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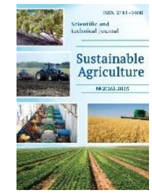

Integration of Smart Farming Technologies for Sustainable Strawberry Production in Controlled Environments

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ABSTRACT

This study examines the effects of planting period and cultivation methods on the quality of strawberry cultivars "Arihyang", "Seolhyang", "Santa", and "Keumsil". The analysis focused on fruit size, weight, sugar content (°Brix), titratable acidity, and water content.

"Arihyang" showed the best results across all parameters, particularly when planted in the first period, with larger fruit size, higher sugar content, and better acidity. "Seolhyang" also performed well, while "Santa" and "Keumsil" were smaller and less sweet. Fruits from the first planting period were superior due to longer vegetative growth and better environmental conditions.

For optimal strawberry production, planting "Arihyang" or "Seolhyang" during the first planting period is recommended.

1. INTRODUCTION

Global warming is anticipated to disproportionately impact agricultural lands in developing nations more severely than in industrialized countries, primarily because land surfaces tend to heat more rapidly and intensely than water bodies. Climate change poses significant threats to crop production through two primary mechanisms: (1) elevated soil evaporation rates and (2) increased temperatures that hinder plants' ability to absorb and efficiently utilize moisture.

By the 2080s, global food demand is projected to triple, driven by continued population growth and rising affluence (Cline, 2008). This intensifies the imbalance between supply and demand—a situation that climate change is expected to further destabilize. Therefore, strengthening agricultural adaptation strategies has become an urgent priority.

Despite this urgency, there remains a dearth of empirical research assessing both the adoption rates and the effectiveness of various adaptation interventions. To bridge this gap, it is crucial to develop an integrated risk-management framework that incorporates the uncertainties of climate variability alongside shifting market dynamics. Moreover, scientific inquiry must remain agile—continuously re-evaluating research priorities and refining agricultural management practices in response to evolving climatic and socioeconomic conditions (Howden et al., 2007).

In response to the growing challenges posed by climate change, soilless smart agriculture technologies present promising pathways for achieving efficient and sustainable food production (Banerjee et al., 2022). These innovative systems are increasingly viewed as pivotal tools for both mitigating the effects of climate change and enhancing agricultural resilience. As the global population continues to rise, so too will the pressure on food systems to produce more with fewer resources.

Climate Adaptation.

With the global population expected to increase substantially, the demand for food will escalate accordingly. Simultaneously, climate change is forecast to amplify the frequency and severity of extreme weather events—such as droughts, floods, and temperature fluctuations—that can severely disrupt conventional agriculture (Altieri et al., 2015). Soilless cultivation methods, however, are generally implemented in controlled environments, making them significantly more resilient to adverse climatic conditions. For example, hydroponic and aeroponic systems operated indoors can effectively shield crops from heatwaves, cold spells, and heavy rainfall (Rayhana et al., 2020).

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Water Use Efficiency.

Traditional farming practices are notoriously water-intensive, posing a serious sustainability issue in water-scarce regions. In contrast, soilless agriculture consumes significantly less water due to its closed-loop systems (Eigenbrod & Gruda, 2015). In hydroponic setups, for instance, water is recirculated and only the volume directly absorbed by the plants is lost. These technologies are particularly suitable for arid and semi-arid regions where conventional farming may not be feasible (Schröder & Lieth, 2002).

Reduced Carbon Footprint.

The carbon intensity of conventional agriculture is substantial, as it relies heavily on chemical inputs such as synthetic fertilizers and pesticides, and involves emission-generating practices (Bozchalui et al., 2015). Soilless systems, by contrast, minimize these inputs and offer more precise control over nutrient delivery, pH balance, and irrigation—factors that contribute to higher yields and lower environmental impact (Eigenbrod & Gruda, 2015; Lakhiar et al., 2018).

Urban Agriculture.

With rapid urbanization, there is growing interest in producing food within city limits. Soilless farming technologies, including vertical farming, enable food production in densely populated urban environments where land for traditional agriculture is scarce (Goldstein, 2018). These systems not only provide access to fresh, locally grown produce, but also reduce the environmental footprint associated with long-distance food transport (Goodman & Minner, 2019). Furthermore, controlled-environment agriculture—such as greenhouse-based systems—facilitates continuous, year-round production while shielding crops from extreme weather conditions (Goodman & Minner, 2019; Rayhana et al., 2020).

However, it is essential to account for the environmental and social trade-offs of these systems, such as the energy requirements for maintaining controlled environments. Ensuring the long-term sustainability of soilless agriculture will require balanced integration of technological efficiency, resource management, and equitable access.

According to projections by the United Nations, India is expected to become the most populous nation by 2030, with a population reaching 1.5 billion (UN DESA, 2022). This rapid demographic expansion will place immense pressure on the country's food systems, underscoring the urgency of adopting innovative and scalable agricultural solutions to ensure food security.

Mineral Nutrition and Essential Elements in Plants.

Out of the 92 naturally occurring mineral elements in the Earth's crust, approximately 60 have been identified in various plant tissues. However, only 16 of these are considered essential elements—those absolutely required for the normal growth, development, and reproduction of higher plants. Essentiality is determined based on three criteria: (1) the element must be directly involved in plant metabolism, (2) its function cannot be substituted by another element, and (3) its absence prevents the plant from completing its life cycle.

Although many non-essential elements can still be absorbed by plants if present in soluble form, nutrient uptake is not a completely passive process. Plant roots exhibit selective absorption mechanisms that regulate ion influx based on metabolic needs, ion competition, membrane transport systems, and environmental availability. As a result, the rate of nutrient uptake does not always correlate linearly with soil concentration. Additionally, different plant species—and even cultivars—show variation in ion selectivity and absorption efficiency, contributing to species-specific nutritional profiles.

Classification of Essential Elements.

Essential elements are broadly classified into two categories based on the relative quantities required:

Macronutrients: Required in large amounts for structural and physiological functions, including:

- Carbon (C), Hydrogen (H), Oxygen (O): Derived primarily from water and carbon dioxide; fundamental to all organic molecules.
- Nitrogen (N): Key component of amino acids, proteins, nucleic acids, and chlorophyll.
- Phosphorus (P): Vital for ATP, nucleic acids, and phospholipids.
- Potassium (K): Involved in osmoregulation, enzyme activation, and stomatal function.
- Calcium (Ca): Important for cell wall structure and signal transduction.
- Magnesium (Mg): Central atom in chlorophyll; activates many enzymatic reactions.
- Sulfur (S): Integral to amino acids like cysteine and methionine and coenzymes.

Micronutrients: Required in trace amounts but are equally crucial for enzymatic and regulatory processes:

- Iron (Fe), Chlorine (Cl), Manganese (Mn), Boron (B), Zinc (Zn), Copper (Cu), Molybdenum (Mo).

Nutritional Disorders and Element Mobility. Imbalances—whether deficiencies or toxicities—of these elements result in nutritional disorders, which manifest through physiological dysfunctions and visible symptoms. Deficiencies generally lead to impaired photosynthesis, growth retardation, chlorosis, necrosis, and distorted organ development, depending on the specific role of the deficient element.

Essential elements also differ in their mobility within the plant:

- Mobile nutrients (e.g., N, P, K, Mg) can be translocated from older to younger tissues during deficiency, leading to early signs in older leaves.
- Immobile nutrients (e.g., Ca, B, Fe) remain fixed at their site of initial assimilation, so deficiency symptoms appear first in new growth.

Strawberry Cultivation and Biotechnological Advances. Strawberry (Fragaria × ananassa) is one of the most popular and widely consumed fruit crops globally, prized both in fresh markets and for processing into products such as jams, sauces, and desserts (Husaini & Abdin, 2008). The growing demand for strawberries can be seen in the sharp increase in production and cultivated area over recent decades.

Between 2003 and 2023, global strawberry production rose by an impressive 53.5%, while the area dedicated to strawberry farming expanded by 12%, as reported by the Food and Agriculture Organization (FAO) in its FAOSTAT database (2023). The most significant growth was observed in Africa, where production soared by 125.9%, and the area under cultivation grew by 70.7%. In Asia, production increased by 64.7%, and the area expanded by 26.4%. The USA saw a 39.1% increase in production and a 20.2% increase in the cultivated area. In Europe, production grew by 21.2%, although the area remained nearly stable, decreasing by a marginal 0.1%. These trends underscore the profitability and rising popularity of strawberries across various regions of the world.

Strawberry Cultivar Selection and Breeding Challenges. The diversity of strawberry cultivars is vast, with hundreds of varieties developed by plant breeders to cater to specific environmental conditions or market demands. No single cultivar dominates worldwide cultivation, as each variety has its own set of environmental preferences, yielding capabilities, and fruit qualities. For instance, octoploid strawberry accessions exhibit considerable variation in morphology, photoperiod sensitivity, and fruit quality (Husaini, 2010). To maximize production, it is crucial to select a cultivar that is well-adapted to the specific growing conditions of a region.

Given the complexity of the octoploid genome (which has eight sets of chromosomes), traditional breeding methods face significant challenges. This has led to the adoption of advanced biotechnological tools, such as recombinant DNA technology, Golden Gate cloning, and CRISPR-Cas systems, which allow for precise genetic modifications. These techniques offer promising solutions for overcoming the limitations of conventional breeding.

Biotechnological Interventions in Strawberry Improvement. One of the most notable examples of biotechnological applications in strawberry cultivation is the improvement of fruit softening, a key postharvest issue. Genetic transformation has enabled the development of strawberries that are more resistant to this problem, thereby extending shelf life and reducing waste. Moreover, biotechnology plays a crucial role in improving traits that confer adaptability to climate change, such as increased drought tolerance, pest resistance, and better overall resilience to environmental stresses (Husaini et al., 2012).

By integrating biotechnology with traditional cultivation practices, strawberry producers can better meet the growing global demand for this popular fruit while addressing challenges such as environmental variability, postharvest losses, and the pressures of climate change.

In conclusion, while vertical farming holds great promise as a sustainable solution for addressing food security and resource constraints in urban environments, its widespread adoption faces significant hurdles, including high energy consumption, technical complexity, and limited crop diversity. However, these challenges are not insurmountable. By integrating renewable energy sources, improving water and nutrient management through advanced technologies, and fostering research into crop diversification, vertical farming can become more efficient and accessible. With continued innovation and support from policymakers and the scientific community, vertical farming has the potential to revolutionize modern agriculture, offering a viable alternative to traditional farming methods in the face of climate change and urbanization.

2. MATERIALS AND METHODS

The research was conducted based on plant samples, laboratory analyses, phenological observations, and measurements. These procedures followed the technological guidelines developed for strawberry cultivation by the Gyeongsangnam-do Agricultural Research and Extension Services. Additionally, international methodologies were applied, including data from "Statistics from MAFRA" (Korea's Ministry of Agriculture, Food, and Rural Affairs) and the BS EN 13031-1:2019 standard, a comprehensive guide for the implementation of commercial greenhouse design and construction.

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.

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·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·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·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.

- 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.

3. RESEARCH RESULTS.

The analysis of the differences in growth and development between strawberries planted in July and August, and those harvested during the winter months, can be summarized as follows:

1. Temperature and Microclimate: Strawberries planted in July and August grow in hot and high-temperature conditions, which helps accelerate their growth. However, excessive heat can stress the plants, potentially negatively affecting fruit quality. In winter, controlling the temperature in greenhouses is essential. Cooler conditions slow down fruit ripening but improve quality. The reduction in high temperatures and preservation of coolness during winter enhances the fruit's color and shape.

2. Light and Photoperiod: In July and August, daylight hours are at their maximum, which accelerates the ripening process. However, high light intensity and heat can reduce fruit quality, causing the fruits to ripen quickly but become softer and more watery. In winter, shorter daylight hours slow down ripening, but providing additional light in a greenhouse can overcome this issue and improve fruit quality.

3. Vegetation Period and Growth Rate: Strawberries planted in July and August experience rapid growth and development, completing their vegetative period in a short time, which results in early fruiting. However, this quick growth can affect fruit quality, as excessive heat can cause the plants to become stressed and lead to softer, waterier fruits. In winter, the growth process is slower, allowing for the production of firmer, higher-quality fruits. Cooler conditions slow down growth but enhance fruit quality.

4. Harvest Storage and Transport: Strawberries harvested from July and August crops ripen quickly, making them less durable and unsuitable for transport. The fruits are softer, which makes storage more difficult. Winter crops, on the other hand, are better preserved due to cooler conditions and are more suitable for transport. The quality of the harvest remains intact, with firmer fruits that can be stored for longer periods.

5. Environmental Conditions and Stress: Strawberries planted in July and August are subject to high temperatures and light intensity, which can lead to quick ripening but also cause plant stress. Excessive heat, water shortages, and nutrient imbalances affect fruit quality. In winter, cooler and more stable conditions reduce stress on the plants. These favorable conditions help strengthen the plants and improve fruit quality.

In conclusion, while strawberries planted in the summer months tend to mature faster, the cooler conditions in winter contribute to better fruit quality, longer shelf life, and more stable plant health, ultimately making winter-grown strawberries more advantageous for consistent and high-quality production.

During the 2017–2018 growing season, studies were conducted to evaluate the effects of planting methods and timings on various strawberry cultivars, focusing on growth organ indicators. Field assessments involved analyzing the establishment of seedlings in nutrient substrates to determine their biological status 30 days after planting.

The results showed that, in the first planting period, the "Arihyang" cultivar exhibited the greatest plant height—reaching 18.5 cm—60 days after planting. This cultivar also recorded the highest number of stems, averaging 5.4 per plant. By the 90th day of the vegetation period, physiological differences among the cultivars became apparent, reflecting their respective ripening rates.

The ethylene–auxin balance within the plants played a crucial role in the formation of organs along the plant axis, thereby promoting overall growth and development. Under the suspended cultivation method, the highest plant height was recorded in the "Maehyang" cultivar, reaching 23.5 cm, while the "Arihyang" cultivar exhibited the greatest number of stems, with an average of 6.5 stems per plant. The highest number of flowers and buds was observed in the 'Santa' cultivar, with values ranging from 4.3 to 5.6, respectively. In contrast, all these parameters were lower under the vertical cultivation method.

Overall, observations during the 180–210 day vegetative period indicated clear varietal differences in ripening characteristics. The highest number of flowers was noted in the "Arihyang" (5.0) and "Seolhyang" (2.4) cultivars. The greatest fruit set was recorded in the "Maehyang" and "Arihyang" cultivars, with 4.2 and 4.3 fruits per plant, respectively. These findings suggest that strawberries grown under the suspended method, which provides improved light exposure, underwent more pronounced developmental changes.

During the second experimental period, plant growth and development dynamics by the 60th day revealed that the "Maehyang" cultivar exhibited a 0.4 cm greater plant height under the suspended method compared to the vertical method. Differences in the number of shoots were minimal; however, the suspended system generally produced slightly better results. By the 120th day, the most notable height difference was observed in the "Seolhyang" cultivar, with plants grown under the suspended method being 0.8 cm taller. In terms of fruit development, the "Arihyang" cultivar had 0.8 more ripe fruits per plant under the suspended method.

By the 210th day, a comparison of both cultivation methods showed that the "Arihyang" cultivar produced the highest number of flowers and ripe fruits, with the vertical method yielding a slightly higher number in this regard. Although growth indicators—such as plant height and shoot number—were consistently higher in the suspended method due to better light exposure and nutrient availability, the vertical method demonstrated advantages in terms of flower and fruit set. Notably, the vertical system allowed for greater planting density and extended the harvesting period due to a higher number of fruiting nodes. Therefore, while the suspended method promotes more vigorous vegetative growth, the vertical method offers space-efficient, high-yield potential.

The LAQUA Twin Pocket Meters (HORIBA, Japan) provide accurate results based on samples obtained from plant sap and analyze nitrate nitrogen (NO3-N), potassium (K+), calcium (Ca2+), and sodium (Na+) ions. This pocket meter allows direct measurement of micro-sized samples, as small as 0.1 ml, within seconds. This enables producers to make quick decisions regarding fertilization and irrigation.

To perform nitrate testing using the LAQUA sensor (HORIBA, Japan), the two most developed trifoliate leaves and their petioles were collected from 20 strawberry plants. These samples were finely chopped and pressed mechanically to extract the leaf sap (Figure 1). A 0.05 mL (approximately one drop) aliquot of the sap was then placed onto the sensor surface for analysis, yielding results in parts per million (ppm) or mg/L. According to HORIBA (2017), the recommended nitrate concentration for strawberry plants is approximately 550 ppm at 60 days and 400 ppm at 90 days of growth.

In parallel, other studies (Menzel, 2018; Osvalde, 2023) employed a protocol involving the collection of ten fully expanded young leaves every three weeks to assess total nitrogen and nitrate-nitrogen (NO_3^--N) levels. Prior to each use, the sensor was calibrated according to manufacturer guidelines: the sensor was rinsed with water, a drop of standard solution was applied, and the calibration button was pressed. A smiley face icon on the display confirmed successful calibration.

This experiment, conducted during the 2017–2018 growing season, used LAQUA technology to monitor nitrate concentrations in strawberry leaves grown under both suspended and vertical hydroponic systems. Measurements were recorded periodically from day 30 to day 210 to evaluate nitrogen dynamics under different cultivation conditions.

Figure 1. Determination of nitrate content in leaves using LAQUA (Twin Pocket Meters).

In the first experimental phase under the suspended hydroponic system, nitrate concentrations in the leaves of all strawberry cultivars exhibited a similar trend—an initial increase followed by a gradual decline. In the "Seolhyang" cultivar, nitrate content rose from 480 ppm to a peak of 740 ppm before decreasing to 390 ppm. "Maehyang" showed a more pronounced increase, from 520 ppm to 800 ppm, followed by a reduction to 420 ppm. The "Santa" cultivar consistently exhibited lower nitrate levels compared to the others, increasing from 390 ppm to 610 ppm and then decreasing sharply to 220 ppm. In "Arihyang", nitrate levels increased from 470 ppm to 720 ppm, followed by a decline to 350 ppm. Similarly, "Keumsil" showed a rise from 510 ppm to 780 ppm before dropping to 410 ppm.

The observed pattern of nitrate accumulation peaking around day 120 and subsequently declining is attributed to physiological processes, including the breakdown and translocation of nitrate within aging leaves and its utilization during reproductive development. The decline also coincided with the removal of older foliage. Notably, the "Santa" cultivar maintained the lowest nitrate levels throughout the vegetative period, indicating more efficient nitrate assimilation and possibly a shorter vegetative phase (Table 1).

Table 1

Nitrate content in strawberry leaves depending on cultivar, planting period, and cultivation method (LAQUA, Japan).

№	Strawberry cultivars	Nitrate content in leaves after transplanting strawberry seedlings, ppm						
		After 30 days	After 60 days	After 90 days	After 120 days	After 150 days	After 180 days	After 210 days
	1st period, 2017–2018							
	Suspended method (hydroponics)							
1.	"Seolhyang"	480	580	670	740	680	470	390
2.	"Maehyang"	520	630	720	800	720	530	420
3.	"Santa"	390	490	540	610	440	270	220
4.	"Arihyang"	470	560	630	720	650	420	350
5.	"Keumsil"	510	600	710	780	700	500	410
	Vertical method (hydroponics)							
6.	"Seolhyang"	510	640	730	810	720	530	440
7.	"Maehyang"	550	670	750	830	740	550	430
8.	"Santa"	420	510	560	640	470	340	240
9.	"Arihyang"	500	580	640	750	660	440	370
10.	"Keumsil"	520	620	740	800	720	530	440
	2st period, 2017–2018							
	Suspended method (hydroponics)							
11.	Seolhyang”	450	730	940	880	690	500	340
12.	“Maehyang”	480	760	980	920	730	530	400
13.	“Santa”	360	660	700	620	500	300	200
14.	“Arihyang”	430	700	910	820	640	420	340
15.	“Keumsil”	460	730	960	900	680	500	340

	Vertical method (hydroponics)							
16.	"Seolhyang"	470	750	970	900	740	520	320
17.	"Maehyang"	510	780	1100	930	800	530	380
18.	"Santa"	390	690	720	650	530	280	180
19.	"Arihyang"	440	720	930	840	660	380	300
20.	"Keumsil"	480	760	980	890	680	400	340

Overall, strawberry plants cultivated using vertical hydroponic systems exhibited higher nitrate accumulation in leaf tissues compared to those grown in suspended systems. For instance, under vertical cultivation, the nitrate concentration in "Seolhyang" peaked at 810 ppm on day 120, followed by a decline to 440 ppm. "Maehyang" reached a maximum of 830 ppm before decreasing to 430 ppm. "Santa" peaked at 640 ppm and dropped to 240 ppm, while both "Arihyang" and "Keumsil" reached peak values between 750–800 ppm.

The slightly elevated nitrate levels observed under vertical systems may be attributed to differences in light exposure, microclimate conditions, and nutrient solution distribution. Among all cultivars, "Santa" consistently showed the lowest nitrate concentrations, indicating efficient nitrate utilization or uptake regulation.

In the second cultivation period, nitrate accumulation was notably higher across all systems compared to the first. For example, in the suspended system, "Seolhyang" increased from 450 ppm to 880 ppm by day 120, then declined to 340 ppm. "Maehyang" peaked at 920 ppm before dropping to 400 ppm. "Santa" ranged from 360 ppm to 620 ppm and declined to 200 ppm, while "Arihyang" and "Keumsil" reached between 820–900 ppm before reducing to approximately 340 ppm.

In the vertical hydroponic system, all strawberry cultivars exhibited higher maximum nitrate concentrations. "Seolhyang" reached up to 900 ppm, while "Maehyang" recorded the highest value at 1100 ppm. "Santa" peaked at 650 ppm, whereas "Arihyang" and "Keumsil" ranged between 840–890 ppm.

A comparative analysis of the two experimental periods indicated that nitrate accumulation was significantly greater in the second period. This increase is likely attributed to elevated ambient temperatures during the winter season, which influenced the physiological processes and metabolic activity of the plants. Higher temperatures impacted water and nutrient uptake efficiency, increasing plant stress and decreasing nitrate assimilation rates. As a result, nitrate accumulated in leaf tissues due to reduced nitrate reductase enzyme activity and slower nutrient cycling. Additionally, disruptions in the water–air balance within the substrate and partial inhibition of photosynthesis further contributed to this accumulation.

Key findings of the 2017–2018 study:

- ***Nitrate Dynamics:*** All strawberry cultivars showed increased leaf nitrate concentrations up to day 120, followed by a decline. Plants grown under vertical hydroponics accumulated more nitrates than those in suspended systems.

- ***Environmental Influence:*** Nitrate accumulation was significantly higher during the second planting period, likely due to elevated winter temperatures that induced plant stress and disrupted nutrient assimilation and metabolism.

- ***Cultivar Comparison:*** The "Santa" cultivar consistently recorded the lowest nitrate levels across all treatments, highlighting its potential as a low-nitrate, environmentally sustainable option.

- ***Highest Accumulator:*** The "Maehyang" cultivar showed the highest nitrate content during the second period, especially under vertical cultivation (up to 1100 ppm), influenced by light exposure and imbalances in substrate nutrient and water conditions.

Soluble Solids Content (°Brix) in Strawberry Fruits. The °Brix value is a key indicator of total soluble solids (TSS) in fruits and is commonly used to evaluate sweetness and overall fruit quality. In strawberries, TSS is predominantly composed of sugars—mainly sucrose, glucose, and fructose—which directly contribute to the fruit's sweet taste. However, other soluble compounds such as organic acids (e.g., citric, malic, tartaric), amino acids, phenolic compounds, and soluble pectin's also play a role in determining the °Brix value.

Although sugars account for approximately 75–80% of TSS in strawberries, the presence of non-sugar solutes may influence the °Brix reading, slightly altering perceived sweetness or flavor intensity. For instance, high organic acid concentrations can increase tartness and affect the sweetness-to-acidity balance, which is a critical component of consumer taste preferences.

The °Brix level is measured using a digital or optical refractometer, which detects the refractive index of the juice. This method is fast, non-destructive, and widely adopted in both research and commercial production settings.

Sindarov (2024) emphasizes that °Brix values vary significantly depending on cultivar genetics, ripening stage, cultivation system (e.g., hydroponic vs. soil-based), and environmental factors such as light exposure and temperature. Therefore, °Brix measurement is not only a practical quality control tool but also a valuable parameter in breeding and agronomic optimization programs.

Brix serves as a multifactorial indicator of fruit maturity, sugar content, and flavor potential. Regular monitoring of °Brix in strawberry fruits enables producers to determine the optimal harvest time, enhance marketability, and ensure consistent consumer satisfaction.

The experiment conducted between 2017 and 2020 assessed the quality of strawberry fruits using organoleptic characteristics such as fruit length, width, weight, sugar content (Brix), titratable acidity, and water content. These parameters varied significantly based on the planting time and cultivation method (suspended or vertical hydroponics).

Additionally, the presence of soluble amino acids was noted in the fruits; however, proteins were excluded from this category due to their insolubility. Other non-soluble compounds, including fats, minerals, alcohols, and flavonoids (such as Vitamins C and A), also contributed to the overall nutritional profile.

Regarding the physical characteristics of the fruit, fruit length and width were measured to evaluate size. The data revealed that strawberries from the "Arihyang" and "Seolhyang" cultivars, planted during the first planting period, were longer and wider compared to those planted in the second period. Specifically, fruits from the first planting period were generally larger, with a noticeable difference in size, particularly for the "Arihyang" and "Seolhyang" cultivars.

The longer vegetative growth phase of plants in the first planting period provided more resources for fruit development and complete ripening. In contrast, the shorter vegetative phase in the second period limited the ability of plants to grow larger fruits. For example, the "Arihyang" variety, planted in the first period, had an average fruit size of 5.6 × 4.1 cm, whereas fruits from the second period measured 5.4 × 4.0 cm, indicating a decrease of 0.2 cm in both dimensions (Figure 2).

This analysis confirms that planting time significantly influences the size of strawberries, with earlier planting periods leading to larger fruit sizes, likely due to a longer growing season and more optimal conditions for fruit development.

When analyzing the results based on fruit weight, the average weight was higher in the first planting period, with a slight decrease in the second period. This can be attributed to the longer feeding duration of strawberries planted in the first period, allowing for more complete development and larger fruit size. In contrast, the second planting period experienced a shorter vegetative growth stage, limiting the time available for nutrient accumulation, which resulted in a reduction in fruit weight. Other factors, such as variations in light, temperature, and nutrient availability between the two planting periods, also contributed to differences in fruit size.

For instance, the "Arihyang" cultivar had an average fruit weight of 35.7 g in the first period, compared to 35.3 g in the second period, showing a slight reduction of 0.4 g.

Regarding sugar content (°Brix), strawberries from the first planting period exhibited slightly higher sugar levels, reaching a maximum of 13.8 °Brix. In contrast, those from the second period had a slightly lower maximum of 13.6 °Brix. This difference can be explained by the longer exposure to sunlight during the first period, which enhanced photosynthesis and promoted a greater accumulation of sugars. On the other hand, the second period experienced shorter days with less sunlight, which led to a slower photosynthetic process and a reduction in sugar content. For example, the "Arihyang" cultivar recorded 13.8 °Brix in the first period and 13.6 °Brix in the second, reflecting a 0.2 °Brix decrease.

These results indicate that the first planting period, with its longer growing season, provided more favorable conditions for fruit development and sugar accumulation, while the second period was constrained by shorter days and less sunlight, leading to lower fruit weight and sugar content.

In terms of titratable acidity, the results revealed that strawberries from the first planting period had slightly higher acid content compared to those from the second period, which showed slightly lower acidity levels. Since acidity is closely linked to photosynthesis and metabolic activity, the longer fruit development period in the first planting phase likely provided more time for the synthesis of organic acids. The extended exposure to sunlight and the longer vegetative growth phase allowed for greater metabolic activity, contributing to higher levels of acidity.

Conversely, the second planting period had a shorter vegetative growth stage, leading to less photosynthetic activity and a reduced capacity for organic acid synthesis. As a result, the fruit in the second period had lower acidity. For instance, the "Seolhyang" cultivar exhibited a titratable acidity of 0.83% in the first period, which decreased to 0.82% in the second period, reflecting a small 0.01% drop.

This indicates that fruit development in the second period was more limited in terms of metabolic activity, particularly in the synthesis of organic acids, due to the shorter growth phase.

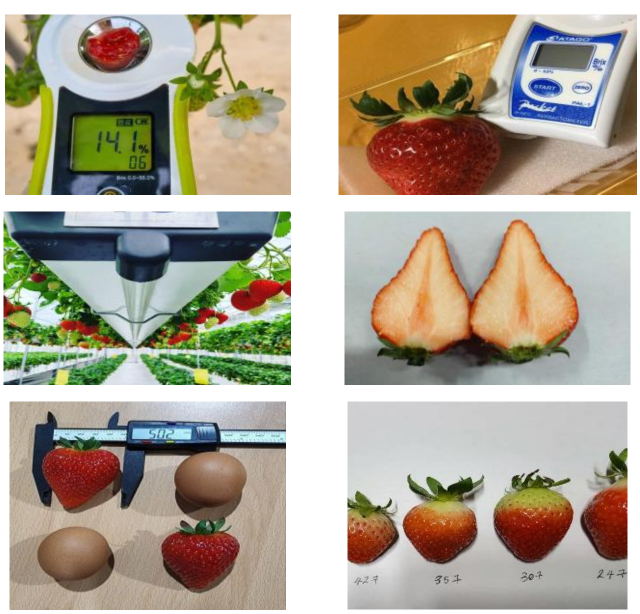

Figure 2. Determining the sugar content of strawberries using the ATAGO PR-101 digital refractometer and the internal appearance of the "Seolhyang" cultivar.

According to the analysis of water content, strawberries from the first planting period exhibited a higher percentage of water compared to those from the second period. This difference can be attributed to the better soil moisture conditions and enhanced water uptake during the first period, which contributed to higher water retention in the fruits.

In contrast, the second planting period experienced changes in the water distribution within the soil and hydroponic solution, coupled with a decrease in air temperature. These factors led to a slight reduction in water content in the fruits. For example, in the "Keumsil" cultivar, fruits from the first period had a water content of 87.8%, while those from the second period contained 87.4%, showing a decrease of 0.4%.

In the first planting period, under the suspended cultivation method, the "Arihyang" cultivar exhibited the highest fruit weight at 35.7 g, which was 7.1 g heavier than the "Seolhyang" cultivar, which weighed 28.6 g. Additionally, "Arihyang" had a higher sugar content, reaching 13.8 °Brix, compared to 13.1 °Brix in "Seolhyang". Although the "Santa" cultivar had a larger fruit shape, it had the lowest fruit weight at 25.1 g, along with a relatively low sugar content of 12.4 °Brix. The "Keumsil" cultivar was the smallest and least sweet, with a sugar level 0.6 °Brix lower than the others.

In comparison, "Arihyang" displayed superior quality, being both larger and sweeter, with 13.4 °Brix versus 12.7 °Brix in "Seolhyang". Meanwhile, "Santa" consistently showed the lowest values in both fruit weight and sugar content, while "Keumsil" remained the smallest and least sweet cultivar overall.

As a result of the scientific research conducted, we have come to the following conclusion:

1. Fruit Size and Weight Analysis:

- ***Findings:*** "Arihyang" showed the largest fruit size and weight across all cultivation methods and planting periods, with a recorded weight of 35.7g, significantly higher than other cultivars such as "Seolhyang" (28.6 g).

- ***Justification:*** The larger size and greater weight of "Arihyang" can be attributed to the longer vegetative period during the first planting period, which provides the plant with more time to accumulate nutrients and grow. Additionally, "Arihyang" likely has a genetically predisposed ability to produce larger fruits, which is further supported by favorable growing conditions in the hydroponic system.

- ***Implication:*** Larger fruits are often considered more desirable in the market due to their visual appeal and potential for higher yields per plant. Therefore, "Arihyang" is particularly valuable for commercial production.

2. Sugar Content (°Brix) Analysis:

- ***Findings:*** "Arihyang" exhibited the highest sugar content, with a °Brix value of 13.8 in the first planting period, compared to "Seolhyang" at 13.1 °Brix. "Santa" and "Keumsil" had the lowest sugar levels, with "Keumsil" showing a significant decrease in sweetness.

- ***Justification:*** The higher sugar content in "Arihyang" can be attributed to the extended exposure to sunlight during the first planting period, which enhances photosynthesis and sugar production. The shorter days and reduced light in the second planting period likely led to lower photosynthetic activity and thus less sugar accumulation.

- ***Implication:*** High sugar content is often associated with better taste and sweetness, making "Arihyang" and "Seolhyang" more desirable for fresh consumption and high-quality strawberry products, such as jams and juices.

3. Fruit Quality and Acidity (Titratable Acidity) Analysis:

- ***Findings:*** The titratable acidity was higher in the first planting period, particularly for "Arihyang" and "Seolhyang", which aligns with the longer fruit development period. "Keumsil" exhibited lower acidity.

- ***Justification:*** The longer growth period in the first planting period allows for more organic acids to accumulate in the fruits, contributing to higher acidity. In contrast, a shorter vegetative period in the second planting results in less acid synthesis.

- ***Implication:*** Acidity is a key component of the fruit's overall flavor profile, contributing to its balance between sweetness and tartness. Higher acidity, along with high sugar content, enhances the overall flavor, which is crucial for consumer preference.

4. Water Content Analysis:

- ***Findings:*** The water content in the fruits from the first planting period was higher, with "Keumsil" showing a slight reduction in water content in the second planting period.

- Justification: The higher water content in the first period is likely due to better soil moisture and the plant's ability to absorb water during a longer vegetative phase. The second planting period saw a decrease in water content, likely due to changes in water distribution in both the soil and the hydroponic system, as well as cooler temperatures that reduced water uptake.

- Implication: Water content impacts fruit texture and shelf life. Higher water content often leads to juicier, fresher strawberries, which are preferred for direct consumption.

5. Cultivar Performance Across Periods:

- Findings: All cultivars performed better in the first planting period compared to the second, which was likely due to the longer vegetative growth period, better light conditions, and greater nutrient availability.

- Justification: Longer periods of vegetative growth allow plants to better establish their root systems, take in more nutrients, and allocate more resources to fruit development. Shorter periods in the second planting limit these processes, which leads to smaller, less sweet, and less acidic fruits.

- Implication: This supports the recommendation to plant "Arihyang" or "Seolhyang" during the first planting period for optimal yield and quality. Early planting maximizes the plant's growth potential and fruit quality.

6. Summary of Key Factors Impacting Strawberry Quality:

- Planting Period: Longer growth periods lead to better fruit size, weight, sugar content, and acidity. The first planting period, with its extended vegetative phase, supports better overall fruit development.

- Cultivation Method: Hydroponic and suspended systems offer better control over water, nutrients, and environmental conditions, leading to superior fruit quality.

- Cultivar Selection: "Arihyang" and "Seolhyang" are more suited for high-quality production due to their larger size, higher sweetness, and better overall quality compared to "Santa" and "Keumsil", which are smaller and less sweet.

4. CONCLUSION:

The data analysis shows that the combination of planting period, cultivation method, and cultivar selection has a significant impact on the quality of strawberries. "Arihyang" performed best across all parameters, making it the most suitable cultivar for optimal strawberry production. "Seolhyang" also demonstrated excellent quality traits and should be considered as a secondary option for high-quality fruit production. For the best results, it is recommended to plant these cultivars during the first planting period to maximize fruit size, sweetness, and overall yield.

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