to include growing premium crops such as paprika with precisely controlled micro- and macroenvironments [2]. Plant factories have been adopted to resolve the issues surrounding land resources. This is increasingly becoming a major source of income for rural dwellers [3–6], especially in the Republic of Korea, from as early as the 1980s [7,8], where premium crops such as paprika and strawberries are cultivated and exported to countries in the region.

Sustainable growth of food, especially vegetables, faces many challenges, including water and land resources [9] and climate conditions in some countries [10,11], which limit the year-round production of crops required for healthy living, such as fruits and vegetables. Protected cultivation systems are crucial in global food security, as they offer a controlled environment for high-value crops, including medicinal plants, which are essential for the wellbeing of humans. Generally, crops grown using protected cultivation systems are healthy and have higher yields [12]. Other benefits of protected cultivation systems are the ease in adopting and implementing technologies, such as wireless communication systems [13], and their ability to save water, as water shortages are a global problem caused by droughts associated with climate change [14,15]. These protected cultivation systems use less water for irrigation than normal farming because moisture is trapped in the structures and prevented from evaporating. Protected cultivation delivers opportunities for sustainable global food production with precise environmental control [16,17].

However, protected cultivation systems have drawbacks, such as skilled labor shortages due to the migration of young people to urban areas and the aging of the current rural dwellers. This is a major challenge in the Republic of Korea and other Organization for Economic Co-operation and Development (OECD) countries [18–20]. Generally, the availability of skilled labor to complete repetitive tasks in the harsh climate condition of greenhouses is rapidly decreasing [21]. The environment in greenhouses is usually hazardous compared to the open-field cultivation systems because of the poor air circulation [22]. Other authors [23] studied the occupational risk factors in greenhouse workers, and concluded that there are possible adverse health effects among greenhouse workers that are exposed to biological agents, pesticides, and other factors of their specific work environment. Consequently, robotics is currently being explored worldwide, especially in OECD countries, to mitigate the risks and hazards associated with the use of protected cultivation systems. These systems are usually termed “smart farms,” which involve the fusion of information and communication technologies.

Protected cultivation systems are capital-intensive systems compared to open-field cultivation [20]. Consequently, different factors determine the choices made before and during the operation of these systems. These include the availability of energy, which takes more than 50% of the operational cost [24–26]; regional infrastructure and market opportunities; climate condition of proposed area and resources, such as water and soil quality in terms of topography and natural disasters; land resources and capital accessibility; and a more pertinent issue, which is availability and cost of skilled labor [27].

As mentioned above, market factors, which are major drivers in the selection of crops for protected cultivation systems, led watermelons, cucumbers, tomatoes, zucchinis, paprika, and strawberries to be the choice crops in the Republic of Korea, with paprika, strawberries, and tomatoes being the most commonly grown crops in protected systems around the world.

In the Republic of Korea, the overall annual strawberry production is around 166,594.5 Mg, and its cultivation occupies around 6062 hectares (ha), which is the fourth-largest cultivation area in the country. The protected cultivation of strawberries occupies 5539 ha and produces 165,011.5 Mg [28]. Thus, more than 99% of strawberries are cultivated in protected greenhouses rather than outdoors [29]. The labor time required per 1000 m² at each step during strawberry cultivation is as follows: 238.5 h for picking, 122.2 h for sorting and packing, and 87.8 h for cutting off sprouts and thinning [28,30–32].

Various factors have limited the use of robots in protected cultivation systems. These include the efficiency of current technologies compared to human labor and the cost of purchase and implementation of robots. However, the necessity for automation has and is continuously increasing because of the abovementioned reasons.
The efficient adoption of automation requires a requisite model to compute the time required in the various units. A detailed representation of system characteristics is usually provided using a simulation model. This is analyzed by sequences in work operations. Delmia Quest software version 5 (Quest Software Inc., Aliso Viejo, CA, USA) [33] has been adopted in different scenarios and has been demonstrated to be a powerful tool in assessing the required changes before recording improvements. Some of the applications of this software include simulations of the Hotayi Electronic production line [34] and delivery planning control for an industrial raw material system inventory of product service [35]. Others include analyzing and optimizing a mechanical parts machining sequence in a manufacturing cell [36], simulating integrated total quality management [37], analyzing immunoglobulin and T cell receptor [38], designing a flexible manufacturing system [39], and developing simulation strategies [40].

Thus, we aimed to analyze and improve the work efficiency of robots and conduct a work efficiency comparative analysis between a robot and human workforce in a standard strawberry greenhouse in the Republic of Korea. We applied harvesting robot specifications as the basis for the unmanned greenhouse design, in which the maximum amount of robotic harvesting time was allocated to the strawberry crop with the maximum profit per unit area. A series of analytic processes in Delmia Quest software was applied to derive practical improvements to the application of robots for harvesting strawberries in protected cultivations to verify the improvements and to explore their real-world application in the field.

The objectives of this study were to: (1) find an optimized operation process, (2) design a virtual strawberry cultivation greenhouse by adopting three-dimensional (3D) simulation modeling and validation, and (3) analyze the work efficiency of robots compared to that of a human workforce.

2. Materials and Methods

2.1. Problem Formulation

Data were acquired using structured questionnaires from growers adopting a protected cultivation system (Figure 1 and Table 1). The schematic structure of the greenhouse is depicted in Figure 1 and an explanation and statistics are provided in Table 1. These data were used to model a three-dimensional protected cultivation system for strawberry cultivation using Delmia Quest software [41]. The logics for both robot and human workforces were then formulated and modeled for harvesting and transportation to analyze the work efficiency of robots compared to that of a human workforce. This was performed according to changes in specifications, such as harvesting hours, robot battery performance and charging time, and robot movement speed.

Figure 2 presents a flow chart summarizing how the optimal scenario was implemented in Delmia Quest software. This process was as follows: (a) data collection, storage, and modeling; (b) monitoring and analyzing resources; and (c) setting targets and measuring all available resources. In (a), data were collected from field surveys using a structured questionnaire and a literature review. This was applied for modeling the layout in accordance with currently obtainable resources. The data included the pipe diameters, the bed width and length, and the distance between beds. This was followed by a sequence of events that included selecting specifications, building and running the Delmia Quest simulation models, measuring performance of the different categories (robots and humans), computing and analyzing performance, conducting comparative analyses between the robot and human categories, and evaluating the results. If the results were not satisfactory, iterations were performed until the desired output was achieved. Selection of specifications for humans included the following factors: (1) harvesting time (seconds), (2) work range (mm), (3) maximum velocity (m/s), (4) acceleration/deceleration (m/s²), (5) maximum capacity (kg), and (6) break time (hours).

In robots, the specifications were divided into two groups (harvesting and transportation robots). The following factors were considered for both harvesting and transportation robots: (1) maximum velocity (m/s), (2) acceleration/deceleration (m/s²), (3) size of the greenhouse (L × W × H, mm), (4) battery capacity (hours), (5) charging time (hours), (6) maximum capacity (kg), and (7) driving
direction. Other factors were considered for the harvesting robots: (1) harvesting time (seconds), (2) work range (mm), (3) maintenance time (hours), and (4) maintenance rate (hours). These factors best reflect the parameters that were vital for assessing the work efficiency between humans and robots. They also reflected the limitations of the categories studied. The human category was divided into three groups based on their expertise, whereas the robots’ specifications were altered to cover the current and future scenarios. In (b), the available resources were analyzed and fed to (a) while targets were set, and resources were determined from the modeling in (c).

Figure 1. Schematic diagram of a conventional strawberry greenhouse (A–N are described in Table 1).

Table 1. Surveyed data used in modeling a three-dimensional greenhouse.

| Factor                                    | Average (mm) | SD       |
|-------------------------------------------|--------------|----------|
| A-1. Width of greenhouse                  | 9000         | 295.08   |
| A-2. Length of greenhouse                 | 110,000      | 2174.6   |
| A-3. Diameter of pipe used in construction| 26           | 1.45     |
| B. Height of greenhouse in the center     | 2750         | 20.72    |
| C. Height of greenhouse at the edge       | 1400         | 61.1     |
| D. Crop height                            | 1300         | 96.6     |
| E-1. Bed height                           | 950          | 28.98    |
| E-2. Bed length                           | 82,400       | 966.09   |
| F. Bed width                              | 280          | 34.21    |
| G. Distance between bed                   | 900          | 193.21   |
| H. Distance between crop (minimum)        | 500          | 36.6     |
| I. Distance between crop (maximum)        | 750          | 66.91    |
| J. Crop dip length                        | 200          | 10.3     |
| K. Truss width                            | 9000         | 466.09   |
| L. Top height of truss                    | 1000         | 123.21   |
| M. Truss to crop distance                 | 1350         | 93.84    |
| N. Ground to truss distance               | 1750         | 193.18   |
Data collected from the site and literature review were used to create the virtual strawberry greenhouse. The differences in the performance data were comparatively analyzed to determine the efficiency of the harvesting robot in the strawberry greenhouses, as shown in Equation (1). To derive the standard harvesting time used in the simulation, the harvesting work for robotics and human workforce was computed with a 0.5 standard deviation for the robot and human workforce. The simulation was repeated 30 times by dividing the 2000 m²-based strawberry collection into robots and human workforce in Equation (2).

\[
\text{ST} = \frac{\sum_{i=1}^{n} y_i}{n} \pm \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n - 1}},
\]

where \(\text{ST}\) is standard time (s) and \(y\) is harvesting time (s);

\[
\text{TP} = A \times B \times \frac{\sum_{i=1}^{n} Ci(D) i}{n},
\]

where \(\text{TP}\) is total production (kg), \(A\) is the number of branches, \(B\) is the number of beds, \(C\) is the number of strawberries per branch, and \(D\) is the weight per strawberry (g).
2.2. Selection of Greenhouse for Protected Strawberry Cultivation

A 1050 m² protected greenhouse suitable for growing strawberries using a bed system was designed. It was 50 m wide and 7 m long, as shown in Figure 3A. Figure 3B shows the strawberries growing in beds with access paths for human and robot movement, while a navigation platform for attaching a robot is shown in Figure 3C.

Figure 3. Schematic layout design for growing strawberries in a greenhouse (A), access path for robots in a strawberry greenhouse (B), and mobile platform for robot navigation (C).
2.3. Setup of Planting Distance and Harvesting Work Range

The virtual planting distance for the strawberries was 200 mm and sowing was performed in a zig-zag pattern as shown in Figure 4. The work range for harvesting was set to a 500 mm distance to the right and left, i.e., a total of 1000 mm for both humans and robots.

![Figure 4. Strawberry plant spacing on a bed in a greenhouse.](image)

2.4. Path Design for Strawberry Harvesting and Transportation Using Robots

The work path was set by separating the process into harvesting and transportation. Space was allocated at the center of the greenhouse for sorting, packing, and installation of a recharging station for the harvesting and transportation robots. The work paths of the harvesting and transportation robots were designed to not interrupt each other, as shown in Figure 5.

![Figure 5. Traveling path for a harvesting and transportation robot in a conventional greenhouse.](image)

2.5. Development of Logics for Strawberry Harvesting and Transportation by Robots and Humans

For the harvesting work, each robot had a work range of 1000 mm (500 mm to both the right and left) and was designed to move to the harvesting position and load the picked strawberries to the transportation robot (Figure 6). This involved process and decision stages. The first step was moving the robot to the harvesting location and deploying it into the greenhouse. Using a recognition algorithm, the harvesting robot scans every strawberry bed to the left and right as it travels up and
down each aisle. The image processing algorithm processes the acquired image for acceptable size and color and decides to harvest or not. The current robots carry out this process in $5 \pm 0.5$ s, which is the current drawback in adopting robotics. After harvesting, one of two decisions needs to be made: (a) determine if the battery is still above 5% and (b) determine if the capacity of the transportation robot is over 10 kg. Based on this, the robot decides to go charge if it is at a 5% state of battery charge, which is enough power to travel to the charging station. The robot then moves to the station at the center of the greenhouse for recharging or waits for the transportation robot to travel to empty the harvested strawberry at the center of the greenhouse and return back to its previous position. In the latter situation, the harvesting robot waits for the transportation robot to travel to and from the warehouse. If the harvesting task for the day is concluded, and the battery state of charge does not require charging or has charged to a satisfactory level, the robot moves to the harvest location where it is transported for storage.

**Figure 6.** Harvesting robot logics for strawberry picking in a greenhouse (Y: yes, N: no).

Two transportation robots were allocated to each harvesting robot. To convey the harvested strawberries, the transportation robot moved to the back of the harvesting robot for docking and picked strawberries were loaded (Figure 7). If the loaded strawberries weighed more than 10 kg, the transportation robot was programmed to move to the sorting and packing area located at the center of the greenhouse.
2.6. Setup of Parameters for Strawberry-Harvesting with Transportation Robots and Human Workers

The time required to pick a strawberry, which determined the machine performance in relation to the parameters set for the harvesting robots, was set to 5 s based on the current parameters of the Rubion commercial robot (Octinion, Heverlee-Leuven, Belgium) [42]. The work range was set to 1000 mm from the center of the robot arm to the right and left. The maximum moving speed was set to 0.3 m/s, and the dimensions were set to $1000 \times 700 \times 300$ mm, as the bed spacing was 1000 mm. A battery...

The harvesting and transportation work for the human workforce was different from that of the robot in terms of rest time and the maximum loading weight. Each human worker moved to the harvesting position and first checked whether they required a rest before harvesting, then work continued until the maximum load of 20 kg was reached (Figure 8). Additional personnel or devices were not used to convey the harvested strawberries to the sorting and packing area; instead, each worker conveyed the harvested strawberries.

---

**Figure 7.** Transportation robot logics for strawberry conveyance in a greenhouse (Y: yes, N: no).

**Figure 8.** Human logics for strawberry picking in a greenhouse (Y: yes, N: no).
2.6. Setup of Parameters for Strawberry-Harvesting with Transportation Robots and Human Workers

The time required to pick a strawberry, which determined the machine performance in relation to the parameters set for the harvesting robots, was set to 5 s based on the current parameters of the Rubion commercial robot (Octinion, Heverlee-Leuven, Belgium) [42]. The work range was set to 1000 mm from the center of the robot arm to the right and left. The maximum moving speed was set to 0.3 m/s, and the dimensions were set to 1000 × 700 × 300 mm, as the bed spacing was 1000 mm. A battery capacity of 2 h and recharging time of 10 h were used as the parameters for the harvesting robot, and these were used in the simulations (Table 2).

Table 2. Specifications of the strawberry harvesting robot in a greenhouse.

| Units                          | Specifications                        |
|-------------------------------|---------------------------------------|
| Harvesting time (average ± SD, s) | 5 ± 0.5                               |
| Work range (mm)               | 1000                                  |
| Maximum velocity (m/s)        | 0.3                                   |
| Acceleration/deceleration (m/s²) | 10                                    |
| Size (L × W × H, mm)          | 1000 × 700 × 300                      |
| Battery (h)                   | Maximum 10                            |
| Charging time (h)             | 2                                     |
| Maximum capacity (kg)         | 10                                    |
| Driving direction             | 2 direction                           |
| Maintenance time              | 30 min after 10 h working (with charging) |
| Maintenance rate              | 2 h after 1000 h working (with charging) |

The moving speed of the transportation robot was set to 0.3 m/s based on the moving speed of the harvesting robot, and the transportation robot was programmed to dock with the harvesting robot. The dimensions of the transportation robot were set to 500 × 500 × 300 mm based on the loading space required for 10 kg of strawberries. A battery capacity of 2 h and recharging time of 10 h were used for the parameters of the transportation robot, and these were used in the simulations (Table 3).

Table 3. Specifications of the strawberry transportation robot in a greenhouse.

| Units                          | Specifications                        |
|-------------------------------|---------------------------------------|
| Maximum velocity (m/s)        | 0.3                                   |
| Acceleration/deceleration (m/s²) | 10                                    |
| Size (L × W × H, mm)          | 500 × 500 × 300                       |
| Battery (h)                   | Maximum 10                            |
| Charging time (h)             | 2                                     |
| Maximum capacity (kg)         | 10                                    |
| Driving direction             | 2 direction                           |

For harvesting strawberries by a human, the workers were divided into three skill grades based on the data collected during the survey: experienced, average, and beginner. The experienced worker was set to harvest one strawberry per 1 s, the average worker one strawberry per 1.5 s, and the beginner worker one strawberry per 2 s. The work range was set to 1000 mm, equal to the robot’s work range, considering the average height of female workers. The maximum load was set to 20 kg. A parameter of 10 min of rest time for every 1 h labor was used in the simulations (Table 4). A schematic diagram for harvesting of strawberry is shown in Figure 9.
Table 4. Specifications for human operation in a strawberry greenhouse.

| Units                              | Specifications       |
|------------------------------------|----------------------|
| Harvesting time (average ± SD, s)  | Experienced: 1.0 ± 0.1 |
|                                    | Average: 1.5 ± 0.1   |
|                                    | Beginner: 2.0 ± 0.1  |
| Work range (mm)                    | 1000 (Worker center line ± 500) |
| Maximum velocity (m/s)            | 1                    |
| Acceleration/deceleration (m/s²)  | 10                   |
| Maximum capacity (kg)             | 20                   |
| Break time                         | 10 min after 1 h of work |

Figure 9. Delmia Quest simulation model for harvesting strawberries.

3. Results

The average weight of a strawberry was 15 g; thus, the total production was 1215 kg. Based on this, the robot’s work hours and daily average production and the human’s required daily average production were calculated using the Delmia Quest simulation program. The results are shown in Table 5. The results were 137.2 ± 0.03 h for robot work hours and 170.21 ± 1.83, 244.05 ± 1.28, and 336.18 ± 2.21 h work hours for experienced, average, and beginner workers, respectively (Figure 10).

Table 5. Average daily output compared to total production.

| Units                     | Division          |
|---------------------------|-------------------|
|                           | Robot             | Experienced | Average | Beginner |
| Number of days * (day)    | 5.7               | 7.1         | 10.2    | 14.0     |
| Average production per hour ** (kg/h) | 8.9       | 42.8        | 29.9    | 21.7     |
| Average production per day *** (kg/day) | 212.5  | 171.3       | 119.5   | 86.7     |

* Working Time/24; ** Robot = Total production/days × 24; Human = Total production/days/24 × 4; *** Robot = Average production per hour × 24; Human = Average production per hour × 4.
3. Results

The average weight of a strawberry was 15 g; thus, the total production was 1215 kg. Based on this, the robot’s work hours and daily average production and the human’s required daily average production were calculated using the Delmia Quest simulation program. The results are shown in Table 5. The results were 137.2 ± 0.03 h for robot work hours and 170.21 ± 1.83, 244.05 ± 1.28, and 336.18 ± 2.21 h work hours for experienced, average, and beginner workers, respectively (Figure 10).

Table 5. Average daily output compared to total production.

| Units              | Harvesting Time (h/s) |
|--------------------|-----------------------|
| Number of days * (day) | 1 ± 0.5 | 3 ± 0.5 | 5 ± 0.5 |
| Average production per hour ** (kg/h) | 1.2 | 3.5 | 5.7 |
| Average production per day *** (kg/day) | 42.6 | 14.5 | 8.9 |
| Dates * (day) | 1021.3 | 347.9 | 212.5 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

3.1. Productivity of Harvesting Robot According to Harvesting Time

The harvesting time per strawberry for the current robot was set to 1, 3, and 5 s (Table 6). The strawberry harvesting times were 28.5 ± 0.02, 83.8 ± 0.01, and 137.2 ± 0.03 h, respectively (Figure 11).

Table 6. Harvesting robot productivity analysis by variation in harvesting time.

| Units Harvesting Time (s)                 |
|-------------------------------------------|
| Number of days * (day)                    | 1 ± 0.5 | 3 ± 0.5 | 5 ± 0.5 |
| Average production per hour ** (kg/h)     | 1.2 | 3.5 | 5.7 |
| Average production per day *** (kg/day)   | 42.6 | 14.5 | 8.9 |
| Dates * (day)                             | 1021.3 | 347.9 | 212.5 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

3.2. Productivity of Harvesting Robots According to Battery Performance

The robot battery performance at 8 h was the best with 142 ± 0.01 h of worktime (Figure 12). The results for the average production per hour and day is provided in Table 7. These were 203, 206, 212, 216, and 219 kg/day for 8, 9, 10, 11, and 12 h, respectively.

Table 7. Harvesting robot productivity analysis by variation in battery performance.

| Units                        | Harvesting Time (h) |
|------------------------------|---------------------|
| Number of days * (day)       | 1 ± 0.5 | 3 ± 0.5 | 5 ± 0.5 |
| Average production per hour ** (kg/h) | 1.2 | 3.5 | 5.7 |
| Average production per day *** (kg/day) | 42.6 | 14.5 | 8.9 |
| Dates * (day)                | 1021.3 | 347.9 | 212.5 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

Figure 10. Daily production of strawberries for different harvesting categories in relation to work time.

Figure 11. Average daily output of different times taken to harvest a strawberry in relation to work time.
3.2. Productivity of Harvesting Robots According to Battery Performance

The robot battery performance at 8 h was the best with 142 ± 0.01 h of worktime (Figure 12). The results for the average production per hour and day is provided in Table 7. These were 203, 206, 212, 216, and 219 kg/day for 8, 9, 10, 11, and 12 h, respectively.

![Figure 12. Battery performance in relation to work time.](image)

Table 7. Productivity analysis corresponding to harvest robot battery performance.

| Units                        | Battery Performance (h) |
|------------------------------|-------------------------|
|                              | 8 | 9 | 10 | 11 | 12 |
| Number of days * (day)       | 5.9 | 5.7 | 5.7 | 5.6 | 5.5 |
| Average production per hour ** (kg/h) | 8.4 | 8.5 | 8.8 | 9.0 | 9.1 |
| Average production per day *** (kg/day) | 203 | 206 | 212 | 216 | 219 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

3.3. Productivity of the Harvesting Robot Based on the Battery Recharge Time

The daily average production was 212 kg based on a 2 h recharge, 183 kg for 4 h, and 231 kg for 1 h, resulting in about a 15% difference in productivity (Table 8). The working times with battery charging times of 1, 2, 3, and 4 h were 126 ± 0.02, 137 ± 0.03, 148 ± 0.01, and 159 ± 0.02 h, respectively (Figure 13).

![Figure 13. Productivity analysis by harvesting robot in relation to battery charging time.](image)

Table 8. Productivity analysis by harvesting robot in relation to battery charging time.

| Units                        | Battery Charging Time (h) |
|------------------------------|---------------------------|
|                              | 1 | 2 | 3 | 4 |
| Number of days * (day)       | 5.2 | 5.7 | 6.1 | 6.6 |
| Average production per hour ** (kg/h) | 9.6 | 8.8 | 8.1 | 7.6 |
| Average production per day *** (kg/day) | 231 | 212 | 196 | 183 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.
Table 7. Productivity analysis corresponding to harvest robot battery performance.

| Units          | Battery Performance (h) |
|----------------|-------------------------|
| Number of days * (day) | 5.9 5.7 5.7 5.6 5.5     |
| Average production per hour ** (kg/h) | 8.4 8.5 8.8 9.0 9.1 |
| Average production per day *** (kg/day) | 203 206 212 216 219 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

3.3. Productivity of the Harvesting Robot Based on the Battery Recharge Time

The daily average production was 212 kg based on a 2 h recharge, 183 kg for 4 h, and 231 kg for 1 h, resulting in about a 15% difference in productivity (Table 8). The working times with battery charging times of 1, 2, 3, and 4 h were 126 ± 0.02, 137 ± 0.03, 148 ± 0.01, and 159 ± 0.02 h, respectively (Figure 13).

Table 8. Productivity analysis by harvesting robot in relation to battery charging time.

| Units          | Battery Charging Time (h) |
|----------------|---------------------------|
| Number of days * (day) | 5.2 5.7 6.1 6.6     |
| Average production per hour ** (kg/h) | 9.6 8.8 8.1 7.6 |
| Average production per day *** (kg/day) | 231 212 196 183 |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

3.4. Productivity of Harvesting Robots in Relation to Velocity

Figure 14 shows the velocity of the harvesting robot. When the velocity was set to 0.1 m/s, the time taken was 144 ± 0.03 h. The results were 138 ± 0.02, 137 ± 0.03, 136 ± 0.01, and 135 ± 0.02 h at 0.2, 0.3, 0.4, and 0.5 mm/s, respectively (Table 9).

Table 9. Productivity analysis according to the movement speed of harvesting robot.

| Harvest Robot Velocity (m/s) | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  |
|------------------------------|------|------|------|------|------|
| Number of days * (day)       | 6    | 5.8  | 5.7  | 5.6  | 5.5  |
| Average production per hour ** (kg/h) | 8.4  | 8.7  | 8.8  | 8.9  | 9.0  |
| Average production per day *** (kg/day) | 201  | 209  | 212  | 213  | 214  |

* Working time/24; ** Total production/days × 24; *** Average production per hour × 24.

Figure 13. Battery charging time in relation to worktime.

Figure 14. Harvesting robot movement speed in relation to worktime.
3.5. Economic Analyses of Robot Usage

Data from the Korea Rural Economic Institute put changes in annual increase of rural wages at 10.1% [43] and the Korea Evaluation Institute of Industrial Technology computed the cost of robot annual decrease at 5% [44]. These data were used to compute and project the cost of operating robots in greenhouses against utilizing human labor (Figure 15) in the case of the Republic of Korea, which is similar to other OECD countries.

![Figure 15. Current and projected changes in human wages and cost of using robots (KRW, South Korean won).](image)

4. Discussion

Plant production is becoming increasingly difficult because of global challenges caused by climate change, increasing population, and competition with other sectors for limited land resources. The adoption of protected cultivation systems can help overcome these issues [45,46]. Protected cultivation has been used for centuries and has helped communities grow essential and fragile crops. However, in the past century, the major focus has been on growing vegetables during freezing winters and dismantling the structures after the winter season. These structures have transformed to solve food production challenges caused by the irregular weather patterns due to climate change and the necessity to feed the growing global population with limited natural resources such as land and water. These global issues (climate change, human population increase, and limited natural resources) are intertwined. Food security will be most likely affected by climate change at the local, regional, and global levels. These global issues are expected to impact food production and quality.

In agronomy, changes in precipitation patterns, reductions in water availability, projected increases in temperatures, and changes in extreme weather events could all negatively affect agricultural productivity. However, as protected cultivation systems advance, occupational hazards and shortages of skilled labor to perform repetitive tasks are limiting the optimal and efficient adoption of these systems. Thus, robotics is currently being explored globally as a potential solution to issues associated with growing in protected systems. Implementation of robotics in protected cultivation would help with the efficient and safe production of crops where temperature can be controlled to the optimal,
natural resources such as water could be optimally used, and plants could be grown in stacks to save resources and improve productivity. Additionally, losses and safety issues associated with the harvesting of crops such as strawberries mostly occur because of improper handling and lack of skilled labor, or accessibility to labor in general, such as during the current COVID-19 pandemic caused by the SARS-CoV-2 virus [47] that has limited international travel for migrant workers.

Robotics in protected cultivation could help with strengthening agronomic practices where optimal growing conditions for different plants, which have been studied and documented over the years, could be easily controlled and safe handling of plants can be easily implemented in systems such as greenhouses. For example, a harvesting robot can work around the clock and prevent cross contamination and bruises from improper handling as robots are programmed to be precise compared to humans, especially in repetitive tasks. A pertinent issue with the adoption of robotics in agriculture is efficient deployment because of the huge investment cost.

Consequently, to demonstrate an application of robotics to solve the issues around safe harvesting of strawberries, we analyzed production in a single span 1000 m² greenhouse, and the number of strawberries per cluster was calculated based on 450 branches per bed, amounting to 81,000 strawberries (450 branches × 30 beds × 6 strawberries (number of average strawberries per branch)).

A comparative analysis between robot and different levels of skilled human workforce showed approximately 19%, 78%, and 145% reductions in time required for the robot to complete the task compared to experienced, average, and beginner human workers, respectively. This is because the robots can work 24 h a day, whereas human workers can only work 4 h a day due to the hot weather in the greenhouse during the summer season. When the hourly average production was calculated based on this, the robot’s hourly production was 8.85 kg, whereas human’s hourly production was 42.84 kg, which is approximately five times higher (Table 5). Considering daily output (Figure 10), the harvesting robot produced a 20% improvement compared to the human workforce, which makes it economically feasible to use a robot in this case. This improvement is projected to increase with advances in technology.

However, if the harvesting time per strawberry was shortened to 3 s, the 6-day workload based on 1215 kg total production would be completed in 4 days, resulting in a daily average production improvement from 212 to 347 kg, which is about a 63% increase (Table 6). If it were shortened to 1 s, 1215 kg of strawberries could be harvested in two days and the daily average production increased to 1021 kg (Table 6).

The constant increases in labor cost and the projected demand for strawberries, and the associated increase in price, would increase the economic feasibility of robots [48]. For example, an economic analysis using data from the Republic of Korea showed that human wages were increasing 10.1% annually, while the cost of operating robots in a greenhouse was declining 5% annually. This declining rate could increase as robot technology becomes better and more widespread. At the current rate (Figure 15), the cost of operating robots in a small greenhouse (less than 1750 m²) is more expensive than human labor, and this result does not change for at least five years. However, as the size of the greenhouse increases to commercial size (above 1750 m²), the cost of operating robots starts decreasing. This shows a need for proper economic analyses before purchasing robots. Furthermore, with the constant decline in the availability of skilled labor as discussed earlier, greenhouse growers face the risk of losing all their product if they rely on human labor.

Batteries are a crucial factor in the use of robots as it affects the total worktime of the robot, including the time taken for the robot to travel to and from the charging station and the time required to complete charging.

Different scenarios were simulated by increasing and reducing the original 10 h battery capacity. This was conducted to investigate the impact of battery capacity on the improvement in the robot use time. The analyses showed that if the battery capacity was reduced to 8 h, the daily average production was 203 kg, which is about 5% lower than the 212 kg achieved with 10 h capacity. When the battery performance was increased to a 12 h capacity, the daily average production increased
to 219 kg, which is about 5% more (Table 7). However, battery replacement was not considered to be economically beneficial because of the high cost of batteries in relation to the improvement in performance. Thus, the battery capacity of 10 h per charge, which was used in the simulation, was found to be appropriate (Figure 12). The effect of battery recharge time was also analyzed based on a 2 h recharge. The change in productivity was analyzed when 1 h recharge time was added or subtracted.

These results indicated that the battery recharge time is more closely correlated with production than battery capacity. Thus, a fast recharge would be more beneficial than increased battery capacity. Rapid charging and replaceable batteries would benefit this system more than increasing the battery capacity. Consequently, the battery recharge time needs to be improved.

The robots’ movement pace was analyzed by adding or subtracting 0.1 m/s to/from 0.3 m/s in the simulation. The results (Table 9 and Figure 14) showed an approximately 5% difference in the daily average production due to the difference in travel speed, but this relationship was not linear because the robot’s travel speed is a variable related to the precision of the harvesting work. The precision of the sensor that detects the ripened fruit needs to be improved as the speed of the harvesting robot increases, which would lead to an increase in the manufacturing cost of the robot. Thus, 0.3 m/s was considered to be an appropriate velocity for the harvesting robot at the current level of technical development. In the interim, robots and human workers can work simultaneously since the layout was not changed and the number of workers and robots is dependent on several factors such as the size of the greenhouse, the required task, expected production output, and the availability of skilled workers.

These findings will facilitate the efficient adoption of protected cultivation systems such as greenhouses in the production of crops that are vital to food security. This will help in resolving issues around the health concerns of workers in these systems and problems due to skilled labor shortages especially in OECD countries. Furthermore, the findings can be used to work toward the efficient use of scarce and limited resources, such as water and land, as production in these systems utilize fewer resources compared to open field cultivation.

5. Conclusions

The work efficiency of humans in comparison to a harvesting robot was analyzed. The average hourly production of the robot was recorded to be about five times lower than that of skilled workers, but the robot was found to be more productive because it could work around the clock irrespective of climatic conditions. In addition, with the continuous advances in agriculture robotics, reductions in harvesting time per strawberry to 3 and 1 s would result in increases in daily production of 347.93 kg and 1021.30 kg, respectively. This is a five-fold increase in comparison to the present. Furthermore, enhancing the battery charging method to a fast charge or replacement method is recommended. A 10% improvement would result in the battery capacity gaining two extra hours from the current 10 h and cut the current 2 h needed for charge to 1 h. The robot navigation speed is directly linked to the precision in harvesting. An increase in the navigation speed would require improvement in the accuracy of the sensor to detect and harvest each strawberry. Currently, the improvement in production compared to the cost is shown to be around 5% lower. Consequently, 0.3 m/s is considered suitable.

We modeled and proposed a system that can simulate a harvesting task in a strawberry greenhouse with the objective to improve work efficiency. This would help improve food security, profitability, and the quality of life of the rural growers.

Author Contributions: S.W.: conceptualization, methodology, software, formal analysis, investigation, data curation, and writing—original draft; D.D.U.: investigation, methodology, validation, and writing—review and editing; J.K., Y.K., and S.K.: methodology, investigation, software, formal analysis, and data curation; K.C.K. and S.Y.L.: supervision, validation, resources, and project administration; W.S.L.: methodology, visualization, validation, and writing—review and editing; Y.H.: conceptualization, methodology, resources, visualization, supervision, funding acquisition, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.
Funding: This research was funded by the Cooperative Research Program for Agriculture Science and Technology Development, Rural Development Administration, Republic of Korea, grant number PJ013871-02 and the APC was funded by the Rural Development Administration, Republic of Korea.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hall, E.M.A. Kim Sŏnghwan’s ‘Mr. Kobau’: Editorial Cartoons as Genre Weapons in South Korean Search for Democracy, 1945–1972. Ph.D. Thesis, University of Washington, Seattle, WA, USA, 2019.
2. Iqbal, Z.; Islam, N.; Jang, B.E.; Ali, M.; Kabir, S.N.; Lee, D.H.; Na, K.D.; Park, S.B.; Chung, S.O. Monitoring the Operating Status of an Automatic Harmful Fly Collector for Smart Greenhouses. *J. Biosyst. Eng.* 2019, 44, 258–268. [CrossRef]
3. Spehia, R.S. Status and impact of protected cultivation in Himachal Pradesh, India. *Curr. Sci.* 2015, 108, 2254–2257.
4. Choudhary, A.K. Scaling-up of protected cultivation in Himachal Pradesh, India. *Curr. Sci.* 2016, 111, 272–277. [CrossRef]
5. Sharma, K.D.; Pathania, M.S.; Bala, B.; Gupta, M. Progress of Protected Cultivation under Rural Infrastructural Development Fund (RIDF) Project in Himachal Pradesh. *Indian J. Agric. Econ.* 2015, 70, 285.
6. Negi, V.S.; Maikhuri, R.K.; Rawat, L.S.; Parshwan, D. Protected cultivation as an option of livelihood in mountain region of central Himalaya, India. *Int. J. Sustain. Dev. World Ecol.* 2013, 20, 416–425. [CrossRef]
7. Son, D.S.; Kim, Y.S.; Jeong, S.B.; Lee, K.K. A survey on the cultivated condition and management in main protected cultivation of grapes in Korea. *Res. Rep. Rural Dev. Adm.* 1989, 31, 22–29.
8. Kim, M.K. Trend of protected cultivation for adjusting to high technology in Korea. *Acta Hortic.* 1988, 230, 505–514. [CrossRef]
9. Jensen, M.H. Food Production in Greenhouses, in Plant Production in Closed Ecosystems; Springer: Berlin/Heidelberg, Germany, 1997; pp. 1–14.
10. Maracchi, G.; Sirotenko, O.; Bindi, M. Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. *Clim. Chang.* 2005, 70, 117–135. [CrossRef]
11. Jensen, M.H. Controlled Environment agriculture in deserts, tropics and temperate regions—A World Review. *Acta Hortic.* 2002, 578, 19–25. [CrossRef]
12. Anil, K.; Tiwari, G.N.; Subodh, K.; Mukesh, P. Role of greenhouse technology in agricultural engineering. *Int. J. Agric. Res.* 2010, 5, 779–787.
13. Park, S.H.; Park, T.; Park, H.D.; Jung, D.H.; Kim, J.Y. Development of Wireless Sensor Node and Controller Complying with Communication Interface Standard for Smart Farming. *J. Biosyst. Eng.* 2019, 23, 41–45. [CrossRef]
14. Li, Y.; Ye, W.; Wang, M.; Yan, X. Climate change and drought: A risk assessment of crop-yield impacts. *Clim. Res.* 2009, 39, 31–46. [CrossRef]
15. Mukherjee, S.; Mishra, A.; Treberth, K.E. Climate change and drought: A perspective on drought indices. *Curr. Clim. Chang. Rep.* 2018, 4, 145–163. [CrossRef]
16. Syed, A.M.; Hachem, C. Review of Design Trends in Lighting, Environmental Controls, Carbon Dioxide Supplementation, Passive Design, and Renewable Energy Systems for Agricultural Greenhouses. *J. Biosyst. Eng.* 2019, 28–36. [CrossRef]
17. Basak, J.K.; Qasim, W.; Okyere, F.G.; Khan, F.; Lee, Y.J.; Park, J.; Kim, H.T. Regression analysis to estimate morphology parameters of pepper plant in a controlled greenhouse system. *J. Biosyst. Eng.* 2019, 44, 57–68. [CrossRef]
18. Bryden, J.; Bollman, R. Rural employment in industrialised countries. *Agric. Econ.* 2000, 22, 185–197. [CrossRef]
19. Labrianidis, L.; Sykas, T. Migrants, economic mobility and socio-economic change in rural areas: The case of Greece. *Eur. Urban Reg. Stud.* 2009, 16, 237–256. [CrossRef]
20. Jeong, O.Y.; Park, H.S.; Baek, M.K.; Kim, W.J.; Lee, G.M.; Lee, C.M.; Bombay, M.; Ancheta, M.B.; Lee, J.H. Review of rice in Korea: Current status, future prospects, and comparisons with rice in other countries. *J. Crop Sci. Biotechnol.* 2020, 1–11.
21. Sweeper. ICT Robotic Use Cases Project in the H2020 Programme of the EU. 2020. Available online: http://www.sweeper-robot.eu/ (accessed on 2 August 2020).

22. Sammons, P.J.; Furukawa, T.; Bulgin, A. Autonomous pesticide spraying robot for use in a greenhouse. In Australian Conference on Robotics and Automation; Commonwealth Scientific and Industrial Research Organisation: Canberra, Australia, 2005.

23. Jurewicz, J.; Kouimitzis, D.; Burdorf, A.; Hanke, W.; Chatzis, C.; Linos, A. Occupational risk factors for work-related disorders in greenhouse workers. J. Public Health 2007, 15, 265–277. [CrossRef]

24. Iddio, E.; Wang, L.; Thomas, Y.; McMorrow, G.; Denzer, A. Energy efficient operation and modeling for greenhouses: A literature review. Renew. Sustain. Energy Rev. 2020, 117, 109480. [CrossRef]

25. Tatara, K.; Giannini, E.; Kavvadias, K.; Maroulis, Z. Cogeneration Economics for Greenhouses in Europe. Energies 2020, 13, 3373. [CrossRef]

26. Ahamed, M.S.; Guo, H.; Tanino, K. Modeling heating demands in a Chinese-style solar greenhouse using the transient building energy simulation model TRNSYS. J. Build. Eng. 2020, 29, 101114. [CrossRef]

27. Hanan, J.J. Radiation p. 91–166. In Greenhouses: Advanced Technology for Protected Horticulture; CRC Press Inc.: Boca Raton, FL, USA, 1998.

28. Yang, J.-Y. Current Status of Big Data-Based Smart Agriculture and Promotion Direction, Korea; Agency of Education, Promotion & Information Service in Food, Agriculture, Forestry: Sejong-si, Korea, 2017.

29. Nam, Y.-I. Present Status and Developmental Strategy of Protected Horticulture Industry in Korea. KCID J. 2003, 10, 15–23.

30. Kim, G.-C. Development of Thermal Storage Greenhouse and Environment Control System for Protected Cultivation of Strawberry, Rural Development Administration: Jeonju, Korea, 2016.

31. Technology Management Division. Changes and Characteristics of Agricultural Labor Time of Protected Fruits and Vegetables; Rural Development Administration: Jeonju, Korea, 2019.

32. Marketing & Consumer Policy Bureau Horticulture Industry Division. Current Status of Protected Vegetable Greenhouse and Production Performance of Vegetables in 2018. Available online: https://www.mafra.go.kr/mafra/366/subview.do?enc=Zm5jdDF8QEB8JTJGymJzJTJGbWfmcElMkY3MSUyRjMyMTY2OCUyRmFydGNsVmlldy5kbyUzRg%3D%3D (accessed on 10 February 2020).

33. Quest. Quest Software. 2020. Available online: https://www.quest.com/ (accessed on 1 May 2020).

34. Lim, M.W.H. Simulation and Validation of a Surface Mount Technology Line Using Delmia Quest. Bachelor’s Thesis, Tunku Abdul Rahman University College, Kuala Lumpur, Malaysia, 2020.

35. Hamzah, N.; Ismail, S.Z. Integrating comprehensive industrial raw material delivery planning and product-service system inventory control. J. Mod. Manuf. Syst. Technol. 2020, 4, 14–22.

36. Bzymek, Z.M.; Nunez, M.; Li, M.; Powers, S. Simulation of a machining sequence using delmia software. Comput.-Aided Des. Appl. 2008, 5, 401–411. [CrossRef]

37. Salleh, N.A.; Kasalong, S.; Jafar, A. Simulation of integrated total quality management (TQM) with lean manufacturing (LM) practices in forming process using Delmia Quest. Procedia Eng. 2012, 41, 1702–1707. [CrossRef]

38. Giudicelli, V.; Chaume, D.; Lefranc, M.P. IMGT/V-QUEST, an integrated software program for immunoglobulin and T cell receptor V–J and V–D–J rearrangement analysis. Nucleic Acids Res. 2004, 32, W385–W440. [CrossRef]

39. Pasca, G.; Maniu, I. Synthesis of the Design of Flexible Manufacturing System Using Delmia Quest Software. Available online: https://www.thefreelibrary.com/Synthesis+of+the+design+of+flexible+manufacturing+system+using...-a0224712539 (accessed on 4 July 2020).

40. Mohora, C.; Anania, D.; Calin, O.A. Simulations Strategies Using Delmia Quest. Available online: https://www.thefreelibrary.com/Simulations+strategies+using+Delmia+Quest.-a0224712359 (accessed on 11 June 2020).

41. Kim, S.-Y.; Lee, G.-S.; Lee, H.-J. Digital Factory Construction by MI-NPS(Meta Intelligent-New Production System) Technique(I)- The best Manufacturing System Construction of Mini Computer Manufacturing Factory. J. Korean Product. Assoc. 2005, 19, 171–190.

42. Octinion. Discover the World’s First Strawberry Picking Robot. 2020. Available online: https://picking.technology/ (accessed on 12 May 2020).

43. Korea Rural Economic Institute. Changes in Income Wages. 2019. Available online: http://www.krei.re.kr/krei/researchReportView.do?key=67&pageType=010101&biblioid=518380 (accessed on 15 June 2020).
44. Korea Institute for Industrial Economics and Trade. Robot Technology Trends and Prospects. 2019. Available online: https://itech.keit.re.kr/index.do#03040100 (accessed on 20 July 2020).

45. Syed, A.M.; Hachem, C. Review of Construction; Geometry; Heating, Ventilation, and Air-Conditioning; and Indoor Climate Requirements of Agricultural Greenhouses. *J. Biosyst. Eng.* **2019**, *23*, 18–27. [CrossRef]

46. Kim, S.H.; Kwon, J.K.; Kang, Y.K.; Moon, J.P.; Kim, H.K.; Joen, J.G. Thermal-Load Analysis of Semi-Basement-Type Single-Span Greenhouse. *J. Biosyst. Eng.* **2019**, *44*, 146–151. [CrossRef]

47. World Health Organization. *Coronavirus Disease (COVID-19): Situation Report*; World Health Organization: Geneva, Switzerland, 2020; p. 182.

48. Korea Evaluation Institute of Industrial Technology. *Technical Status and Future Prospects of Logistics Robots*; Korea Evaluation Institute Of Industrial Technology: Cheonan-si, Korea, 2019.

**Publisher’s Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).