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TECHNOLOGIES FOR GROWING STRAWBERRIES IN HYDROPONIC CONDITIONS

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Abstract

The study highlights the importance of selecting the right strawberry variety and cultivation method based on environmental conditions and production goals. The "Arihyang" variety stands out for greenhouse cultivation due to its high photosynthetic efficiency and leaf growth, while the "Santa" variety is optimal for early ripening, and the "Maehyang" variety is promising for export. The vertical method provides a stable root temperature and higher CO_2 levels, but the hanging method generally supports better vegetative growth.

Keywords: *strawberry, varieties, IoT, CO_2, pH, EC, smart, hanging, vertical, method, duration, SPAD, leaf.*

Introduction. The global agricultural and food system faces increasing constraints, particularly due to the depletion of non-renewable resources such as freshwater, minerals, and soil nutrients. Climate change is exacerbating these challenges both directly—through extreme weather events, droughts, and glacier melt—and indirectly—via pest outbreaks, rising sea levels, and ecosystem disruptions (UNESCO, 2019). Additionally, biodiversity loss, including the decline of seeds, pollinators, and beneficial plant organisms, threatens ecosystem stability (FAO, 2019a, b). Competition over land and water resources is further intensified by the use of biomass for energy and large-scale reforestation efforts aimed at CO_2 capture. This strategy, known as "negative emissions," is recognized by the IPCC as a crucial tool in all scenarios for limiting global temperature rise to 2°C. Furthermore, the yield of staple cereal crops, essential for global food security, appears to have reached its growth limit (Maurel et al., 2022).

Climate change is driving an increase in erratic and extreme weather events across many regions (Li et al., 2021). Global warming has led to severe droughts, storms, and floods, significantly impacting different parts of the world (FAO, 2021). The efficiency of agricultural production depends on the complex ecological effects of global warming and climate change, both in the short and long term (Hatfield et al., 2011). Extreme heat, cold, humidity, and drought are among the key factors that cause severe damage to crops (Hatfield & Prueger, 2015; FAO, 2019a, b). Additionally, agriculture is increasingly challenged by trade restrictions, the spread of epidemics and plant diseases, rising prices of seeds and fertilizers, increasing labor costs, and climate-related disruptions such as floods and heat waves.

The agricultural sector is a major contributor to greenhouse gas emissions, water pollution, and biodiversity loss, highlighting the unsustainable trajectory of current farming systems (Springmann et al., 2018). To address these challenges and meet future demands, countries must develop sustainable policies and programs. One of the most effective approaches is fostering innovation through modern genetic and information technologies, which enhance agricultural efficiency while balancing economic, environmental, and social outcomes (Bacco & Antle, 2020).

Industrial agriculture is the most significant human-driven ecosystem service, influencing nearly all biogeochemical cycles and causing substantial ecological impacts (Park et al., 2016). Between 2005 and 2030, production is expected to increase by 100–110%, intensifying the demand for limited resources such as freshwater, fertile soil, sunlight, and non-renewable nutrients like phosphorus. Modern intensive farming contributes to soil degradation, aquifer depletion, salinization, runoff, eutrophication, and greenhouse gas emissions (CO_2, N_2O), exacerbating global warming and resource scarcity (Cohen et al., 2022). Moreover, many farmers lack adequate measurement, modeling, and control systems to optimize crop growth (Dawson & Hilton, 2011).

Additionally, due to extended supply chains, food losses—primarily in the form of waste—can reach up to 40% from harvest to consumption (Cohen et al., 2022). Various internal conditions influence crop quality and yield (Gibson, 2018; Engler & Krarty, 2021). Scientific literature highlights four key factors essential for creating optimal indoor crop-growing conditions:

- Temperature: A crucial factor for crop growth and development. Sudden temperature fluctuations can negatively impact photosynthesis and reduce yield.
- Humidity and Transpiration: Essential for water exchange and plant respiration. Maintaining optimal humidity levels ensures efficient transpiration.
- Chemical Balance: The equilibrium of essential nutrients in soil or hydroponic environments. Proper nutrition enhances photosynthesis and boosts yield.
- Photosynthetic Photon Flux (PPF): A crucial factor in supplying adequate light energy for plants. Proper management of the light spectrum influences growth rate and crop quality.

Hydroponics is a soilless method of growing plants using nutrient-rich water solutions, offering an efficient and sustainable approach to food production. This method significantly reduces water usage—up to 20 times less than traditional farming—while enhancing yields (AlShrouf, 2017). Hydroponic farms have been shown to outperform conventional open-field and greenhouse farming in efficiency (Romeo et al., 2018). Additionally, vertical hydroponic farming, when powered by carbon-neutral energy sources like wind power, can further optimize resource use and sustainability.

Sharma et al. (2018) examined various hydroponic systems, including the rod system, ebb and flow, drip irrigation, deep water culture, and nutrient film technique (NFT), identifying NFT as the most commercially utilized method. Sambo et al. (2019) emphasized that soilless farming demands specialized expertise, particularly in nitrate (NO_3^-) management and crop quality enhancement. While advancements such as nanoparticles and PGPR (plant growth-promoting rhizobacteria) show promise, further research is needed to understand nutrient uptake and localization in plant tissues. Additionally, the study highlighted the necessity of specialized service centers for smart agriculture, ensuring efficient hydroponic system operation by integrating hardware and software components.

Hydroponic systems offer significant advantages over traditional field cultivation, including water reuse, better control of environmental factors, and reduced reliance on conventional farming practices. However, they also have limitations such as high initial investment, rapid pathogen spread, and the need for specialized management (Lui et al., 2018). To facilitate the widespread adoption of commercial hydroponic technologies, cost-effective and innovative solutions must be developed to minimize plant diseases while enhancing food quality and yield. Although hydroponics is often considered a modern agricultural innovation, its origins trace back to ancient civilizations. The Hanging Gardens of Babylon, the Aztec floating gardens, and Chinese water gardens exemplify early forms of soilless farming. Egyptian hieroglyphs from as early as 1000 BC also depict plants growing in water. Scientific exploration of hydroponic cultivation dates back to Theophrastus (372–287 BC), who conducted early experiments on plant nutrition, followed by Dioscorides in the 1st century BC, who furthered botanical research.

The first scientific studies on plant nutrition were conducted in the 1600s by Belgian scientist Jan van Helmont. He performed a classic experiment in which he planted a willow sapling in a 0.09 m^3 container of dried soil and watered it only with rainwater for five years. The sapling grew from 5.7 cm to 184.3 cm, while the soil lost less than 2 ounces in weight. Based on this, Helmont concluded that plant growth occurs solely due to water, though he was unaware of the role of carbon dioxide (CO_2) and oxygen (O_2) from the air. Later, in 1699, English scientist John Woodward conducted experiments by growing plants in water with varying soil content. He found that plants grew best in water containing more soil, leading to the conclusion that growth was influenced by substances absorbed from the soil rather than water alone.

Further research progressed with advancements in chemistry and scientific methods. In 1804, De Saussure proposed that plants obtain chemical elements from water, soil, and air, a theory later confirmed in 1851 by French chemist Bussingo. He grew plants in sand, quartz, and coal while adding solutions of known chemical composition, determining that hydrogen is essential for plant growth and that dry matter consists mainly of carbon, hydrogen, and oxygen from the air. Bussingo also identified nitrogen and other mineral elements in plants. Scientists had previously demonstrated that plants could grow in an inert medium moistened with nutrient-rich water. The next breakthrough came in 1860–1861 when German scientists Sachs and Knop successfully grew plants solely in a mineral solution, eliminating the solid medium. This method revolutionized plant nutrition research and became a foundation for laboratory studies in plant physiology.

Early studies demonstrated that plant roots could grow normally when placed in a solution containing nitrogen (N), phosphorus (P), sulfur (S), potassium (K), calcium (Ca), and magnesium (Mg). With advancements in laboratory technology and chemistry, scientists later identified essential trace elements required in minimal amounts, including iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo). Over time, various researchers, such as Arnon, Hoagland, Robbins, Shive, Tollens, Tottenham, and Trelease, developed foundational nutrient formulas, some of which are still used in plant physiology studies today. Practical interest in these nutritional methods remained low until 1925 when the greenhouse industry sought alternatives to soil replacement due to issues with pests, declining fertility, and structural degradation. Between 1925 and 1935, significant efforts were made to adapt laboratory-based plant nutrition techniques for large-scale agricultural applications.

In the early 1930s, W.F. Gericke of the University of California expanded laboratory experiments in plant nutrition to an industrial scale, coining the term "hydroponics" from the Greek words “hydro” (water) and “ponos” (labor), meaning “working with water.” Hydroponics is a method of growing plants without soil, using substrates such as gravel, sand, peat, vermiculite, pumice, perlite, coconut fiber, sawdust, or rice husks, which are moistened with a nutrient-rich solution. Since many hydroponic systems use inert media, the method is often called "soilless culture," though true hydroponics involves growing plants solely in a water-based nutrient solution. Gericke successfully cultivated various vegetables, including root crops like beets, radishes, carrots, and potatoes, as well as grains, fruits, and ornamental flowers. His hydroponic tomatoes grew so tall that he needed a ladder to harvest them, demonstrating the method’s potential for high-yield agriculture.

The American press initially exaggerated hydroponics as a revolutionary breakthrough, leading to unrealistic expectations and fraudulent schemes selling unnecessary equipment. However, over time, hydroponic farming was scientifically validated, with two key advantages recognized: high crop yields and suitability for regions where traditional agriculture was impractical. During World War II, hydroponic systems were deployed in the early 1940s to supply food to troops stationed on barren Pacific islands. In 1945, the US Air Force successfully used hydroponics to grow fresh vegetables on rocky, unfarmable islands. Following the war, the military continued utilizing hydroponics, notably establishing a 22-hectare hydroponic farm in Chofu, Japan. By the 1950s, hydroponics gained commercial popularity and spread across countries such as Italy, Spain, France, England, Germany, Sweden, the USSR, and Israel.

Over the past 65 years, hydroponics has evolved into a highly specialized method, adapted for various environments, from open fields to greenhouses and even space applications. This technology enables intensive food production in limited areas, making it particularly beneficial for developing countries. However, its main constraints are the availability of fresh water and nutrients. In regions with scarce freshwater resources, hydroponics can be supported through seawater desalination. This method is especially crucial for enhancing food security in deserts or other regions unsuitable for traditional farming. Hydroponic farms can be established in coastal areas using beach sand as a substrate and can efficiently operate alongside desalination plants powered by petroleum, solar, or nuclear energy. For countries with limited arable land and dense populations, hydroponics presents a valuable agricultural solution, particularly in small nations where tourism is a key economic sector.

In regions with abundant sunlight, water minerals often exceed plant needs, potentially leading to equipment corrosion, clogged cooling pads, misting system failures, and structural damage to the growing medium. Advances in artificial lighting technology are making indoor plant cultivation economically viable, particularly in northern latitudes during fall and winter when natural sunlight is limited. Since crop prices are higher during these seasons, the use of artificial lighting can be commercially advantageous. Modern LED lighting shows great potential for this purpose, though it remains costly and requires a significant number of units to provide adequate illumination. Additionally, the heat generated by LED lights can be repurposed to warm greenhouses, further enhancing energy efficiency in

hydroponic farming.

Plant Factories with Artificial Lighting (PFALs) are advanced closed-system farming methods that cultivate plants entirely under artificial lighting. These systems integrate LED lighting, hydroponics, smart monitoring, and automated climate control to maximize efficiency.

Key advantages of PFALs include:

- Year-round production independent of external climate conditions.
- High productivity due to vertical stacking and optimized growing environments.
- Resource efficiency, consuming significantly less water and fertilizer than traditional farming.
- Reduced pesticide use, as the controlled indoor environment prevents pest infestations.

PFAL systems are widely used in urban agriculture, high-quality organic production, and food security initiatives, offering a sustainable alternative to conventional farming methods.

Closed Plant Production Systems (CPPS) are advanced agricultural systems where all essential factors for plant growth—light, temperature, humidity, CO_2 levels, and nutrients—are precisely controlled in an artificial environment.

Key Features of CPPS:

- Closed environment – Enables cultivation independent of external conditions.
- Artificial lighting – Uses LED, fluorescent, or other light sources to support plant growth.
- Resource efficiency – Maximizes water and nutrient use through hydroponic or aeroponic methods.
- Pesticide-free production – Ensures clean and safe crops in a controlled setting.

CPPS technology is widely applied in urban farming, food security initiatives, and high-yield agricultural production, offering a sustainable solution to modern agricultural challenges.

Difference Between CPPS and PFAL:

- CPPS (Closed Plant Production System): A broad term for indoor plant production, covering various controlled-environment growing methods.
- PFAL (Plant Factory with Artificial Lighting): A specialized type of CPPS that relies entirely on artificial lighting for plant growth.

Key Uses:

- CPPS is commonly applied in scientific research, seed production, genetic modification, and food safety experiments.
- PFALs are mainly used for commercial production of functional or specialized plants, including leafy greens (e.g., lettuce, arugula, kale, basil) and microgreens, which are especially popular in the U.S.

PFALs provide a sustainable, high-yield farming solution, particularly in urban environments where traditional agriculture is limited.

Commercial cultivation of medicinal plants, edible flowers, cherry tomatoes, strawberries, and miniature root crops like mini carrots remains in the small-scale or experimental stage. However, demand for plants grown in PFAL systems is steadily increasing. Medicinal and aromatic plants, in particular, are widely used across industries such as food, beverages, cosmetics, and health supplements. In Japan, specially designed PFAL and CPPS systems are used for producing various grafted plants, including tomatoes, cucumbers, watermelons, and eggplants (Kozai et al., 2015). Recently, specialized PFALs have also been utilized for pharmaceutical production, such as developing genetically modified plants for periodontal disease treatment.

Electricity consumption in PFAL systems is influenced by several factors, including:

- Growing period – the number of days required for plant growth,
- Photoperiod – the duration of daily light exposure,
- Photosynthetic Photon Flux Density (PPFD) – the intensity of light provided to the plants.

To enhance the efficiency of PFAL operations, electricity usage must be optimized by carefully balancing light intensity, photoperiod duration, and overall growing period.

Extensive research is currently underway to develop hydroponic systems for vegetable cultivation on space stations. Scientists are designing and testing closed-loop recirculation systems adapted to function in microgravity, aiming to provide a sustainable food source for astronauts on long-term space missions.

Beyond space applications, hydroponic greenhouse systems and rooftop gardens hold significant potential in large cities, particularly in regions where food must be transported over long distances. An article by D. Despommier, published in the November 2009 issue of Scientific American, explores the concept of 30-story vertical farms in urban environments. These advanced hydroponic systems utilize solar panels for power, convert plant waste into energy, and rely on treated urban wastewater for irrigation. Sunlight and artificial lighting together ensure optimal plant growth in these futuristic urban farms.

Water, along with dissolved minerals, moves upward through the plant via the xylem tissue. The xylem, composed of various cell types, forms a conductive system commonly referred to as plant veins. These veins consist of both xylem and phloem tissues, with the xylem responsible for transporting water and minerals, while the phloem distributes nutrients produced through photosynthesis.

The mechanism of photosynthate translocation through the phloem remains partially understood. In general, water and minerals ascend through the xylem to sites of photosynthesis, while photosynthates are distributed to other parts of the plant.

The upward movement of sap follows the cohesion-tension theory, proposed by Dixon and Renner. According to this hypothesis, water absorption by plant roots is driven by the suction force created by water evaporation from leaf cell walls. Water continuously rises due to molecular cohesion (the attraction between water molecules) and capillary action within the xylem

Water uptake in the xylem is influenced by the capillary size of xylem elements. This process occurs due to negative water potential, which is transmitted from the evaporating leaves down to the plant root cells and soil, creating an upward driving force.

MATERIALS AND METHODS

The experiment was conducted in the Geochang region of Gyeongsangnam-do province from 2017 to 2020 to examine the effects of planting dates and methods on local strawberry varieties, including "Seolhyang", "Maehyang", "Santa", "Arihyang" and "Keumsil". Accordingly, in 2017, planting in the experiment was carried out in the first term on August 1, and in the second term on September 2, depending on the timing.

- The strawberry nutrient solution developed by the Gyeongsangnam-do Agricultural Research Council was delivered through drip irrigation hoses. Smart cultivation systems—which integrate organic cocopot irrigation, fertilization systems, and adjustable cultivation lines—are used in greenhouse conditions. These systems have the ability

to adjust their position based on light availability to optimize growth. For the implementation of AI-driven agrotechnology, various analyzes are conducted using IoT-based programs on a computer, enabling real-time monitoring and automation of the cultivation process.

- It was carried out on the basis of "Seolhyang", "Maehyang", "Santa", "Arihyang", "Keumsil", which are grown from seeds. Strawberry seedlings with 3-4 leaves, crown diameter of 5-6 mm were obtained.

- Plants were placed in 60 × 34 × 10 cm propagation trays (manufactured by Hwaseong Industrial Co. Ltd., Okcheon, Korea) from 2016 to 2020. Each tray was filled with a specialized nutrient-rich substrate (coir) derived from coconut husk.

For rooting enhancement, the following media were used:

- CO (coir): Pure coconut peat supplied by Cocopeat Co. Ltd., Dummalasuriya, Sri Lanka.
- MIX: A custom-blended medium with a coir-to-perlite ratio of 8:2, ensuring optimal aeration and moisture retention

- The physical properties of the media—total porosity, specific container (cocopeat) capacity, air voids, and bulk density—were measured following the methodology of Kim and Jeong (2003). Additionally, the chemical properties, including electrical conductivity (EC) and pH, were analyzed using a pH/EC meter (Enzo 8200M, GOnDO Electronic Co. Ltd., Taipei, Taiwan), following the procedures outlined by Kim et al. (2016).

- Temperature and relative humidity within the single-span greenhouse were recorded every 5 seconds using an environmental data logger (MAGMAPLUS-1000, Green Control System, Damyang, Republic of Korea).

- In order to compare the growth of studied cultivar and hybrid strawberry plants under different conditions, leaf band (petiole) length, leaf length, leaf width, leaf number analysis (SPAD) values, crown diameter, root length, leaf area and fresh and dry weight of shoots and roots were measured after 14 and 28 days after cutting.

- After humidification, the nutrient solution was supplied through drip tapes using the strawberry nutrient solution developed by the Gyeongsangnam-do Agricultural Research and Extension (RDA, 2013). The composition of the solution was as follows:

Macro-elements ($me \cdot L^{-1}$): NO_3^-: 13.0, NH_4^+: 1.0, $H_2PO_4^-$: 4.0, K^+: 6.0, Ca^{2+}: 8.0, Mg^{2+}: 4.0, SO_4^{2-}: 4.0.

Micro-elements ($mg \cdot L^{-1}$): Fe: 3.0, B: 0.5, Mn: 0.5, Zn: 0.2, Cu: 0.04, Mo: 0.04.

The tap water analysis showed the following composition ($me \cdot L^{-1}$): Ca^{2+}: 0.90, Mg^{2+}: 0.49, SO_4^{2-}: 0.31, HCO_3^-: 0.60, K^+, NH_4^+, NO_3^-, and $H_2PO_4^-$ were not detected in tap water.

- Chlorophyll content was expressed using the SPAD value and measured with a portable chlorophyll meter (SPAD-502, Konica Minolta Inc., Tokyo, Japan). Chlorophyll fluorescence was recorded using a portable fluorometer (FluorPen FP100, Photon Systems Instruments spol., Drasov, Czech Republic).

- Fresh weights of shoots and roots were determined with an electronic scale (EW220-3NM, Kern & Sohn GmbH, Balingen, Germany).

- Dry weights of shoots and roots were measured after drying in a drying oven at 70°C for 72 hours and then weighed with an electronic scale.

- Leaf areas were assessed using a leaf area meter (LI-3000, LI-COR Inc., Lincoln, NE, USA).

- In strawberry varieties, the length of the stem, the number of petals, the number of pods, fruit elements (flowers and nodes), the number and yield indicators, morpho-phenological observations were measured on the first day of every month and analyzed. In the varieties and hybrids determined in the analysis, 25 plants were selected from each variant of phenological observation and observation was carried out in these plants.

RESEARCH RESULTS

The study analyzed key agrotechnical parameters for strawberry cultivation in greenhouse conditions, including pH, relative humidity, temperature, and electrical conductivity (EC). These parameters were monitored over the years, and their average values were calculated.

The MIX substrate (coir:perlite = 8:2) used in the experiment demonstrated excellent liquid retention properties. However, to prevent excess salt accumulation and potential root damage, maintaining an optimal EC level through constant monitoring is essential.

The MIX substrate effectively balances moisture and aeration, ensuring a favorable environment for root development. This balance regulates EC levels and promotes healthy root growth, leading to improved plant performance.

Electrical conductivity (EC) reflects the concentration of nutrients available to plants in the solution. Experimental data over three years showed that the average EC in the hanging method remained around 1.5 mS/cm from the beginning of the season through the growing period, while in the vertical method, it averaged 1.6 mS/cm. Since the optimal EC range for strawberries is 1.2–1.8 mS/cm, both methods maintained suitable nutrient conditions for plant growth.

The study examined agrotechnical practices based on the planting dates of various strawberry varieties in 2017–2018. Observations were made on leaf development and characteristics in both hanging and vertical planting methods for five genetically distinct varieties: "Seolhyang", "Maehyang" "Santa", "Arihyang", and "Keumsil". Additionally, from 2017 to 2020, research focused on optimizing greenhouse agrotechnical management using smart technologies (Figure 1).

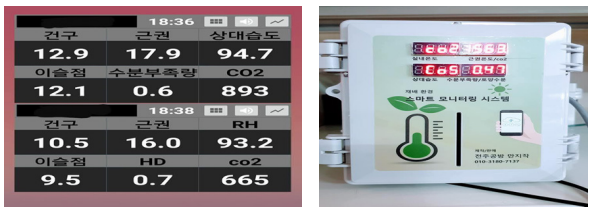


Figure 1. Monitoring system designed to ensure compliance with agrotechnical requirements in a greenhouse.

In the experiment, the root temperature of strawberry varieties grown in the greenhouse heat zone showed a gradual increase over the years, rising from day 30 to day 210 in each of the three years. In the first year (2017–2018), the temperature increased from 10.4°C to 15.9°C. In 2018–2019, it rose from 10.7°C to 15.7°C, while in 2019–2020, the increase was from 10.1°C to 15.7°C. These results indicate a continuous improvement in temperature stability, with the changes in 2019–2020 being relatively more stable compared to previous years.

The humidity level of the substrate in the greenhouse increased from the 30th to the 90th day of each year before gradually decreasing. The results show that in 2017–2018, humidity rose from 68.3% at the beginning of the season to 71.7% at the end. In 2018–2019, it increased from 70.4% to 72.6%, while in 2019–2020, it rose from 69.4% to 73.9%.

These findings indicate that smart technologies have contributed to improved humidity retention. However, in the final year, the humidity level remained higher at the end of the season compared to previous years.

During the first period, the substrate's moisture deficit relative to humidity decreased from -7.0% to -4.0% in 2017–2018. In 2018–2019, it dropped from -5.0% to -3.0%, and in 2019–2020, it shifted from -6.0% to +2.0%, indicating a significant improvement in moisture retention.

The most significant change was observed in 2019–2020, when on day 210, the moisture deficit turned positive. This indicates that smart technologies successfully provided sufficient moisture.

CO_2 serves as the primary source of energy for plants. They absorb CO_2 along with sunlight and water to synthesize organic compounds (carbohydrates). The fundamental photosynthesis reaction is as follows:

6CO2+6H2O+light --- C6H12O6+6O2

An increase in CO_2 levels accelerates photosynthesis, enabling plants to produce more organic matter. This, in turn, promotes faster growth and higher yields.

CO_2 levels varied across the study years, increasing from 488 ppm to 575 ppm in 2017–2018, 467 ppm to 569 ppm in 2018–2019, and 473 ppm to 553 ppm in 2019–2020.

The CO_2 concentration increased until day 90, peaked around day 150, and then gradually declined. This trend aligns with periods of heightened photosynthetic activity. In 2019–2020, the CO_2 levels decreased slightly in the final phase, which may be attributed to increased plant absorption or improved greenhouse ventilation.

Maintaining moisture balance was crucial for vertically grown strawberries from 2017 to 2020, as moisture levels directly influenced transpiration, photosynthesis, and nutrient exchange. The substrate humidity in the greenhouse ranged between 70% and 77%, staying within the optimal range.

In 2017–2018, humidity peaked at 77.2% around day 90, followed by a gradual decline. However, in 2019–2020, a more noticeable decrease in humidity was observed, likely due to the effects of ventilation and irrigation systems.

CO_2 played a key role in enhancing photosynthesis and improving yield. In 2017–2018, CO_2 levels rose to 998 ppm, nearing the optimal range. However, in 2019–2020, CO_2 levels declined from 939 ppm to 611 ppm, potentially slowing the photosynthesis process. Effective control of CO_2 levels through ventilation adjustments and CO_2 injectors helped optimize plant growth.

During 2017-2020, the humidity level of the substrate in the greenhouse decreased from 73.1% to 70.3% in the hanging method in 2017-2018. In 2018-2019, it was maintained in the range of 72.2% to 72.2%. In 2019-2020, it fluctuated between 71.3% and 72.7%. In the vertical method, it fluctuated between 72.2% and 73.9% in 2017-2018, respectively. In 2018-2019, it decreased from 71.5% to 71.8%. In 2019-2020, it decreased from 72.3% to 71.3%.

The moisture deficiency level in the hanging method decreased from -2.0% on day 30 to -5.0% on day 210 in 2017-2018, remained stable at -3.0% throughout 2018-2019, and ranged between -4.0% and -3.0% in 2019-2020. In the vertical method, it was -3.0% on day 30 and improved to -2.0% on day 210 in 2017-2018, remained constant at -4.0% in 2018-2019, and fluctuated between -3.0% and -4.0% in 2019-2020.

In the suspended state, CO_2 levels showed a decreasing trend over the years, dropping from 491 ppm to 561 ppm in 2017-2018, from 472 ppm to 542 ppm in 2018-2019, and from 467 ppm to 532 ppm in 2019-2020. In the vertical state, CO_2 levels fluctuated between 504 ppm and 658 ppm in 2017-2018, between 482 ppm and 631 ppm in 2018-2019, and decreased from 475 ppm to 604 ppm in 2019-2020.

The results indicated that the vertical method maintained higher root temperatures and a more stable moisture deficit, while the hanging method provided more stable relative humidity. Additionally, CO_2 levels were higher in the vertical method, potentially improving carbon dioxide availability for plant growth.

The formation of vegetative and generative organs depends on natural conditions such as nutrients, water, and various biotic and abiotic factors. In the experiment, growth and development were analyzed by monitoring the number of vegetative and generative organs over a period of 60 to 210 days.

The data indicate that after 60 days of planting, the "Arihyang" strawberry variety had the greatest plant height (18.5 cm) and the highest number of branches (5.4). By the 90th day, physiological changes reflecting early ripening were observed, influenced by the ethylene-auxin balance. In the hanging method, the tallest plant was the "Maehyang" variety (23.5 cm), while "Arihyang" had the most branches (6.5), and "Santa" had the highest number of flowers and nodes (4.3–5.6). Overall, all other indicators were lower in the vertical method.



Figure 2. The process of determining the growth of strawberry seedlings

Between the 180th and 210th days of the growing season, the ripening index varied among the studied strawberry varieties, with "Arihyang" producing 5.0 flowers, "Seolhyang" 2.4 flowers, and "Maehyang" and "Arihyang" yielding 4.2–4.3 fruits. In the hanging method, plant development was influenced by light exposure.

In the second period of the experiment, by day 60, the "Maehyang" variety showed a 0.4 cm greater plant height in the hanging method, with minimal differences in shoot numbers, generally favoring the hanging method. By day 120, the "Seolhyang" variety had a 0.8 cm height advantage in the hanging method, while the "Arihyang" variety produced 0.8 more ripe fruits. By day 210, the "Arihyang" variety had the highest number of flowers, and the vertical method showed a greater difference in ripe fruit production.

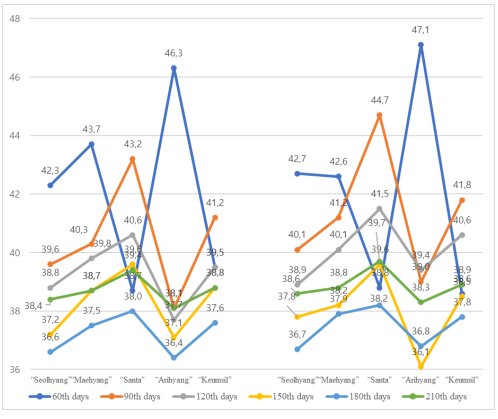


Figure 3. Changes in chlorophyll (SPAD) depending on the planting method and timing of different strawberry varieties (period 1, 2016-2017)

In the first period of the study, after 60 days of planting in the hanging method, physiological characteristics varied across varieties: the longest leaves (6.90 cm) were observed in the "Maehyang" variety, the widest leaves (6.53 cm) in the "Santa" variety, and the highest leaf number (4.7 more than in the vertical method) in the "Arihyang" variety. Additionally, in the hanging method, the "Arihyang" variety had a leaf thickness of 0.49 mm, a chlorophyll content of 47.1, and a leaf area of 180.8 cm² per plant.

After 90 days, the "Santa" variety had the longest leaves at 6.97 cm in the vertical method and the widest leaves at 6.83 cm in the hanging method. The highest number of leaves, reaching 6.8, was recorded in the "Seolhyang" variety in the hanging method, while the thickest leaves, measuring 0.52 mm, were observed in both the "Seolhyang" and "Arihyang" varieties in the hanging method. The highest chlorophyll content, 44.7 SPAD, was found in the “Santa” variety in the vertical method, whereas the "Arihyang" variety had the largest leaf area at 295.5 cm² per plant in the hanging method. These results indicate that while the "Santa" variety excelled in leaf length and width, the "Arihyang" variety demonstrated superior leaf number and area, highlighting its better adaptation to the hanging method.



Hanging method (hydroponics) Vertical method (hydroponics)

Figure 4. Overview of hanging and vertical methods

After 120 days, the longest leaves were observed in the "Santa" variety with a length of 7.82 cm in the hanging method, while the widest leaves were found in the "Seolhyang" variety with a width of 6.93 cm in the hanging method. The highest number of leaves was recorded in the "Arihyang" variety, reaching 8.0 in the hanging method. Leaf thickness was also highest in the “Arihyang” variety at 0.55 mm in the hanging method. The "Santa" variety had the highest chlorophyll content at 41.5 SPAD in the vertical method, and the largest leaf area was observed in the “Arihyang” variety at 408.6 cm² per plant in the hanging method. Overall, the "Arihyang" variety excelled in most growth indicators, while the “Santa” variety’s high chlorophyll content suggests a potential advantage in early crop ripening.

After 150 days, during the final phase of the flowering-harvesting period, the longest leaves were observed in the "Maehyang" variety (8.45 cm, hanging method), while the widest leaves were found in the "Seolhyang" variety (7.83 cm, vertical method). The highest number of leaves (9.2), the thickest leaves (0.62 mm), and the largest leaf area (564.6 cm²/plant) were recorded in the "Arihyang" variety (hanging method). The highest chlorophyll content (39.6 SPAD) was in the "Santa" variety (hanging method). These results highlight the superior efficiency of "Arihyang" in terms of leaf number, thickness, and area, promoting high photosynthesis and growth, while "Maehyang" stood out for its long leaves.



Figure 5. Changes in chlorophyll (SPAD) depending on the planting method and timing of different strawberry varieties (2nd period, 2016-2017)

The data indicate that root temperature was higher in the vertical method, suggesting that this method helps maintain a more stable root temperature (Figure 4-5).

While relative humidity remained stable in the hanging method, it decreased in the vertical method. The humidity deficit showed similar variations in both methods but was more stable in the vertical method. Additionally, the CO_2 level was higher in the vertical method, potentially enhancing carbon dioxide supply to the plants.

Overall, the "Arihyang" strawberry variety excelled in leaf number, thickness, and surface area, making it well-suited for greenhouse conditions due to its high photosynthesis and growth rates. The "Santa" variety, known for its fast ripening, showed superiority in chlorophyll content and efficient light absorption, making it effective in various environments. Meanwhile, the "Maehyang" variety, ideal for export, stood out for its leaf length.

A comparative analysis of strawberry cultivation in soil culture and substrate-based (soilless) methods under controlled agrotechnical conditions revealed significant differences in plant growth and productivity. These findings are presented in Table 1 below.

Based on the results, we can draw the following scientific conclusions:

1. Optimal Variety for Greenhouses – The "Arihyang" strawberry variety demonstrated superior performance in terms of leaf number, thickness, and surface area, which suggests that it is well-suited for greenhouse cultivation due to its high photosynthetic activity and growth potential.

2. Impact of Cultivation Methods – The hanging method generally resulted in better vegetative growth, including larger leaf area and higher chlorophyll content in some cases. The vertical method, while maintaining a more stable root temperature, led to reduced humidity and slightly lower CO_2 levels, which could impact overall plant productivity.

3. Light Absorption and Early Ripening – The "Santa" variety, which had higher chlorophyll content, exhibited characteristics favorable for early ripening. This suggests that it can efficiently absorb light and convert it into energy, making it a strong candidate for environments that prioritize early fruit production.

4. Varietal Suitability for Market Needs – The "Maehyang" variety, which exhibited longer leaves, appears to be well-suited for export due to its structural characteristics. This suggests that different varieties can be strategically selected based on market demands, such as early ripening ("Santa"), high yield and greenhouse suitability ("Arihyang"), and export potential ("Maehyang").

5. Photosynthesis and CO_2 Utilization – The higher CO_2 levels observed in the vertical method indicate a potential advantage in carbon dioxide absorption, but the hanging method may be more effective in promoting overall vegetative growth. Controlling CO_2 levels through ventilation and injectors remains a key factor in optimizing plant development.

Table 1
Advantages of Soilless Culture versus Soil Culture

Agrotechnical activities	Soil culture	Soilless culture
Sterilizing the growing medium	Steam and fumigants are commonly used sterilization methods, but the process is labor-intensive and requires a long lead time, typically at least 2–3 weeks.	Some systems use steam or chemical fumigants, while others rely on bleach or hydrochloric acid (HCl), requiring only short sterilization times.
Plant nutrition	Highly variable and often locally scarce, nutrients in soil may be unavailable to plants due to poor soil structure or imbalanced pH. Additionally, soil conditions are unstable, making sampling, testing, and regulation challenging.	Controlled and relatively stable, nutrient availability in soilless systems is uniform for all plants. These systems ensure sufficient nutrient supply, allow for precise pH control, and make testing, sampling, and regulation easy.
Plant spacing distance	Limited by soil nutrient content and natural light availability.	Enables closer plant spacing, limited only by available light; increases plant density per unit area, maximizing space efficiency and boosting overall yield.
Weed control, cultivation	Weeds present, cultivate regularly	No weeds, no cultivation
Diseases and soil inhabitants	Prone to soil-borne diseases, nematodes, insects, and animals that threaten crops; requires frequent crop rotation to manage infestations.	Free from soil-borne diseases, insects, and animals; eliminates the need for crop rotation.
Water	Plants often experience water stress due to poor soil-water relations, inadequate soil structure, and low water-holding capacity. Saline water cannot be used. Water use is inefficient, with significant losses from deep percolation beyond the root zone and evaporation from the soil surface.	No water stress due to complete automation with moisture-sensing devices and a feedback mechanism. Reduces labor costs, allows the use of relatively high-salinity water, and ensures efficient water use. No water loss from deep percolation or surface evaporation; when properly managed, water loss is limited to transpiration.
Fruit quality	Fruit quality is often compromised, becoming soft or puffy due to potassium and calcium deficiencies, leading to a reduced shelf life.	Fruit is firm and has a long shelf life, allowing growers to harvest vine-ripened produce and ship it over long distances. Additionally, minimal spoilage occurs at supermarkets. Some studies have even indicated higher vitamin A content in hydroponically grown tomatoes compared to those cultivated in soil.
Fertilizers	Requires large quantities when applied to soil, leading to nonuniform distribution among plants. A significant portion (50%–80%) is leached past the root zone, resulting in inefficient nutrient utilization.	Uses small quantities, ensures uniform distribution to all plants, prevents leaching beyond the root zone, and maximizes efficiency.
Transplanting	No need to prepare soil or uproot plants, eliminating transplanting shock. Easy to control temperature and disease, ensuring healthy transplants.	No preparation of medium required before transplanting; transplanting shock is minimized, ensuring faster establishment and growth. Medium temperature can be kept optimal, and the absence of soil-borne diseases promotes healthier plants.
Permanence	In a greenhouse, soil must be replaced periodically every few years due to the deterioration of its fertility and structure.	No need to replace the medium in gravel, sand, or water cultures; no fallowing required. Sawdust, peat, coco coir, vermiculite, perlite, and rockwool can last for several years with proper sterilization.
Yields	Greenhouse strawberry yield ranges from 10 to 20 tons per hectare, depending on factors such as variety, climate control, and cultivation method.	With higher planting densities and optimized greenhouse conditions, strawberry yields can reach 30 to 60 tons per hectare. This is achieved through vertical growing systems, hydroponics, and controlled environment agriculture.

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