

## ABSTRACT

JONSON, JOY. Evaluation of Yield, Fruit Chemistry, and Firmness of Seven Strawberry (*Fragaria xananassa*) Cultivars and Four NCSU Advanced Strawberry Selections in an Eastern North Carolina Greenhouse. (Under the direction of Dr. Mark Hoffmann).

Strawberries (*Fragaria xananassa*) are an important fruit crop in the United States, generating over \$2 billion in annual revenue. Since the 1970s, virtually all strawberries in the US have been produced using annual hill plasticulture. However, challenges including the rising cost of labor and production, increasing pest and disease pressure, and climate change associated risks of unfavorable weather, as well as the opportunity to extend the harvest season into favorable winter markets has led to frequent exploration of alternative protected culture strawberry production in areas of the US, including North Carolina. One of these systems is tabletop greenhouse production, where strawberries are produced in soilless substrates in raised gutters. The transition to this system requires high up-front investment but could help mitigate the previously mentioned issues and potentially open non-accessible winter fruit markets for growers, especially in the southern US. The use of soilless media can also help minimize the risk of soil-borne pathogens. However, questions remain about the efficacy of different strawberry cultivars in this new production system in the southeastern US. Therefore, two studies were conducted to evaluate different strawberry cultivars and North Carolina State University advanced selections in a soilless greenhouse environment in Eastern North Carolina. The first study aimed to evaluate the growth, yield, postharvest chemistry and fruit firmness of seven strawberry cultivars (Albion, Brilliance, Camino Real, Fronteras, Monterey, Sensation, and Sweet Charlie) in a commercial tabletop greenhouse in eastern North Carolina over two growing seasons (2022-23 and 2023-24). In general, long-day (everbearing/day-neutral) cultivars Albion and Monterey produced higher yields than other cultivars in the winter, while the short-

day cultivars yielded the most in the early spring months. However, ‘Brilliance’ and ‘Sensation’ produced yield in both the winter and spring months. Additionally, ‘Brilliance’ showed high fruit firmness across both years, and high sweetness in one of the two years. This study confirms that ‘Albion’ is a quality choice as a standard greenhouse cultivar for growers in the southeastern US, due to consistent yields, good postharvest chemistry and firmness throughout seasons. However, this study also shows the cultivars Monterey, Brilliance and Sensation can perform well under greenhouse conditions. Those cultivars might become a reliable alternative for southeastern greenhouse strawberry growers in the future.

The second study assessed four advanced strawberry selections from the North Carolina State University (NCSU) breeding program and one standard control variety: ‘Albion,’ ‘NC 19-020,’ ‘NC 20-099,’ ‘NC 21-033,’ and ‘NC 22-004.’ The trial focused on plant growth, yield, primary postharvest chemistry, and fruit firmness. For plant growth measurements, ‘NC 20-099’ showed robust vegetative growth with the highest average number of crowns and foliar dry mass, but this did not correlate strongly with yield. ‘NC 19-020’ had the highest total marketable yield, producing more fruit than all other selections and ‘Albion.’ The selection NC 21-033 exhibited high postharvest quality traits, with the highest TA and brix content. For fruit firmness ‘NC 22-004’ demonstrated higher firmness than all other selections across all firmness metrics.

Understanding the performance and characteristics of these advanced selections is crucial for informing breeding decisions and guiding future research directions. By clarifying the various growth and production characteristics of each advanced selection, we contribute valuable insights to the ongoing efforts aimed at developing resilient, high-yielding, and flavorful strawberry cultivars for North Carolina growers.

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Evaluation of Yield, Fruit Chemistry, and Firmness of Seven Strawberry (*Fragaria xananassa*)  
Cultivars and Four NCSU Advanced Strawberry Selections in an Eastern North Carolina  
Greenhouse

by  
Joy Johnson

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## **DEDICATION**

To my parents, Marvin and Lisa Johnson, for their continual support and guidance.

## **BIOGRAPHY**

Joy Johnson grew up on a potato farm in Amble, Michigan. She attended Michigan State University, where she pursued a bachelor's degree in Horticulture with minors in Plant Biotechnology and Beverage Science. During her time at MSU, she worked with the Potato Breeding and Genetics Program and in the Hollender Tree Fruit Physiology Lab. She also served as president of the MSU Student Horticulture Association from 2021 to 2022. Joy graduated from MSU in May 2022. She began her M.S. in Horticultural Science at North Carolina State University in August 2022, also pursuing a minor in Food Science.

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# CHAPTER 1

## Literature Review on Strawberry (*Fragaria xananassa*)

### Greenhouse Industry and Cultivar Evaluations

#### Strawberry (*Fragaria xananassa*) Physiology

The modern cultivated strawberry, *Fragaria xananassa*, is a hybrid of two *Fragaria* species: *Fragaria chiloensis* and *Fragaria virginiana*. This hybrid was first observed in France in the late 18th century and described in detail by Antoine Nicholas Duchesne in 1776 in his book *Histoire naturelle des fraises* (Galletta & Himelrick, 1990). Historical and modern breeding programs have led to the development of hundreds of cultivated varieties, or cultivars, within the *Fragaria xananassa* species. Strawberries can be divided into two main categories: seasonal flowering and perpetual flowering. Short-day cultivars are among the seasonal-flowering varieties, colloquially referred to as “June-bearing.” Day-neutral cultivars fall within the perpetual flowering category and are often called “everbearing” varieties (Heide et al., 2013); in this manuscript, they are referred to as “long-day” plants due to their observed relationship between photoperiod and flowering response.

The short-day response in strawberries is facultative; at temperatures below 16°C (60°F), short-day plants will continue to produce flower buds under long-day conditions (Durner et al., 1984). Cultivars classified as long-day also exhibit facultative tendencies. Although short days do not entirely inhibit flower production in long-day plants, more flowers are produced under long-day conditions. However, this relationship is influenced by temperature; at temperatures under 16°C, long-day plants continue to produce flowers under short-day conditions, making them behave similarly to day-neutral plants. Cultivars that are considered day-neutral produce flowers under any photoperiod, but this relationship is also influenced by temperature. In higher

temperatures, day-neutral plants typically produce more flowers under long-day conditions (Durner et al., 1984).

Strawberry plants are also well-known for their asexual method of propagation. Strawberry “mother” plants produce aerial stolons known as “runners,” which bear many genetically identical “daughter” plants, allowing for easy propagation. This method is utilized in strawberry nurseries, where plants are asexually propagated for the annual production of fruiting fields. For strawberry fruit growers, runnering is considered undesirable as it is a waste of the plant’s phytonutrients into non-fruit-producing structures (Albregts & Howard, 1986). For short-day strawberry cultivars, runnering is encouraged by long-day conditions and hot temperatures (conditions not conducive to flower production). For long-day cultivars, high temperatures combined with a long photoperiod promote flowering *and* runnering; however, high temperatures and a short photoperiod mainly promote runnering (Durner et al., 1984).

### **Strawberry Production and Industry in North Carolina**

In the United States, the primary strawberry production regions are California and Florida (Samtani et al., 2019). Although North Carolina produces a comparatively small percentage of the nation’s strawberries, the industry remains highly relevant to local agriculture and the state economy. In 2018, the USDA reported that strawberries contributed approximately \$21.4 million to the North Carolina economy (USDA NASS, 2022). The majority of strawberry farms in North Carolina are small-scale farms that market directly to consumers through roadside stands, farmers’ markets’, and pick-your-own locations (Samtani et al., 2019).

Most strawberry production in North Carolina utilizes the annual hill plasticulture method (Samtani et al., 2019). Annual hill plasticulture gained popularity for several commodities like tomato (*Solanum lycopersicum*), bell pepper (*Capsicum annuum*), melon

(*Cucumis melo*), and strawberry (*Fragaria ×ananassa*) in the 1970s. This method offers advantages like weed control, higher yields, and a shorter production period for these high-value crops (Locascio, 2005). However, it also has drawbacks, such as higher input costs – for plastic, drip irrigation, and annual plant purchases – and the need for more intensive management compared to the traditional perennial matted row system. These disadvantages became justified, and production began moving toward annual hill plasticulture in North Carolina in the late 1990s with new research and the development of new, more productive cultivars like ‘Chandler’ and ‘Camarosa’ (Poling & Durner, 1986; Hoffmann et al., 2024).

The annual hill plasticulture method involves preparing the field site with raised beds covered with plastic mulch. Growers then plant either plug plants, which are rooted “tips” (daughter plants), or bare-root plants in the plastic-mulched bed in the early fall. The plants are established in the field for a few months before going dormant over the winter. During this period, row covers are often employed to protect the plants from frost damage, and they have also been shown to improve the yields of some cultivars. As temperatures begin to rise, the plants begin to grow again and start flowering in the late winter to early Spring; harvesting typically begins in April and lasts into May, but more extended harvest periods can be achieved by staggering early- and late-fruiting cultivars (Hoffmann et al., 2024).

Strawberry growers face numerous challenges with this production system. Using row covers for frost protection can be expensive and time-consuming. Soil-borne pathogens like *Phytophthora cactorum* (crown rot) and *Fusarium spp.* are significant issues in the field (Hoffmann et al., 2024; Williamson et al., 2012). Several other pathogens are prevalent too, such as *neopestalotiopsis* (pestalotia leaf spot and fruit rot), *Botrytis cineraria* (gray mold), and *Colletotrichum acutatum* (anthracnose crown and fruit rot) (Baggio et al., 2023; Hoffmann et al.,

2024; Poling, 2008). Additionally, factors like extreme weather events - heavy spring rains and hail - and the rising cost of labor present further challenges for growers in the East Coast region (Samtani et al., 2019).

### **Alternative Production Systems**

Most strawberry production in the United States takes place outdoors using the annual hill plasticulture system, but using alternative production methods, like soilless tabletops, high tunnels, and greenhouses, is an emerging industry in North America (Fessler et al. 2023; Samtani et al., 2019). This growing industry mirrors broader trends in agriculture where controlled environment agriculture (CEA) has successfully enhanced production stability for crops like tomatoes (*Solanum lycopersicum*), cucumbers (*Cucumis sativus*), and leafy greens and has prompted researchers to explore similar applications for strawberries (Cantliffe et al., 2007; Kroggel & Kubota, 2017)

Moreover, greenhouse production is prevalent in other areas of the world. In Asia, countries such as South Korea, China, and Japan produce a lot of greenhouse strawberries. In those regions, it is viewed that controlled environment production not only allows for an extended production season but also ensures locally available, high-quality fresh fruit (Ahn et al., 2021; Feng et al., 2019). In Northern Europe, countries such as the Netherlands, Belgium, and parts of Scandinavia have a significant amount of strawberry production in greenhouses (Van Delm et al., 2016; Fruit Logistica, 2021). The controlled environment of the greenhouse allows for an extended growing season and niche local markets despite the cold climate in these regions. This trend is also developing in the northern areas of North America, such as the Northern U.S. and Canada (Samtani et al., 2019).

Some advantages of alternative production systems include increased sustainability, production stability, and improved fruit quality. Sustainability not only encompasses environmental concerns but also addresses economic and social issues. Studies have shown that tabletop production uses less plastic and is less labor-intensive than annual hill plasticulture, contributing to both aspects of environmental and social sustainability (Fessler et al., 2023). Soilless media is also less reliant on chemical fumigation, which is commonly practiced for annual hill plasticulture (Fennimore et al., 2013). Hydroponic systems are also able to more closely monitor water and chemical fertilizer applications compared to open-field production (Hernández-Martínez et al., 2023). Additionally, alternative production systems can help growers achieve more consistent yields throughout the season and from year to year, increasing production stability and economic sustainability (Demchak, 2009). Some studies have also shown that strawberries produced in soilless media have better fruit quality traits than when grown in soil (Cecatto et al., 2013; Qiu et al., 2023).

Season extension is also a significant draw for growers considering investing in alternative production methods. Fessler et al. (2023) demonstrated that combining the use of long-day cultivars with soilless tabletop production outdoors could extend the harvest season in Minnesota by approximately 15 weeks. Another study that was conducted in Nebraska showed that both short- and long-day cultivars could produce flowers and fruit over the cold winter months when grown in a temperature-controlled greenhouse with no supplemental lighting. Additionally, Guan et al. (2022) showed that using high tunnels in southern Indiana could extend the harvest season, with yields beginning four to six weeks before open-field strawberries. A study by Takeda and Hokanson (2003) found that the best method for obtaining out-of-season yields was to use “frigo” (cold-treated bare-root plants) plants in the greenhouse for over-winter

production. In North Carolina, Gu et al. (2017) showed that when using high tunnel production, long-day strawberry cultivars could produce fruit as early as November, and short-day cultivars yielded fruit in December – both are several months ahead of open-field production in the region.

There is a growing interest in protected culture (greenhouse and high tunnel) strawberry production in the U.S. Despite the other advantages described above, this trend is primarily driven by an increasing consumer preference for local markets (Kroggel & Kubota, 2017). Studies have shown the importance consumers place on local produce, which ranks higher than factors like price and pesticide use (Hinson & Bruchhaus, 2008). Moreover, consumption of strawberries in the United States has seen a dramatic increase within the last 30-40 years, increasing from around 2 pounds per person in 1980 to about 8 pounds per person in 2013 (USDA ERS, 2014). Additionally, obstacles such as fumigation, high land costs, limited land availability near urban markets, adverse environmental conditions, difficulties with pests and diseases, a shortage of labor, and unpredictable weather patterns are factors that may drive growers toward alternative production methods. With mounting challenges to outdoor production, an increasing preference for locally grown produce, and an increase in overall consumption of strawberries, there is undoubtedly a capacity for small-scale, localized farms to supplement the primary production areas of the U.S. (Samtani et al., 2019).

The term “protected culture” describes a wide variety of production systems, from simple high-tunnel structures to very high-tech glass greenhouses. High tunnels are among the most common types of greenhouse structures used for strawberry production due to their cost-effectiveness, ease of construction, and ability to provide protection from the environment (Demchak, 2009). However, there are more high-tech greenhouses used for strawberry

production, too. In high tunnels, it is common for strawberries to be planted in the ground using either the annual hill plasticulture method or the perennial matted row system. However, there are also areas where it is common to use tabletop production, even in simple, high-tunnel structures or entirely outdoors (Fessler et al., 2023).

For systems that use tabletop production, soilless media is typically used for the growing substrate. In Europe, soilless cultivation commonly utilizes “grow bags” (enclosed polyethylene bags with drainage holes) filled with coconut coir, peat, or other soilless substrates (Lieten et al., 2004). Fessler et al. (2023) showed that the type of soilless media used for cultivation had a significant role in the overall yield of an outdoor tabletop production system; the study results showed that a peat-and-perlite mix led to the highest yields. Despite these findings, coconut coir grow bags have become the predominant substrate for indoor strawberry cultivation in North America due to the cost, convenience of storage, shipping, and containment (pers. communication Austin Wrenn, FreshPik Produce; Greg France, California Giant Farms). Overall, organic substrates are favored for their cost-effectiveness, biodegradability, and high productivity potential (Depardieu et al., 2016).

Numerous research efforts have helped to clarify the best production practices for protected culture strawberry production, which is essential for establishing this growing industry. Kroggel and Kubota (2017) investigated strategies for mitigating tipburn – a calcium deficiency disorder – in greenhouse strawberry plants. The researchers found that maintaining a nighttime humidity  $\geq 95\%$  was sufficient for tipburn prevention, and this could be accomplished by intermittent misting or using plastic coverings on the plants. Several studies have also investigated using advanced techniques like LED lighting and CO<sub>2</sub> supplementation to increase yields in the greenhouse. Diaz-Galian et al. (2021) examined the effects of using LED lighting to

increase flowering in the greenhouse. The experiment used treatments with different spectra and intensities and showed that LEDs could be used to effectively extend the day length in the greenhouse, resulting in up to a 300% increase in flowering. Another study by Qiu et al. (2023) investigated the effects of elevated CO<sub>2</sub> and supplemental LED lighting on greenhouse strawberries. The results of the study showed that elevated CO<sub>2</sub> alone increased yield by 23.4% and supplemental LED lighting alone improved yield by 21.46%; when combined, CO<sub>2</sub> plus LED supplementation resulted in a significant yield increase of 51.3%. Moreover, Takeda et al. (2003) highlighted that extending flower removal until mid-October for winter greenhouse fruit production could increase average fruit size and overall yield.

### **Cultivar Evaluation in Greenhouse Production**

The timing of flowering plays a critical role in strawberry production and is primarily influenced by temperature and photoperiod during crown development. To understand how short- and long-day strawberry plants perform in a greenhouse at a specific location, cultivar evaluation experiments in on-farm, greenhouse settings are essential to determine the reproductive habits of these cultivars for greenhouse production (Garcia & Kubota, 2017). For instance, research by Zahedi et al. (2023) revealed significant variations in drought stress responses between the cultivars ‘Camarosa’ and ‘Gaviota’ when grown in a greenhouse, highlighting the critical nature of selecting cultivars based on specific environmental stresses.

There are three primary public strawberry breeding programs in the U.S., which are located at the University of California, Davis (UC Davis), the University of Florida (UF), and the USDA; there are also smaller public breeding programs at other universities such as North Carolina State University (NCSU), Cornell University, etc. as well as private, industry breeding programs such as California Strawberry Cultivars™ and Plant Science Inc. (PSI). These

programs are focused on enhancing various aspects of strawberry cultivars, including yield, fruit quality attributes, disease resistance, nutritional content, flavor, and cold tolerance (Capocasa et al., 2008; Iezzoni et al., 2020; Karci et al., 2023). However, with so many different traits to consider, breeding programs tend to focus the most efforts on developing what their stakeholders are the most interested in; therefore, the cultivars developed at these programs are often most suited to field production of their local environments.

For example, strawberry cultivars developed at UF often face challenges when cultivated in regions like North Carolina due to their minimal chilling requirements, which cause the plants to flower continuously throughout the winter, subsequently being negatively affected by the sublethal winter temperatures. Although day-neutral cultivars like ‘Albion,’ which was developed at UC Davis, have shown value in the Southeastern region, their full yield potential is typically hindered by the hot summer’s characteristic of that area (Samtani et al., 2019). However, greenhouse conditions are vastly different from outdoor conditions, meaning there is the possibility that cultivars which are not well-suited for field production in North Carolina, may be suitable for greenhouse production. The necessity of matching cultivar characteristics with environmental conditions is a concept supported by the findings of Cecatto et al. (2013), who reported that some cultivars had higher yields when grown in soil. However, others like ‘Camarosa’, ‘Florida Festival’, and ‘Portola’ had higher yields when grown in soilless media in the same high tunnel environment.

Most CEA strawberry producers in the U.S. prefer cultivars considered day-neutral to ensure that flower initiation is not solely reliant on day length. Consequently, cultivars like ‘Albion’ and ‘Monterey’ are often chosen for greenhouse cultivation due to their day-neutrality and acceptable flavor (Samtani et al., 2019). Studies have shown that other day-neutral cultivars

such as ‘San Andreas’, ‘Chandler’, and ‘Benicia’ can also perform well in protected culture environments (Guan et al., 2022; Gu et al., 2017). An experiment conducted to evaluate the feasibility of winter strawberry production in a temperature-controlled greenhouse found that ‘Portola’ was a top-yielding cultivar, and ‘Evie-2’ and ‘Seascape’ also had adequate yields (Paparozzi et al., 2018). However, short-day strawberry varieties may offer other advantages, like simultaneous fruit production and better flavor qualities (Lewers et al., 2020). Additionally, cultivars which are considered short-day, but with low-chill requirements, may perform well in the warm environment of a greenhouse. For example, Gu et al. (2017) found that when using a high tunnel production system, the cultivars ‘Florida Radiance’, and ‘Winterstar’, showed high yield potential. These studies underscore the importance of trialing different types of strawberry cultivars to understand their regional performance in alternative production methods.

### **Fruit Quality Parameters**

In “The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks,” the USDA defines a high-quality strawberry as uniformly red, firm, flavorful, and free of defects and disease (USDA 2016). Numerous physical and chemical factors, including appearance, texture, aroma, and taste, impact the flavor of strawberries. A strawberry’s taste is composed of many organic acids and sugars. However, most studies emphasize the significance of three primary flavor components, which are pH, titratable acidity (T.A.), and total soluble solids content (SSC), also known as “brix.” These flavor components are influenced by various pre-harvest and postharvest conditions, such as cultivar, production season, cultivation method, nutrient supply, and storage conditions, as highlighted by Chandra et al. (2015).

Strawberry fruit is non-climacteric, meaning that it will not continue to ripen after being harvested from the plant. As such, the level of ripeness at harvest is one of the most influential

factors affecting the postharvest quality of the fruit; once harvested, the fruit quality will begin to decline (USDA ARS, 2016). In controlled environments, maintaining optimal conditions, such as elevated CO<sub>2</sub> levels and supplementary LED lighting, can enhance quality traits like SSC and phenolic content (Qiu et al., 2023). Additionally, Cecatto et al. (2013) reported that strawberries grown in soilless media within high tunnels exhibited improved fruit quality traits such as SSC and T.A. when compared to those grown in soil in the same environment, which suggests that the choice of substrate can significantly impact fruit quality.

Another critical aspect of the postharvest quality of strawberry fruit is firmness. The firmness of strawberry fruit is crucial not only for its relationship to flavor perception but also for the fruit's ability to withstand transportation. Soft fruits are prone to significant losses from physical damage during shipping. The same factors mentioned previously that affect the flavor characteristics of strawberry fruit also influence the fruit firmness (cultivar, maturity level, temperature, storage conditions) (Chandra et al., 2015). Methods used to measure the firmness of strawberry fruit vary widely across studies, but most studies use a method of penetration testing, which is also recommended by the USDA (USDA ARS, 2016). Guan et al. (2022) found that firmness varied widely among cultivars and across production seasons in a high tunnel system, identifying 'Chandler' as a softer variety compared to more firm varieties like 'San Andreas', 'Florida Radiance', 'Camino Real', and 'Sweet Sensation'.

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## CHAPTER 2

# Evaluation of Yield, Fruit Chemistry, and Firmness of Seven Strawberry (*Fragaria xananassa*) Cultivars in an Eastern North Carolina Greenhouse

### Introduction

Strawberries (*Fragaria xananassa*) contribute more than \$2 billion to annual farm gate revenue in the US (USDA ERS, 2023). The majority of commercial strawberry fruit production in the US relies on the annual hill plasticulture system, with primary production areas located in California and Florida (Holmes, 2024; Samtani et al. 2019). Although North Carolina accounts for less than 1% of the national strawberry industry, strawberry production remains vital to local agriculture and the state economy. In 2018, the USDA reported a farm-gate value of \$21.4 million for the North Carolina strawberry industry (USDA NASS, 2023). The majority of strawberry farms in North Carolina are 1 to 10 acres and primarily sell to local fresh markets, including pick-your-own operations, roadside stands, and farmers' markets (McWhirt et al. 2015; Samtani et al. 2019, Hoffmann et al. 2024).

Despite the popularity and economic impact of locally grown fruit, strawberry growers face challenges such as the rising cost of supplies and labor. In the southeastern US, those challenges are combined with high pest and disease pressure, and a high frequency of undesirable weather events such as frosts and heavy rain falls (Morton, et al. 2017; Samtani et al. 2019, Hoffmann et al. 2024). In addition to these challenges, the demand for strawberry fruit is increasing, and at the same time, consumers are more interested in locally grown produce (USDA ERS, 2023; Hinson and Bruchhaus, 2008). During the winter months, strawberries are

often transported long distances to reach the North Carolina market (USDA NASS, 2022). Given that North Carolina strawberry growers mainly serve local fresh markets, there exists a niche for locally produced winter strawberries.

Extending the typical strawberry season (approx. March to June, in the Southeast) into more profitable winter markets (November to January) has long been a goal of the regional industry. Methods such as planting long-day cultivars for fall production, using low- and high tunnel structures, and employing floating row covers have been investigated and are currently employed by some farmers as means of season extension in North Carolina (Fernandez and Ballington 2003; Ballington et al. 2008; Poling, 2011).

Soilless greenhouse strawberry production is viewed by some in the industry as a potential future production method to reach niche markets at higher price points during the winter months. This notion is supported by consumer acceptance of greenhouse-grown produce (Yue et al. 2011; Caputo 2023). Greenhouse production also avoids climate and disease challenges that come with traditional strawberry production. However, there is a high barrier to entry for growers interested in greenhouse production. Greenhouse production requires significant upfront investment into infrastructure and materials (Savvas et al. 2018). In addition, growing strawberries in soilless substrates in a greenhouse requires a different technical skill set than traditional production (Sabatino, 2020), particularly in areas such as irrigation, fertilization, maintenance, and pest management.

One core component of transitioning to greenhouse strawberry production is understanding cultivar performance in a greenhouse setting. Cultivar availability and consumer acceptance dictate cultivar choices. In the US, there is little information available on cultivar performance in soilless greenhouse environments, which presents a challenge to the industry.

Currently, growers mostly rely on anecdotal knowledge to make cultivar decisions and mainly utilize the long-day (everbearing/day-neutral) cultivar Albion. However, due to the comparatively low yield capacity of ‘Albion’, other cultivars such as those with low chill requirements or early flowering habits could be more favorable in a greenhouse setting in the Southeast. Therefore, the objective of this two-year study was to evaluate the performance of seven strawberry cultivars – Albion, Brilliance (Florida Brilliance®), Camino Real, Fronteras, Monterey, Sweet Sensation® (‘Florida127’), and Sweet Charlie – in a commercial soilless tabletop greenhouse in eastern North Carolina.

The cultivars Albion, Camino Real, Fronteras, and Monterey were developed at the University of California, Davis (UC Davis) and released between 2001 and 2014. ‘Albion’ and ‘Monterey’ were developed especially for the long days and mild conditions at the California Central Coast. Those are long-day cultivars recognized for their capability to continuously produce fruit under long-day conditions. Both cultivars have large fruit size and firm fruit. ‘Albion’ is typically recognized for better flavor attributes, while ‘Monterey’ has higher yield potential in California production fields. ‘Camino Real’ (2001) and ‘Fronteras’ (2014) are short-day cultivars known for their disease resistance and predominately bred for Southern California production cycles. Both have large firm fruit and are high yielding. The cultivars Brilliance, Sweet Sensation, and Sweet Charlie were developed at the University of Florida for Florida production systems. They are short-day cultivars with low-chilling requirements. ‘Brilliance’ and ‘Sweet Sensation’ are newer releases from 2017 and 2013, respectively, and have large fruit size, firm fruit, excellent flavor attributes, and high yield potential in Florida production systems. ‘Sweet Charlie’ was released in 1992 and is known for its early fruit production and consistently sweet fruit, with predominately smaller and softer fruit and lower yield potential (Table 1.1).

In addition to being photoperiod dependent, strawberry flowering is also temperature dependent. Long-day cultivars will continue to induce flowers under short photoperiod conditions if the temperatures remain warm (Darnell et al., 2003). Short-day cultivars, however, are able to produce flowers under long-day conditions if temperatures remain cool. Therefore, we hypothesized that long-day cultivars can extend fruit production into the winter, and short-day cultivars can improve fruit production in the early spring in a North Carolina Greenhouse.

## **Materials and Methods**

### **Location and Trial Design**

The experiment was conducted in a randomized complete block design (4 replicates per cultivar, 16 plants per replicate), using a commercial strawberry greenhouse in Wilson, NC (35.708648, -78.051865) over the course of two production seasons; the first trial season took place from 28 Sep 2022 to 22 May 2023 (236 days), and the second trial season was from 23 Sep 2023 to 2 May 2024 (222 days). The greenhouse was a double polyethylene covered house with roll-up sides for cooling and ventilation and fans and heaters available for further environmental controls (Figure 1). The greenhouse did not feature supplemental lighting but did include incandescent lights suitable for night-interruption. The plants were grown in raised gutters (tabletop system). Four rows of the greenhouse were used, with each row representing a block, and each block contained all seven cultivars (n= 16 plants per replicate, 64 plants per cultivar).

### **Planting Material**

The strawberry cultivars used in this trial were ‘Albion’, ‘Brilliance’, ‘Camino Real’, ‘Fronteras’, ‘Monterey’, ‘Sweet Sensation’, and ‘Sweet Charlie’ (Table 1.1, Figure 2). The plants were received as unrooted daughter plants from Balamore Farm Ltd in Nova Scotia, Canada, and were propagated in 50 cell trays containing an all-purpose media (BM6, Berger, Saint-Modeste,

Quebec). Daughter plants were rooted outdoors with overhead sprinkler irrigation, following grower standard practices. After 23 days of establishment, rooted daughter plants were transplanted into the trial (28 Sep 2022 and 23 Sep 2023). Only plants with fully established root balls, three to five leaves, and which fell within a specific crown diameter range were used (Table 1.2). The rooted daughter plants were transplanted directly into plastic grow bags (Precision Plus Ultra ©, Botanicair Ltd, London, UK), and the bags were located in raised gutters (Haygrove Ltd, UK) that were approximately one meter from the ground.

### **Environmental and Growing Conditions**

Temperature conditions were recorded throughout the season (Elitech RC-5 USB Temperature Data Logger, Elitech Technology Inc., San Jose, CA). The temperature loggers were protected from direct solar radiation by aspirated plastic shade covers and ten of them were distributed throughout the trial area and maintained at canopy height. To track light intensity, two sensors (HOBO MX2202 Pendant Data Logger, Onset, Bourne, MA) were placed at canopy height. Light intensity was recorded in lux (0 to 167,731 lux,  $\pm 10\%$  typical for direct sunlight); the lux measurements were converted to PPFD (photosynthetic photon flux density) using the equations described by Thimijan and Heins (1983), then converted to DLI (daily light integral) (CABA, 2023). The collaborating grower conducted irrigation, fertility, pest, and disease management according to commercial standards (Table 1.3).

### **Plant Growth and Development**

In both seasons (2022-2023; 2023-2024), the crown diameter was measured monthly for the first five months of the trial period (September – January) using an electronic caliper (IP54 Electronic Measuring Tool, Housolution, US). Initially, crown diameter was measured on the solitary primary crown. As plants developed multiple crowns, the total number of crowns was

recorded, and the diameter of the largest visible crown was measured. At the end of the season, a sample of six plants was collected from each replicate for destructive data collection. The selected plants were snapped off at the base of the crowns, and the number of crowns and crown diameter of the largest crown were recorded. Any fruit, including green fruit, was removed from the plants, and the whole plant was placed in a large brown paper bag. The bags were transported to the North Carolina State University Horticulture Field Lab and put in a large drying oven at 75°C for four days, and then their total foliar dry mass was recorded.

Additionally, the number of flowers per plant was recorded weekly for six weeks following the start of blooming. In the 2022-2023 season, the number of flowers was taken from 16 November 2022 to 20 December 2022, and in the 2023-2023 season, it was collected from 30 October 2023 to 6 December 2023. Runners were removed as needed and their count was recorded during both seasons. The number of leaves and leaf length was recorded once per month for the 2022-23 season only. From October 2022 to February 2023, the total number of leaves was counted, and the longest leaf was measured from the base of the leaf at the crown to the tip of the central leaflet.

### **Components of Yield**

Marketable and non-marketable fruit were harvested for each replicate once or twice per week, depending on season specific grower practices. The total mass of marketable yield and non-marketable yield was measured in grams using a portable scale (Cruiser Bench Counting Scales-CCT 32, Adam Equipment, Kingston, UK), and the total number of marketable fruits was counted in order to calculate average fruit size. Fruits were categorized as marketable or non-marketable depending on quality factors like size, shape, color, maturity, and disease presence. Non-marketable fruits included those under ten grams, misshapen, over-, or under-ripe, or

diseased (USDA AMS, 2006). During the 2022-23 season, harvesting began during week 48 (2 December) of 2022 and continued until week 21 (22 May) of 2023, with a total of 29 harvests. For the 2023-24 season, harvesting began during week 48 (1 December) of 2023 and continued until week 18 (2 May) of 2024 with 25 total harvests. Due to very low yields during May in 2023, the second season of the trial was terminated on 2 May 2024.

### **Primary Fruit Chemistry**

In both seasons and for each replicate, up to 10 representative fruits were collected weekly. After removing the calyxes, the fruit was crushed inside sealable plastic bags. The crushed fruit was then placed in a freezer at (-20°C) for eight days. Following the freezing period, the fruit was allowed to thaw at room temperature for several hours. Once sufficiently thawed, the fruit juice was filtered and collected in beakers. The pH of the juice was measured using a pH meter (PC800 pH/Conductivity Meter, APERA instruments, Columbus, Ohio) and collected by submerging the pH probe in the filtered fruit juice. Total soluble solids (TSS, brix) and total acidity ( $T_{\text{acid}}$ ) were measured using a digital brix-acidity meter (Pocket Brix-Acidity Meter, ATAGO USA Inc., Bellevue, Washington). TSS content was measured by placing two to four drops of the filtered fruit juice on the brix-acidity meter to cover the prism, and the  $T_{\text{acid}}$  was measured by diluting one milliliter of the fruit juice in 50 milliliters of deionized (DI) water and then placing a two to four drops of the solution onto the brix-acidity meter to cover the prism.

### **Fruit Firmness**

Fruit firmness was evaluated in the 2023-24 season using a texture analyzer (TA.XTPlus Connect, Hamilton, MA) with a 2mm (TA.52) puncture probe. Up to 10 representative fruits from each replicate were evaluated every week from week 2 (8 January) to week 18 (29 April) of 2024. Individual fruits were cut longitudinally (from calyx to tip), and one-half of the fruit was

placed on the instrument platform with the cut side down. The fruit was lined up so that the broad section of the fruit was in line with the probe. The force required to puncture the outside of the fruit was recorded as the “first peak force” (FPF), the force required to puncture through the inner layer of the fruit flesh was recorded as the “second peak force” (SPF) and the overall force required to puncture the whole fruit was recorded as the “total force” (TF) (Figure 3).

## **Data Analysis**

Environmental data were managed using Google Sheets (Google, LLC, Mountain View, CA, USA), and graphs in Figure 4 were created using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). All other data were analyzed using a one-way ANOVA ( $\alpha \leq 0.05$ ) performed in Rstudio (Rstudio Desktop ver. 2023.06.16, Boston, MA, USA), followed by a post-hoc Tukey’s honestly significant difference (HSD) where appropriate ( $\alpha \leq 0.05$ ). Data were analyzed separately for the two seasons. Prior to data analysis, the fruit firmness data was gathered using a macro developed for Exponent software in collaboration with Texture Technologies (Texture Technologies Corp. and Stable Micro Systems, Ltd., Hamilton, MA).

## **Results**

### **Yield**

For the 2022-23 season, the cultivar with the highest marketable yield at the end of the production period was ‘Sweet Sensation’ which produced 731.0 g/plant. During weeks 48 and 49 of 2022 (2 and 9 December), ‘Monterey’ produced significantly more marketable fruit than all cultivars. During week 50 of 2022 (16 December), ‘Albion’ and ‘Monterey’ both produced more marketable fruit than all other cultivars, and ‘Sweet Charlie’ produced significantly more fruit than all other cultivars during week 21 of 2023 (22 May) (Table 1.6, Figure 4, Table A1). All cultivars had low to moderate yields from week 48 of 2022 (9 December) to about week 11 of

2023 (13 March). However, by week 13 of 2023 (27 March) yields began to increase across all cultivars and peaked during weeks 14 to 17 (3 to 24 April). ‘Sweet Sensation’ had the largest average fruit (20.5 g), and all cultivars had significantly larger fruit than ‘Sweet Charlie’ (11.4 g).

In the 2023-24 season, yields ranged from 277.2 g/plant (‘Camino Real’) to 476.1 g/plant (‘Monterey’). ‘Albion’ produced significantly more marketable fruit than all other cultivars during week 48 of 2023 (1 December). During week 50 and 51 of 2023 (15 and 22 December), ‘Brilliance’ produced significantly more marketable fruit than all other cultivars. All cultivars had low to moderate yields from week 48 of 2023 (1 December) to week 8 of 2024 (19 February). However, by week 9 of 2024 (26 February), marketable yield increased across all cultivars and peaked during week 9 to week 13 of 2024 (25 March) (Table 1.6, Figure 4, Table A1). ‘Fronteras’ had the largest average fruit (33.4 g), significantly larger than all cultivars except ‘Sweet Sensation’ (30.6) (Table 1.6).

## **Environmental Conditions**

### *Light and Temperature*

January was the coldest month during both production seasons, with an average temperature inside the greenhouse of  $9.5^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$  in 2023 and  $12.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$  in 2024. The lowest average minimum temperature observed inside the greenhouse during the 2022-23 season was  $8^{\circ}\text{C}$  (2 and 9 January 2023), and during the 2023-2024 season, it was  $9.1^{\circ}\text{C}$  (25 December 2023). The highest average maximum temperature for the 2022-23 season was  $23.6^{\circ}\text{C}$  (8 May 2023); during the 2023-24 season, it was  $23.1^{\circ}\text{C}$  (29 April 2024). The highest average DLI inside the greenhouse was recorded during week 15 of 2023 ( $26.8 \text{ mol/m}^2/\text{d}$ ) and week 16 of 2024 ( $25.0 \text{ mol/m}^2/\text{d}$ ) (Table 1.4).

## **Plant Growth and Development**

### *Crown Diameter and Number*

For the 2022-23 season, ‘Monterey’ had the largest average crown diameter initially, measuring 14.2 millimeters. By the end of the season (EOS), however, ‘Camino Real’ (20.5 mm) had the largest crown diameter and ‘Sweet Charlie’ (18.5 mm) was the smallest. Additionally, ‘Albion’ (3.0) had a significantly lower average number of crowns at EOS than all cultivars other than ‘Sweet Charlie’ (3.8) and ‘Brilliance’ (3.8) (Table 1.5).

The following season (2023-2024) showed a general increase in average crown diameter across all cultivars (14.3 – 15.9 mm). Additionally, by the EOS, no significant differences were found between cultivars for average crown diameter. The EOS crown number data also showed a general increase in the 2023-24 season; the range in the first season was 3.0-4.5 and in the second season was 3.5-5.6. In general, over both years, crown numbers doubled from the beginning to the EOS for most cultivars (Table 1.5).

### *Leaf Number and Length*

Leaf number and length were assessed in the 2022-2023 season. ‘Fronteras’ (11.9), ‘Monterey’ (11.9) and ‘Sweet Sensation’ (12.3) had significantly more leaves compared to ‘Albion’ (9.0) and ‘Camino Real’ (9.9). ‘Fronteras’ had the highest average leaf length at 14.8 cm, which was significantly longer than the leaves of ‘Camino Real’, ‘Brilliance’, ‘Albion’ and ‘Sweet Charlie’ (Table 1.7).

### *Early-Season Flower Assessment*

Flower numbers were assessed weekly for a total of five weeks following the start of blooming (approx. Nov-Dec). During the early season in 2022-23, ‘Monterey’ and ‘Sweet Charlie’ produced the most flowers of all the cultivars, both averaging 1.47 flowers per plant.

‘Camino Real,’ produced the least number of flowers with an average of only 0.68 flowers per plant (Table 1.7). In the 2023-24 early season, ‘Brilliance’ (1.14) produced significantly more flowers per plant on average than every other cultivar, while ‘Fronteras’ averaged significantly less flowers (0.08 per plant) than all other cultivars (Table 1.7).

#### *Foliar Dry Mass*

At EOS of 2022-23, ‘Fronteras’, ‘Monterey’ and ‘Camino Real’ had significantly higher foliar dry mass, compared to ‘Albion.’ At EOS 2023-24, ‘Sweet Sensation’, ‘Monterey’ and ‘Brilliance’ had significantly higher foliar dry mass, compared to ‘Albion’ and ‘Camino Real’ (Table 1.7).

### **Postharvest Quality**

#### *Fruit Chemistry*

During the 2022-2023 season, the average TSS/T<sub>acid</sub> ratio ranged from 12.6 (‘Albion’ and ‘Brilliance’) to 18.0 (‘Sweet Charlie’). Most cultivars were similar, with TSS/T<sub>acid</sub> ratios around 12.6 to 14.7, except for ‘Sweet Charlie’, which exhibited a significantly higher ratio. In the 2023-2024 season, the ratios ranged from 23.4 (‘Camino Real’) to 30.7 (‘Sweet Sensation’). ‘Sweet Charlie’ and ‘Sweet Sensation’ had the highest TSS/T<sub>acid</sub> ratio, 29.5 and 30.7 respectively, which were significantly higher than the other cultivars.

In 2022-23, ‘Sweet Charlie’ had a significantly higher average pH (3.8) than all other cultivars. The average T<sub>acid</sub> was similar for most cultivars, however ‘Albion’ (0.60%) and ‘Monterey’ (0.58%) had significantly higher average T<sub>acid</sub> than the other cultivars (Table 1.8). ‘Sweet Charlie’ (8.0) had significantly higher TSS overall than most cultivars (Table 1.8). TSS varied over the season for all cultivars (Table A2). During week 9 of 2023 (27 February), ‘Camino Real’ had a significantly lower TSS (4.8) than all other cultivars. ‘Sweet Sensation’ had

its highest average TSS (9.5) during week 7 of 2023 (13 February). ‘Albion’ had its highest average TSS (9.5) during week 12 of 2023 (20 March). ‘Sweet Charlie’ had its highest average TSS (9.6) during week 16 of 2023 (17 April) and this was significantly higher than all other cultivars that week. ‘Camino Real’ had its highest average TSS (8.8) during week 17 of 2023 (24 April), and ‘Brilliance,’ ‘Fronteras,’ and ‘Monterey’ had their highest average TSS (8.2, 8.5, and 9.2, respectively) during week 19 of 2023 (8 May) (Table A2).

In 2023-24, no differences in pH were detected, but  $T_{\text{acid}}$  varied among the cultivars and was highest for ‘Camino Real’ (0.41%). ‘Fronteras’ had significantly lower average overall TSS (7.1) than all cultivars (Table 1.8). TSS varied across cultivars and over the season. ‘Monterey’ (10.3) and ‘Albion’ (10.6) had peak TSS during weeks 2 and 3 of 2024, respectively (8 and 15 January). ‘Fronteras’ had its highest TSS (8.4) during week 6 of 2024 (5 February). ‘Brilliance’ had its highest TSS (10.6) during week 10 of 2024 (4 March), and ‘Camino Real’ (11.3) peaked during week 13 of 2024 (25 March). ‘Sweet Sensation’ and ‘Sweet Charlie’ (11.1 and 10.3) both had peak TSS during week 14 of 2024 (1 April) (Table A2).

### *Fruit Firmness*

For the 2023-24 season as a whole, ‘Brilliance’ had a significantly higher average first peak force (FPF) (149.4 g), average second peak force (SPF) (210.5 g), and average total force (TF) (641.3 g/sec) than all other cultivars (Table 1.9). Notably, ‘Sweet Charlie’ was the only cultivar with a lower average SPF (86.9 g) than FPF (89.0 g), showing that the fruit has relatively soft internal flesh. Additionally, fruit firmness varied over the season for all cultivars (Tables S3-S5).

All cultivars generally declined in their TF over the season. ‘Albion’ (658.7 g/sec), ‘Brilliance’ (865.9 g/sec), ‘Camino Real’ (792.7 g/sec), ‘Fronteras’ (829.9 g/sec), and ‘Sweet

Sensation' (729.6 g/sec) experienced their highest average TF during week 3 of 2024 (15 January). 'Sweet Charlie' peaked in average TF (368.5 g/sec) during week 4 of 2024 (22 January), and 'Monterey' peaked (619.4 g/sec) during week 9 of 2024 (26 February). 'Sweet Charlie' tended to have the lowest average TF and was significantly lower than all cultivars during weeks 7 (12 February), 12 (18 March), and 14 (1 April) of 2024 (Table A3).

The results of the FPF varied over the season for all cultivars, but all showed the highest FPF during the month of January. 'Monterey' had its highest FPF (166.7 g) during week 2 of 2024 (8 January). 'Camino Real' (219.3 g) and 'Fronteras' (138.1 g) exhibited their highest FPF in week 3 of 2024 (15 January). And the following week, 'Albion' (167.8 g), 'Brilliance' (229.2 g), 'Sweet Sensation' (159.7 g), and 'Sweet Charlie' (126.5 g) all had their highest FPF (Table A4).

The SPF results differed from the patterns of the FPF; although the results varied over the course of the season, several cultivars showed their highest SPF toward the end of the season. 'Albion' (210.4 g), 'Camino Real' (235.8 g) and 'Monterey' (178.4 g) had their highest SPF during week 3 of 2024 (15 January). 'Sweet Charlie' (112.3 g) had its highest SPF during week 6 of 2024 (5 February), and 'Fronteras' (240.3 g) peaked in SPF during week 14 of 2024 (1 April). 'Brilliance' (309.9 g) and 'Sweet Sensation' (207.9 g) both had the highest SPF toward the end of the season, during week 17 of 2024 (22 April) (Table A5).

## **Discussion**

The evaluation of strawberry cultivars in US greenhouse production systems is not very well explored. Flowering in strawberries is a complex process that is influenced by both temperature and photoperiod (Durner et al., 1984); since both factors can be regulated in a greenhouse, cultivar evaluation research is essential to determine reproductive habits and yield potential of strawberry cultivars (Garcia & Kubota, 2017). Most protected culture strawberry

producers in the U.S. prefer cultivars like ‘Albion’ and ‘Monterey’ for greenhouse cultivation due to their day-neutral characteristics and acceptable flavor (Samtani et al., 2019).

Studies conducted in the US have shown that other day-neutral cultivars can also perform well in protected culture environments (Guan et al., 2022; Gu et al., 2017). However, short-day strawberry varieties may offer other advantages, like simultaneous fruit production and better flavor qualities (Lewers et al., 2020). Our findings on the yield patterns of the cultivars Camino Real and Fronteras are consistent with this, demonstrating low fruit production in the winter but high, simultaneous yields in the spring, often surpassing those of other cultivars. Additionally, cultivars which are considered short-day, but with low-chill requirements, may perform well in the warm environment of the greenhouse. For example, Gu et al. (2017) found that when using a high tunnel production system, the cultivars ‘Florida Radiance’, and ‘Winterstar’, showed high yield potential. This is further validated by our results, which demonstrate that ‘Brilliance’ and ‘Sweet Sensation’ produced relatively high yields in the greenhouse. Peak yields varied between the cultivars, but generally occurred during April of 2023 and March of 2024. Understanding peak production patterns is important for marketing purposes and could be used to strategically ensure a continuous supply of fruit throughout the season. This strategy is supported by studies such as those by Amyotte and Samtani (2023), which emphasize the importance of cultivar selection in extending the harvest season. ‘Fronteras’ and ‘Sweet Sensation’ had the highest non-marketable yield during both production seasons, suggesting room for improvement of production practices to increase yield and reduce waste.

It is difficult to directly compare greenhouse production to open-field production. However, according to data from the North Carolina State University Strawberry Breeding Program (Fernandez 2023), ‘Albion’ produced more fruit during the greenhouse season than in

typical field production. The cultivars Fronteras, Monterey, Sweet Sensation, and Sweet Charlie generally had similar yields in both the greenhouse and field. No outdoor yield data was available for ‘Brilliance.’

The 2023-2024 season generally had lower yields compared to the first season. The lower yields during the second season could be the result of multiple factors, including possible differences in planting material, increased pest and disease pressure, and environmental variations. The plants were developed from unrooted daughter plants (tips) obtained from the same nursery for both seasons. However, the tips may have varied in age, exposure to disease, and environmental conditions. Despite lower marketable yields in the second season, non-marketable yields were generally the same or slightly higher than the first season, indicating increased pest and disease pressure. Environmental factors also varied between the two seasons. During the first half of the season (Sep – Jan), temperatures were relatively higher in 2023-2024, while during the second half of the season (Feb – May), temperatures were generally lower. Short-day strawberry plants induce more flowers when the short photoperiod is accompanied by cooler temperatures (Darnell et al., 2003). Therefore, the warmer temperatures during the first half of the trial likely reduced floral induction, resulting in lower yields later. On the other hand, long-day strawberry plants continue to induce flowers under short photoperiod conditions if temperatures remain warm (Darnell et al., 2003). However, while ‘Albion’ showed the lowest difference in year-to-year marketable yield, ‘Monterey’ did not follow this trend.

Leaf number and size can be important factors for determining a strawberry plant’s capacity to support fruit development (Carey et al., 2009). This was somewhat supported by our results which showed that ‘Fronteras’, ‘Monterey,’ and ‘Sweet Sensation’ had the highest leaf counts and were also the highest yielding cultivars that year while ‘Albion’ had the fewest leaves

and the second lowest yield overall. Leaf length followed a similar trend, with ‘Fronteras’ having the longest leaves and ‘Albion’ the shortest, showing that ‘Fronteras’ had a more full and vigorous growth habit than ‘Albion.’ Although we did not find a strong correlation between leaf number or leaf length and overall yield (Figure A1), these differences in leaf characteristics highlight the variability of plant morphology between cultivars which can be important for production in terms of spray penetration and ease of harvest (Carey et al., 2009; Gu et al., 2017). These traits are also important for the development of cultivars adapted to greenhouse and controlled environment production.

During the 2022-2023 season, ‘Camino Real,’ ‘Fronteras,’ and ‘Monterey’ had the highest foliar dry mass, but in the 2023-2024 season, only ‘Monterey’ remained in the top three cultivars. Moreover, ‘Camino Real’ had the lowest foliar dry mass in 2023-2024, and this was largely due to significant disease issues affecting the plant health and viability of this cultivar. Additionally, ‘Brilliance’ shifted from having the lowest dry mass in the 2022-2023 season to one of the highest dry masses in the 2023-2024 season, aligning with its higher fruit production during this season. These results underscore the importance of multi-year studies, and the effect that varying environmental conditions can have on plant morphology and yield.

Despite ‘Sweet Charlie’ having a higher average number of early-season flowers, it did not show significant early fruit production in December 2022. This suggests a long development period from flower to fruit or environmental factors such as low temperatures or disease hindering flower development into fruit. This pattern persisted in the 2023-2024 season, where ‘Sweet Charlie’ had relatively moderate early flower production, but low early yields. This observation aligns with studies indicating that temperature is a critical factor in determining the timing of flower to fruit development (Menzel, 2021). Similarly, ‘Brilliance’ had a moderate

number of early-season flowers and low early yields in the 2022-2023 season but produced significant early flowers and yields the following season, possibly due to environmental conditions being more well-suited to this cultivar. In contrast, ‘Albion’ consistently produced significant yields in December of both years despite having a moderate number of early-season flowers, possibly because its flowers had already begun developing into fruit. This observation is supported by studies showing that cultivars may have different developmental timelines, allowing them to convert flowers to fruit more efficiently under certain conditions (Samad et al, 2021). The planting material for all cultivars was obtained from the same nursery for both years of the study, ensuring consistency in the starting material and reducing the likelihood of differences due to initial plant condition.

Hanson et al. (2006) reported that crown diameter and number are positively correlated with fruit yield in several strawberry cultivars grown in high tunnels. Our results did not align with this, as we did not find a strong correlation between yield and crown diameter (Figure A2). This discrepancy might be due to our measurement method, which involved measuring only the diameter of the *largest crown* rather than all crowns collectively. Crown number was a slightly better indicator of yield potential for some cultivars but not all. For instance, ‘Brilliance’ had significantly more crowns than other cultivars in the 2023-2024 season, aligning with its high overall yield, whereas in the 2022-2023 season, both the crown number and average yield were more moderate among the cultivars. Conversely, ‘Sweet Charlie’ had a moderate number of crowns at the end of the season for both years but was on the lower end for overall yield. This lines up with our finding that yield was also not highly correlated with the number of crowns (Figure A3).

Strawberry flavor is a complex fruit trait and consists of sugars, acids (amino and organic) and aromatic compounds. Sugars are an important component of flavor and can vary over time and based on cultivar (Haynes, 2024). Total acid ( $T_{\text{acid}}$ ) is a measurement of non-volatile organic acids in the sample. In the past, acceptable TSS and  $T_{\text{acid}}$  were 7.0% and 0.8% respectively (Kader, 1999). However, recently consumer demands dictate that the TSS minimum be raised to 9.0% and the  $T_{\text{acid}}$  remain around 0.8% (Haynes, 2024).

Our postharvest chemistry results emphasize the variability in fruit quality among the different cultivars and the impact of seasonal changes on these quality parameters. For the 2022-2023 season, ‘Sweet Charlie’ had the highest average TSS of 8.0% and other cultivars ranged from 6.1% (‘Brilliance’) to 7.4% (‘Albion’). The following season, all TSS levels were generally higher and ‘Albion’ was the highest at 9.4% on average. TSS is a crucial quality parameter because it correlates with perceived sweetness and overall fruit flavor, significantly affecting the marketability of strawberries, especially in North Carolina, where most strawberries are sold in local fresh markets (Hoffmann et al, 2024). In the 2022-2023 season, several of the cultivars (Brilliance, Camino Real, and Fronteras) did not meet the 7.0% TSS standard for consumer acceptability. However, in the following season, the majority of cultivars were at or above the newly suggested TSS standard of 9.0% and all of the cultivars were above the 7.0% TSS threshold.

Higher acid levels contribute to the tartness of the fruit, which influences the overall flavor balance (Kader, 1999).  $T_{\text{acid}}$  was variable across cultivars and seasons. In general,  $T_{\text{acid}}$  was higher in the first season (2022-23), ranging from 0.47-0.60%, whereas it ranged from 0.26-0.41% in the second season (2023-24). Strawberry fruit pH varied the least among the components we measured, with the average pH ranging from 3.5 – 3.8 across cultivars and

seasons, with most falling around 3.65. The pH is an important component of flavor, as acidity is inversely related to perceived sweetness in strawberries (Cordenunsi et al., 2003). However, there were mostly no significant differences in pH across the cultivars and seasons in this study.

The 2023-2024 season exhibited higher postharvest fruit quality traits, such as higher total soluble solids (TSS) and lower total acidity ( $T_{acid}$ ), compared to the previous season. These differences can be attributed to the differing environmental factors. The cooler temperatures during the second half of the 2023-2024 season may have contributed to the higher TSS and lower  $T_{acid}$  of the fruit. Temperature conditions during ripening have been shown to affect the postharvest quality of strawberry fruit (Taghavi et al, 2019; USDA ARS, 2016). Additionally, studies have shown that higher light intensity results in higher acid levels in the strawberry fruit, which lines up with our results showing that acidity levels were higher in the 2022-23 season when the light intensity in the greenhouse was comparatively higher (Taghavi et al, 2019). The combination of these factors likely resulted in the observed differences in postharvest fruit quality traits between the two seasons.

Fruit firmness is also an important characteristic for marketability. Studies have shown that harvesting at peak firmness enhances shelf life and consumer satisfaction (Kader, 1999; Vicente et al., 2009). ‘Brilliance’ consistently exhibited high firmness metrics compared to other cultivars, aligning with Whitaker et al. (2019), who reported moderate firmness for ‘Brilliance.’ Conversely, ‘Sweet Charlie’ consistently showed low firmness values. This variation in fruit firmness has practical implications for growers, as understanding the firmness characteristics of different cultivars can guide selection for specific market needs. For example, cultivars with higher firmness, like ‘Brilliance,’ may be preferred for markets requiring longer shelf life,

whereas softer cultivars like ‘Sweet Charlie’ may be more suitable for local markets with quicker turnover between harvest and consumption.

## **Conclusions**

When comparing the two seasons, the data shows a noticeable decline in total marketable yield for most cultivars in the 2023-2024 season. Factors such as environmental conditions, plant age, and pest pressures contributed to this decline. Specifically, lower temperatures and varying light intensities likely influenced the yield outcomes, as evidenced by the recorded environmental conditions inside the greenhouse. These findings highlight the importance of skillful management in the greenhouse environment and the necessity of multi-year studies.

Overall, the findings of this study emphasize the importance of cultivar selection and tailored management practices to optimize strawberry yield under greenhouse conditions. This study confirms that ‘Albion’ is a quality choice as a standard greenhouse cultivar for growers in the southeastern US, due to consistent yields, postharvest chemistry, and firmness throughout seasons. However, this study also shows the cultivars Monterey, Brilliance and Sweet Sensation can perform well under greenhouse conditions. Those cultivars might become a reliable alternative for southeastern greenhouse strawberry growers in the future.

Future research should focus on the long-term performance of these cultivars across multiple growing seasons and the development of production practices including temperature and light optimization for maximizing marketable yield and minimizing losses to non-marketable production. Preconditioning of plants that have been grown in conditions that optimize floral initiation in the nursery could also enhance yield in the winter months. Continuous evaluation and adaptation of greenhouse management practices will be essential to support the sustainable production of high-quality strawberries in North Carolina and similar regions.

## TABLES

Table 1.1. Strawberry cultivars used for this study.

Cultivar	Breeding Program	Year Released	Photoperiod	Chilling Requirements
Albion	University of California, Davis	2004	long-day	250 – 450 hours
Brilliance	University of Florida	2017	short-day	200 – 300 hours
Camino Real	University of California, Davis	2001	short-day	200 – 400 hours
Fronteras	University of California, Davis	2014	short-day	200 – 400 hours
Monterey	University of California, Davis	2008	long-day	250 – 450 hours
Sweet Sensation	University of Florida	2013	short-day	200 – 300 hours
Sweet Charlie	University of Florida	1992	short-day	200 – 300 hours

Table 1.2. Strawberry plug plants were evaluated for crown diameter and leaf number before planting.

Cultivar	2022-2023		2023-2024	
	Crown Diameter (mm)	Leaf Number	Crown Diameter (mm)	Leaf Number
Albion	8.45 ± 0.10 <sup>i</sup>	3.65 ± 0.08 <sup>ii</sup>	9.94 ± 0.17	4.02 ± 0.10
Brilliance	8.57 ± 0.10	3.68 ± 0.08	9.25 ± 0.16	4.08 ± 0.10
Camino Real	8.42 ± 0.10	3.40 ± 0.08	9.73 ± 0.21	3.95 ± 0.16
Fronteras	7.25 ± 0.10	3.37 ± 0.07	9.01 ± 0.17	3.11 ± 0.07
Monterey	9.35 ± 0.10	4.20 ± 0.08	9.59 ± 0.16	3.32 ± 0.09
Sweet Sensation	8.44 ± 0.10	4.55 ± 0.08	8.97 ± 0.16	4.91 ± 0.09
Sweet Charlie	8.69 ± 0.11	4.06 ± 0.08	7.86 ± 0.15	3.40 ± 0.11

<sup>i</sup> Average crown diameter of 23-day old plug plants ± standard error

<sup>ii</sup> Average number of leaves of 23-day old plug plants ± standard error

Table 1.3. Commercial fertilizer rates (feed). All nutrients are in milligrams per liter (mg/L).

	NO <sub>3</sub>	NH <sub>4</sub> <sup>+</sup>	P	K	Mg	Ca	S	Fe	Mn	Zn	B	Cu	Mo	pH	EC
Vegetative <sup>i</sup>	148	9	41	150	36	147	40	2.0	1.0	0.5	0.15	0.1	0.05	5.5	1.4
Fruiting	154	7	41	241	34	114	37	2.0	1.0	0.5	0.17	0.1	0.05	5.5	1.4

<sup>i</sup>The vegetative recipe is used for ~1 month (Sept-October); the fruiting recipe is implemented in October when flower and fruit production begins

Table 1.4. Weekly average temperature (°C) and cumulative daily light integral (mol/m<sup>2</sup>/d) inside the trial area of the commercial greenhouse in Wilson, NC.

Week of the Year	2022-2023				2023-2024			
	Temperature <sup>i</sup> (°C)			DLI <sup>v</sup> (mol/m <sup>2</sup> /d)	Temperature (°C)			DLI (mol/m <sup>2</sup> /d)
	Avg <sup>ii</sup>	Min <sup>iii</sup>	Max <sup>iv</sup>		Avg	Min	Max	
39	-	-	-	13.9	20.9	20.1	22.0	21.0
40	-	-	-	26.1	21.8	20.9	22.7	18.7
41	-	-	-	-	13.9	13.4	14.3	16.3
42	-	-	-	-	17.1	16.2	18.0	19.3
43	-	-	-	-	16.7	15.7	17.7	16.5
44	18.6	17.9	19.8	-	17.1	16.1	18.0	16.1
45	13.5	12.8	14.5	-	15.1	14.2	16.0	10.4
46	11.3	10.6	12.0	-	12.9	12.2	13.6	10.5
47	13.4	12.8	14.2	-	14.1	13.3	14.9	11.6
48	12.1	11.5	12.8	-	10.7	9.7	11.7	8.8
49	12.6	11.8	13.4	-	13.9	13.0	14.7	10.3
50	9.8	9.1	10.6	-	13.6	12.2	16.4	10.5
51	9.4	8.3	10.3	10.9	12.0	10.2	15.3	8.5
52	12.5	11.9	13.4	11.9	13.8	11.6	16.7	10.0
1	8.5	8.0	9.2	11.3	11.1	9.1	13.3	9.5
2	8.7	8.0	9.5	10.7	11.7	9.7	15.6	11.2
3	10.8	10.1	11.8	12.3	11.8	9.5	15.4	10.3
4	10.7	10.0	11.7	11.7	12.8	11.4	14.9	12.4
5	8.9	8.2	9.8	12.6	14.2	13.1	15.2	16.1
6	14.5	12.6	17.8	14.8	12.0	10.5	13.5	12.2
7	14.9	12.4	17.8	15.3	14.3	13.4	15.3	17.3
8	17.1	16.2	18.0	14.4	12.6	11.3	13.9	12.6
9	16.7	15.6	17.8	17.7	13.1	12.2	14.1	12.5
10	11.4	10.2	12.4	17.6	15.1	14.3	15.8	21.1
11	12.3	10.3	14.1	22.4	14.8	13.7	15.9	22.6
12	18.2	17.2	19.6	15.7	16.1	14.9	17.2	17.3
13	15.3	13.9	17.2	21.7	12.9	11.8	14.0	22.7
14	16.6	15.4	18.1	20.4	17.3	16.1	18.4	22.8
15	20.6	19.4	21.9	26.8	13.8	12.4	15.3	25.0
16	20.2	19.1	21.5	26.6	20.8	19.7	21.9	15.6
17	19.1	18.2	20.0	17.6	16.9	15.9	17.9	20.7
18	19.9	18.6	21.0	20.4	21.8	20.7	23.1	n/a
19	22.6	21.4	23.6	18.9	n/a	n/a	n/a	n/a
20	20.7	19.8	21.5	15.8	n/a	n/a	n/a	n/a
21	19.6	18.7	20.5	n/a	n/a	n/a	n/a	n/a

<sup>i</sup> Due to failing data loggers in 2022, no temperature data was collected for the 39th through the 43rd week of the year. Failing data loggers prevented capturing light intensity data in 2022 for weeks 41-50.

- ii Avg represents the weekly average temperature, recorded at two-minute intervals.
- iii Min represents the average minimum temperature.
- iv Max represents the average maximum temperature.
- v DLI (daily light integral) represents the average light intensity for each week.

Table 1.5. Average diameter of largest visible crown and observable crown number of seven greenhouse-grown strawberry cultivars sampled monthly from October - January and at the end of the season (EOS) in both seasons (2022-2023; 2023-2024).

Cultivar	Crown Diameter (mm)	Crown Number	EOS Crown Diameter (mm)	EOS Crown Number
2022-2023				
Albion	13.4 ± 0.17 <sup>i</sup> abc <sup>ii</sup>	1.7 ± 0.05 <sup>iii</sup> b	19.6 ± 0.43 ab	3.0 ± 0.19 b
Brilliance	13.0 ± 0.21 bc	1.8 ± 0.06 ab	19.6 ± 0.37 ab	3.8 ± 0.22 ab
Camino Real	13.2 ± 0.22 bc	1.7 ± 0.05 b	20.5 ± 0.37 a	4.5 ± 0.22 a
Fronteras	12.7 ± 0.22 c	1.8 ± 0.06 ab	20.2 ± 0.44 ab	4.5 ± 0.18 a
Monterey	14.2 ± 0.18 a	1.9 ± 0.06 ab	19.9 ± 0.58 ab	4.3 ± 0.19 a
Sweet Sensation	12.9 ± 0.20 bc	2.0 ± 0.07 a	19.7 ± 0.35 ab	3.9 ± 0.22 a
Sweet Charlie	13.6 ± 0.21 ab	1.8 ± 0.06 ab	18.5 ± 0.44 b	3.8 ± 0.18 ab
2023-2024				
Albion	15.1 ± 0.23 ab	2.0 ± 0.09 abc	19.4 ± 0.37	4.0 ± 0.19 de
Brilliance	15.6 ± 0.25 a	2.4 ± 0.12 a	20.0 ± 0.43	5.6 ± 0.23 a
Camino Real	13.6 ± 0.27 c	1.8 ± 0.92 bc	20.3 ± 0.50	3.5 ± 0.21 e
Fronteras	15.9 ± 0.30 a	1.7 ± 0.08 c	20.2 ± 0.42	4.5 ± 0.17 bcd
Monterey	14.3 ± 0.24 bc	2.2 ± 0.11 ab	19.6 ± 0.38	4.3 ± 0.16 cde
Sweet Sensation	15.6 ± 0.28 a	2.4 ± 0.13 a	20.8 ± 0.45	5.3 ± 0.21 ab
Sweet Charlie	15.4 ± 0.23 a	2.5 ± 0.12 a	19.4 ± 0.56	4.9 ± 0.27 abc

<sup>i</sup> Average crown diameter ± standard error

<sup>ii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Mean comparisons are within the same column and year.

<sup>iii</sup> Average total number of branch crowns ± standard error.

Table 1.6. Average marketable yield, non-marketable yield, and fruit size of seven greenhouse-grown strawberry cultivars per season.

Cultivar	Marketable (g/lm)	Non-Marketable (g/lm)	Marketable (g/plant)	Non-Marketable (g/plant)	Fruit Size (g)
2022-2023					
Albion	4716 ± 169 <sup>i</sup>	600 ± 25	589.5 ± 59.8 <sup>ii</sup>	75.0 ± 8.7	18.6 ± 0.49 <sup>iii</sup> a
Brilliance	5282 ± 221	1001 ± 46	660.2 ± 78.2	125.1 ± 16.3	18.1 ± 1.00 a
Camino Real	4800 ± 271	837 ± 39	600.0 ± 96.0	104.6 ± 13.9	17.5 ± 1.00 a
Fronteras	5523 ± 254	1108 ± 55	690.4 ± 89.7	138.6 ± 19.3	19.0 ± 0.89 a
Monterey	5537 ± 228	741 ± 29	692.1 ± 80.6	92.6 ± 10.3	17.6 ± 0.50 a
Sweet Sensation	5854 ± 206	1092 ± 38	731.0 ± 7.7	136.5 ± 13.5	20.5 ± 0.84 a
Sweet Charlie	4387 ± 137	863 ± 28	584.3 ± 48.3	107.8 ± 9.9	11.4 ± 0.37 b
2023-2024					
Albion	3261 ± 60 a <sup>v</sup>	651 ± 26 bc	414.0 ± 21.5 a	82.6 ± 9.2 bc	19.8 ± 0.45 c
Brilliance	3733 ± 69 a	1086 ± 31 ab	466.6 ± 24.3 a	135.7 ± 10.9 ab	27.1 ± 1.00 b
Camino Real	1559 ± 45 b	258 ± 12 c	277.2 ± 14.9 b	45.8 ± 5.0 c	20.9 ± 0.77 c
Fronteras	3489 ± 145 a	1266 ± 55 a	436.1 ± 51.4 a	158.3 ± 19.6 a	33.4 ± 2.13 a
Monterey	3809 ± 125 a	730 ± 35 bc	476.1 ± 44.2 a	91.2 ± 12.3 bc	20.9 ± 0.84 c
Sweet Sensation	3612 ± 90 a	1140 ± 47 ab	458.7 ± 32.1 a	144.8 ± 16.7 ab	30.6 ± 1.53 ab
Sweet Charlie	3098 ± 81 a	822 ± 29 ab	387.2 ± 28.6 a	102.8 ± 10.1 ab	17.2 ± 0.89 c

<sup>i</sup> Average total marketable yield in grams per linear meter ± standard error

<sup>ii</sup> Average total marketable yield in grams per plant ± standard error

<sup>iii</sup> Average marketable fruit size ± standard error

<sup>iv</sup> The 2023-24 season ended at week 18, so data was removed from weeks 19, 20, and 21 of the 2022-23 season for comparison between years

<sup>v</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Mean comparisons are within the same column and year; columns with no letters showed no significant differences

Table 1.7. Average leaf number and length, flower number, and foliar dry mass of seven greenhouse-grown strawberry cultivars.

Cultivar	2022-2023				2023-2024	
	Leaf Number <sup>i</sup>	Leaf Length (cm)	Flower Number <sup>ii</sup>	Foliar Dry Mass <sup>iii</sup> (g)	Flower Number	Foliar Dry Mass (g)
Albion	9.0 ± 0.3 c <sup>iv</sup>	11.9 ± 0.1 c	1.01 ± 0.05 bc	31.4 ± 2.6 c	0.84 ± 0.05 b	30.7 ± 1.8 b
Brilliance	11.4 ± 0.4 ab	14.0 ± 0.1 b	1.05 ± 0.05 b	31.4 ± 2.4 c	1.14 ± 0.06 a	41.2 ± 2.4 a
Camino Real	9.9 ± 0.3 bc	11.7 ± 0.1 c	0.68 ± 0.05 d	49.6 ± 2.7 ab	0.41 ± 0.04 d	27.2 ± 2.1 b
Fronteras	11.9 ± 0.4 a	14.8 ± 0.1 a	0.83 ± 0.04 bcd	51.1 ± 3.4 a	0.08 ± 0.02 e	36.0 ± 2.0 ab
Monterey	11.9 ± 0.4 a	14.5 ± 0.1 ab	1.47 ± 0.07 a	50.3 ± 2.8 ab	0.75 ± 0.05 bc	41.1 ± 2.6 a
Sweet Sensation	12.3 ± 0.4 a	14.6 ± 0.1 ab	0.79 ± 0.04 cd	39.0 ± 2.4 bc	0.45 ± 0.04 d	44.9 ± 2.6 a
Sweet Charlie	11.0 ± 0.3 ab	13.9 ± 0.1 b	1.47 ± 0.06 a	39.7 ± 3.0 abc	0.58 ± 0.06 cd	36.6 ± 2.4 ab

<sup>i</sup> Leaf number and leaf length were sampled monthly from October 2022 – February 2023. Data shown represent the total average ± standard error

<sup>ii</sup> Flower numbers were sampled weekly from November – December for both seasons. Data shown represents the total average ± standard error

<sup>iii</sup> Foliar dry mass was taken at the end of both seasons and represents only the foliar plant growth. Data shown represents the total average ± standard error

<sup>iv</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey’s Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Tests were performed within each category and within each year.

Table 1.8. Average primary fruit chemistry: pH, total acidity (T<sub>acid</sub>), and total soluble solids (TSS) of seven greenhouse-grown strawberry cultivars over two production seasons.

Cultivar	pH	T <sub>acid</sub> (%)	TSS (%)	TSS/T <sub>acid</sub>
2022-2023				
Albion	3.60 ± 0.02 <sup>i</sup> b <sup>ii</sup>	0.60 ± 0.02 <sup>iii</sup> a	7.4 ± 0.21 <sup>iv</sup> ab	12.6 ± 0.41 <sup>v</sup> b
Brilliance	3.68 ± 0.03 b	0.51 ± 0.02 b	6.1 ± 0.22 c	12.6 ± 0.68 b
Camino Real	3.58 ± 0.02 b	0.49 ± 0.02 b	6.8 ± 0.23 bc	14.1 ± 0.67 b
Fronteras	3.61 ± 0.04 b	0.47 ± 0.01 b	6.7 ± 0.21 bc	14.7 ± 0.69 b
Monterey	3.66 ± 0.02 b	0.58 ± 0.02 a	7.2 ± 0.18 b	12.7 ± 0.41 b
Sweet Sensation	3.63 ± 0.03 b	0.50 ± 0.02 b	7.0 ± 0.15 b	14.4 ± 0.42 b
Sweet Charlie	3.80 ± 0.02 a	0.49 ± 0.02 b	8.0 ± 0.17 a	18.0 ± 1.03 a
2023-2024				
Albion	3.68 ± 0.02	0.39 ± 0.01 ab	9.4 ± 0.13 a	25.0 ± 0.61 cd
Brilliance	3.74 ± 0.02	0.35 ± 0.01 bcd	9.0 ± 0.17 a	26.7 ± 0.64 bc
Camino Real	3.68 ± 0.01	0.41 ± 0.01 a	9.4 ± 0.14 a	23.4 ± 0.70 d
Fronteras	3.68 ± 0.01	0.26 ± 0.01 e	7.1 ± 0.12 c	28.0 ± 0.49 ab
Monterey	3.68 ± 0.02	0.35 ± 0.02 bc	8.1 ± 0.15 b	24.1 ± 0.59 cd
Sweet Sensation	3.72 ± 0.02	0.30 ± 0.01 de	9.1 ± 0.18 a	30.7 ± 0.75 a
Sweet Charlie	3.72 ± 0.02	0.32 ± 0.01 cd	9.0 ± 0.12 a	29.5 ± 0.64 a

<sup>i</sup> Average pH ± standard error

<sup>ii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons

<sup>iii</sup> Average T<sub>acid</sub> (total acidity) ± standard error

<sup>iv</sup> Average TSS (total soluble solids) ± standard error

<sup>v</sup> Average TSS/T<sub>acid</sub> ratio ± standard error

Table 1.9. Average firmness of seven greenhouse-grown strawberry cultivars for the 2023-2024 season.

Cultivar	FPF (g)	SPF (g)	TF (g/sec)
Albion	112.7 ± 2.2 <sup>i</sup> d <sup>ii</sup>	151.0 ± 3.2 <sup>iii</sup> cd	440.3 ± 8.7 <sup>iv</sup> c
Brilliance	149.6 ± 3.2 a	212.2 ± 4.4 a	645.7 ± 13.0 a
Camino Real	138.5 ± 3.1 b	174.0 ± 4.2 b	512.4 ± 12.4 b
Fronteras	111.4 ± 2.6 d	171.0 ± 3.8 b	525.3 ± 11.9 b
Monterey	118.3 ± 2.4 cd	140.5 ± 3.0 d	456.1 ± 9.8 c
Sweet Sensation	123.6 ± 2.0 c	160.1 ± 3.2 bc	503.0 ± 9.7 b
Sweet Charlie	89.0 ± 1.6 e	86.9 ± 1.6 e	286.3 ± 4.6 d

<sup>i</sup> Average force of first peak ± standard error

<sup>ii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Mean comparisons are within the same column and year.

<sup>iii</sup> Average force of second peak ± standard error

<sup>iv</sup> Average total force (total area under the curve) ± standard error

## FIGURES



Figure 1. One bay in a multi-bay, mid-tech, plastic-covered greenhouse with tabletop strawberry production. A) The day of planting. B) Six months after planting. C) At the end of the season, seven months after planting.



Figure 2. Photos taken of each cultivar on 25 March 2024. A) Albion. B) Brilliance. C) Camino Real. D) Fronteras. E) Monterey. F) Sweet Sensation. G) Sweet Charlie.

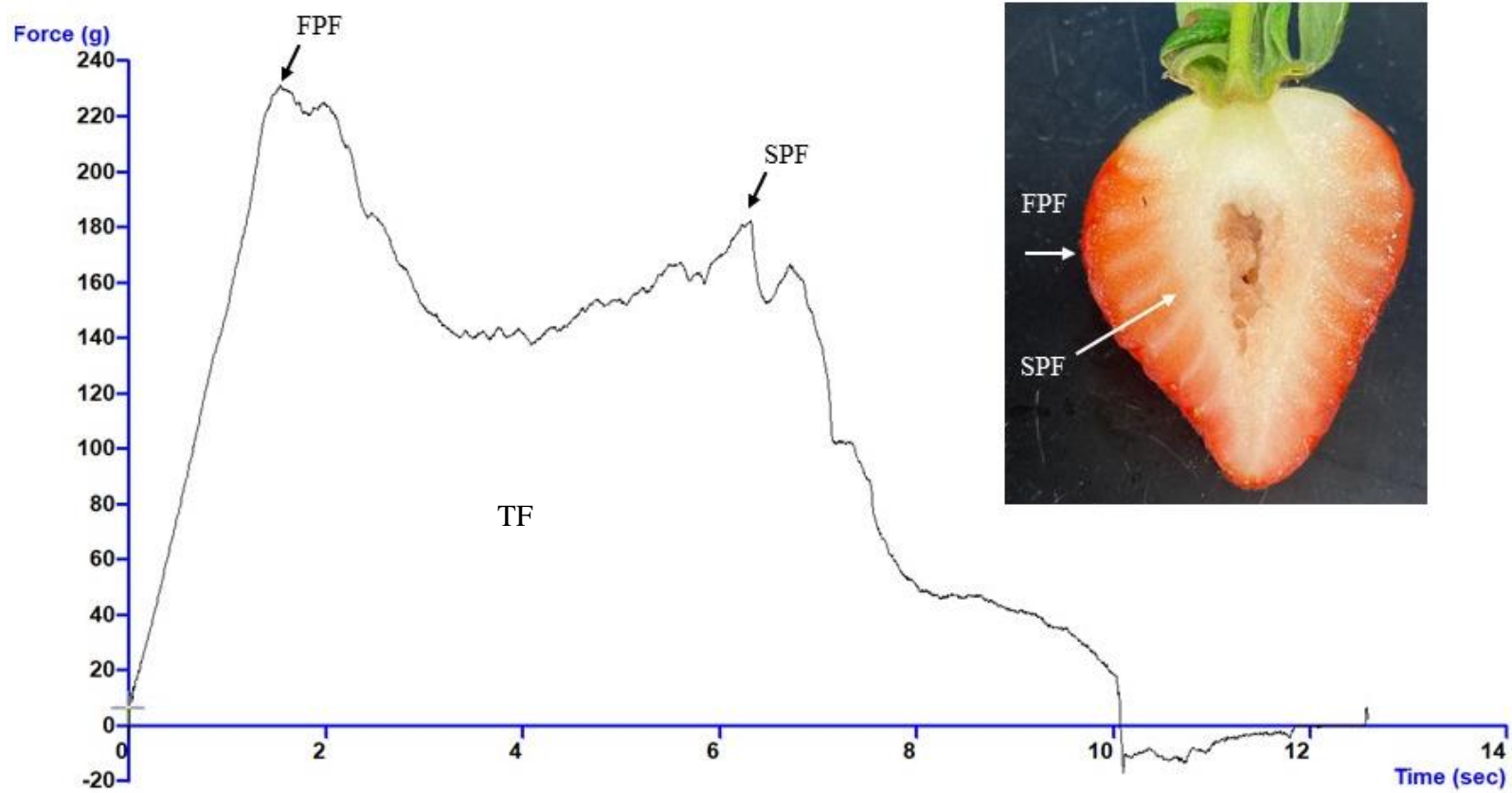


Figure 3. Output of texture analyzer (TA.XTPlus Connect, Hamilton, MA) and cross section of strawberry fruit, showing the first peak force (FPF) required to puncture through the skin of the fruit, the second peak force (SPF) required to puncture through the inner layer of fruit flesh, and the total force (TF) required to go through the whole fruit.

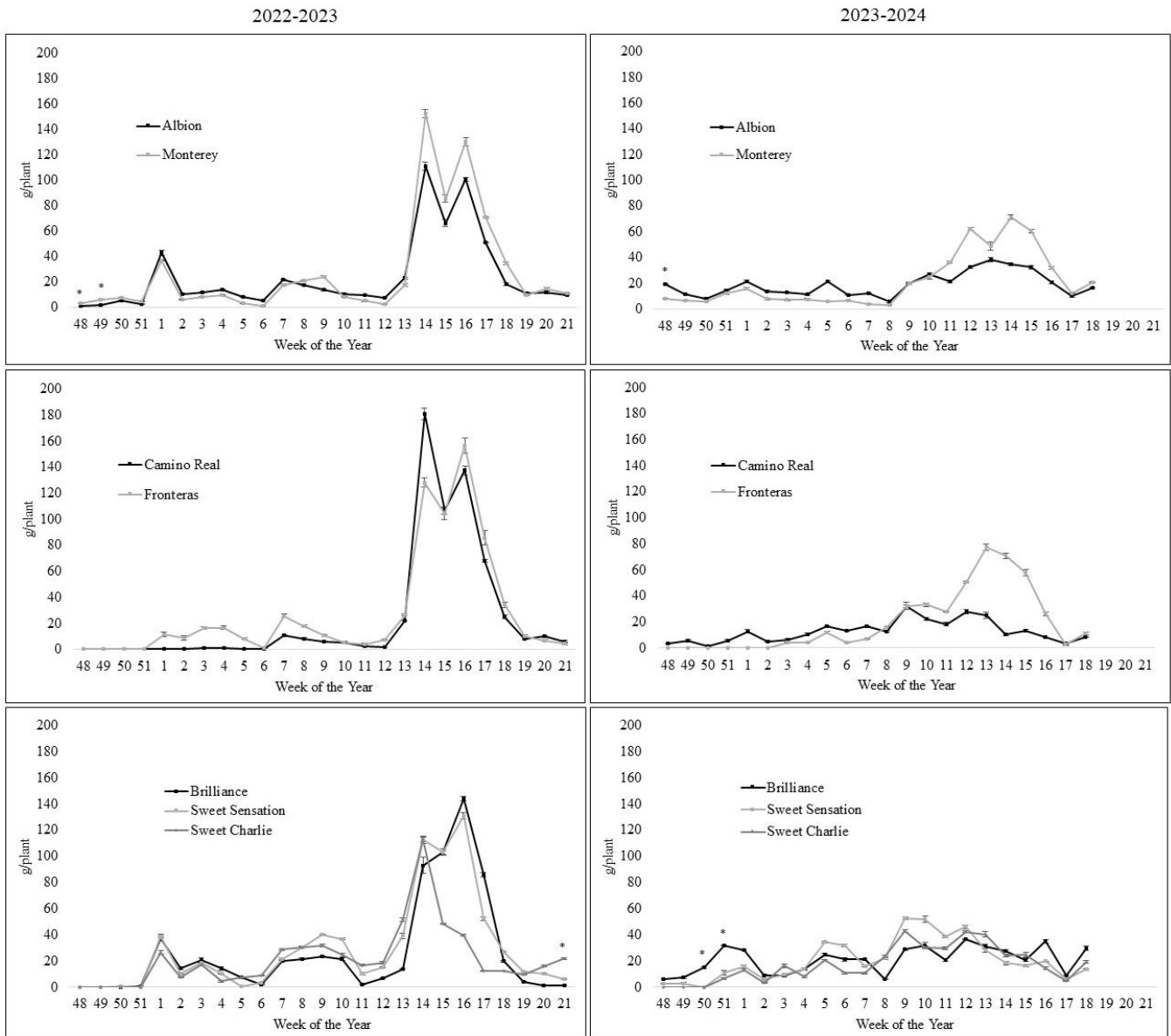


Figure 4. Weekly total marketable yield (g/plant). \* Indicates significant difference across all cultivars, not just those in the graph. Top Row: UC Davis, long-day cultivars Albion and Monterey. Middle Row: UC Davis, short-day cultivars Camino Real and Fronteras. Bottom Row: UF, short-day cultivars Brilliance, Sweet Sensation, and Sweet Charlie.

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## CHAPTER 3

# Evaluation of Yield, Fruit Chemistry, and Firmness of Four North Carolina State University Advanced Strawberry Selections in an Eastern North Carolina Greenhouse

### Introduction

The most commonly cultivated strawberry (*Fragaria xananassa*) is a hybrid of two strawberry species: *Fragaria chiloensis* and *Fragaria virginiana*. Although these species are native to South and North America, respectively, the hybridization of the species was first documented in France in the 17th century. Both species had been brought back to Europe from the America's during the previous centuries. Although there were wild strawberries (*Fragaria vesca*) available throughout Europe, the new hybrid strawberry was found to have both good flavor and large fruit (Galletta, G. J., & Himelrick, D. G., 1990).

Consumption of strawberries in the United States has had a notable rise over the last thirty years, increasing from around 2 pounds per person in 1980 to about 8 pounds per person in 2013 (USDA, 2014). Additionally, in 2018, the North Carolina strawberry industry was valued around \$21.4 million (USDA NASS, 2022), with most strawberry growers utilizing local markets through roadside stands, farmer's markets, and pick-your-own operations (McWhirt et al. 2020; Samtani et al., 2019). This strong local market highlights the importance of the continued cultivation, research, and improvement of strawberry cultivars for North Carolina growers. The North Carolina State University (NCSU) breeding program has an important role in developing new cultivars aimed at enhancing traits such as yield, flavor, and fruit size. The

program is also focused on developing cultivars with resistance to anthracnose and which are adapted to the local environmental conditions (Hoffmann, 2020).

The primary objective of this study was to evaluate the performance of four advanced selections from the NCSU breeding program and one standard greenhouse variety as a control. Performance was evaluated based on plant growth measurements, yield assessments, and postharvest quality metrics. Through these evaluations, we seek to identify selections that perform well in the greenhouse, and which may be further utilized for new cultivar development.

The standard control used in this study was ‘Albion’ which is a long-day variety developed at the University of California, Davis (UC Davis), and it is a commonly grown variety for protected culture systems in North Carolina. The four advanced selections included in this trial were NC 19-020, NC 20-099, NC 21-033, and NC 22-004. ‘NC 19-020’ does not have the FaPFRU (perpetual flowering) marker, indicating that it has a short-day phenotype; it has previously shown phytophthora crown rot resistance and high fruit firmness. ‘NC 20-099’ has the FaPFRU marker indicating that it has a day-neutral phenotype; it has also shown a vigorous growth habit, general disease resistance, and high yields. ‘NC 21-033’ does not have the FaPFRU marker, indicating that it has a short-day phenotype; it has previously displayed a good flavor profile and phytophthora resistance. ‘NC 22-004’ has not been evaluated for genetic markers, but it has displayed a compact growth habit that allows fruit trusses to be well-exposed from the plant canopy and has also demonstrated good flavor and fruit firmness. These selections were chosen for their potential to perform well in the greenhouse due to disease resistance, yield potential, and adapted plant architecture.

Understanding the performance and characteristics of these advanced selections is crucial for informing breeding decisions and guiding future research directions. By clarifying the

strengths and weaknesses of each advanced selection, we contribute valuable insights to the ongoing efforts aimed at developing resilient, high-yielding, and flavorful strawberry cultivars for North Carolina growers.

## **Materials and Methods**

### **Location, Trial Design, and Planting Material**

The trial was conducted in a commercial strawberry greenhouse in Wilson, NC (35.708648, -78.051865) from October 6th, 2023, to 2 May 2024. The trial was structured using a modified block design to accommodate spatial constraints within the greenhouse. It included three replicates per cultivar and eight plants per replicate. The arrangement of the replicates across the greenhouse was as follows: The first row featured the entire first replicate along with two selections from the second replicate. The second row contained the remaining three selections of the second replicate and the entirety of the third replicate. The greenhouse was a double polyethylene covered house with roll-up sides for cooling and ventilation, with fans and heaters available for further environmental control. The greenhouse did not feature supplemental lighting but did include lights suitable for night-interruption lighting. The plants were grown in raised gutters (tabletop system).

The advanced selections used in this trial were NC 19-020, NC 20-099, NC 21-033, and NC 22-004, and the cultivar Albion was used as a standard control (Figure 2.1). The plants used for the trial were propagated from the NCSU strawberry breeding nursery. Daughter plants were harvested from mother plants and propagated on the same day. They were propagated in 50 cell trays containing an all-purpose soilless media (Metro-Mix® 830, Sun Gro Horticulture Canada Ltd., Agawam, MA) and were rooted under mist on a standard greenhouse bench. After 21 days of rooting, the largest and most well-established daughter plants were transplanted on 6 October

2023, and planted directly into soilless plastic grow bags (Precision Plus Ultra ©, Botanicoir Ltd, London, UK). The bags were placed in raised gutters (Haygrove Ltd, UK) that were approximately three feet above the ground.

### **Environmental and Growing Conditions**

Temperature conditions were recorded throughout the season (Elitech RC-5 USB Temperature Data Logger, Elitech Technology Inc., San Jose, CA). The temperature loggers were protected from direct solar radiation by plastic shade covers and ten of them were distributed throughout the trial area and maintained at canopy height. To track light intensity, two sensors (HOBO MX2202 Pendant Data Logger, Onset, Bourne, MA) were placed at canopy height. Light intensity was recorded in lux; the lux measurements were converted to PPFD (photosynthetic photon flux density) using the equations described by Thimijan and Heins (1983), then converted to DLI (daily light integral) (CABA, 2023). The collaborating grower conducted irrigation, fertility, pest, and disease management according to commercial standards (Table 1.1).

### **Plant Growth and Development**

The crown diameter was measured monthly for the first four months of the trial period (October - January) using an electronic caliper (IP54 Electronic Measuring Tool, Housolution, US). Initially, crown diameter was measured on the solitary primary crown, but as plants developed multiple crowns, the total number of crowns was recorded, and the diameter of the largest crown was measured. Runners were removed as needed and their count was recorded. At the end of the season, all plants were collected for destructive data collection. The plants were snapped off at the base of the crowns, and the number of crowns and crown diameter of the largest crown were recorded. Any fruit, including green fruit, was removed from the plants, and

the whole plant was placed in a large brown paper bag. The bags were then placed in a large drying oven at 75°C for four days, and then their total foliar dry mass was recorded.

### **Components of Yield**

Marketable and non-marketable fruit were harvested for each replicate once or twice per week, depending on season specific grower practices. Harvesting began during week 3 (15 January) of 2024 and ended during week 18 (29 April) of 2024. The total mass of marketable yield and non-marketable yield was measured in grams using a portable scale (Cruiser Bench Counting Scales-CCT 32, Adam Equipment, Kingston, UK), and the total number of marketable fruits was counted. Fruits were categorized as marketable or non-marketable depending on quality factors like size, shape, color, maturity, and disease presence. Non-marketable fruits included those under ten grams, misshapen, over- or under-ripe, or diseased (USDA AMS, 2023).

### **Primary Fruit Chemistry**

For each replicate, up to 10 representative fruits were collected weekly. After removing the calyxes, the fruit was crushed inside sealable plastic bags. The crushed fruit was then placed in a freezer set to -20°C for eight days. Following the freezing period, the fruit was allowed to thaw at room temperature for several hours. Once sufficiently thawed, the fruit juice was filtered and collected in beakers. The pH of the juice was measured using a pH meter (PC800 pH/Conductivity Meter, APERA instruments, Columbus, Ohio) and collected by submerging the pH probe in the filtered fruit juice. Total soluble solids (TSS, brix) and total acidity (TA) were measured using a digital brix-acidity meter (Pocket Brix-Acidity Meter, ATAGO USA Inc., Bellevue, Washington). TSS was measured by placing two to four drops of the filtered fruit juice on the brix-acidity meter, and the TA was measured by diluting one milliliter of the fruit juice in

50 milliliters of deionized (DI) water and then placing two to four drops of the solution onto the brix-acidity meter.

### **Fruit Firmness**

A texture analyzer (TA.XTPlus Connect, Hamilton, MA) with a 2mm (TA.52) puncture probe was used to test fruit firmness. Up to 10 representative fruits from each replicate were evaluated weekly from week 10 (4 March) to week 18 (29 April) of 2024. Individual fruits were cut longitudinally (from calyx to tip), and one-half of the fruit was placed on the instrument platform with the cut side down. The fruit was lined up so that the broad section of the fruit was in line with the probe. The force required to puncture the outside of the fruit was recorded as the “first peak force” (FPF), the force required to puncture through the inner layer of fruit flesh was recorded as the “second peak force” (SPF) and the overall force required to puncture the whole fruit was recorded as the “total force” (TF) (Figure 1.3).

### **Data Analysis**

Environmental data were managed using Google Sheets (Google, LLC, Mountain View, CA, USA), and graphs were created using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). All other data were analyzed using a one-way ANOVA ( $\alpha \leq 0.05$ ) performed in RStudio (RStudio Desktop ver. 2023.06.16, Boston, MA, USA), followed by a post-hoc Tukey’s honestly significant difference (HSD) where appropriate ( $\alpha \leq 0.05$ ). Prior to data analysis, the fruit firmness data was gathered using a macro developed for Exponent software in collaboration with Texture Technologies (Texture Technologies Corp. and Stable Micro Systems, Ltd., Hamilton, MA).

## **Results**

### **Environmental Conditions**

January was the coldest month of the trial period, with an average temperature inside the greenhouse of 12.5°C. The lowest average minimum temperature inside the greenhouse was 9.1°C (25 December 2023). The highest average maximum temperature was 23.1°C (29 April 2024). The highest weekly cumulative DLI inside the greenhouse was recorded during week 16 of 2024 at 174.8 mol/m<sup>2</sup>/d (Table 1.2).

### **Plant Growth and Development**

For the first four months of the trial there were no significant differences between the selections for crown diameter. However, ‘NC 19-020’ had the highest average number of crowns per plant (2.2) which was significantly more than ‘Albion’ (1.8) and ‘NC 21-033’ (1.6). By the end of the season (EOS), ‘Albion’ (21.5 millimeters) had a significantly larger average crown diameter than ‘NC 21-033’ (18.4 mm) and ‘NC 22-004’ (17.8 mm). Additionally, ‘NC 20-099’ (7.6 per plant) had significantly more crowns per plant than all others. ‘NC 20-099’ also had the highest foliar dry mass at the end of the season with an average of 95.8 g which was significantly higher than all other selections (Table 2.1).

### **Components of Yield**

The selection with the highest average marketable yield for the whole season was NC 19-020 at 350 g/plant, and this was significantly higher than NC 21-033 (157.5 g/plant) (Table 2.2). Yield varied across cultivars and over the course of the production season. ‘Albion’ and ‘NC 22-004’ had their highest yields during week 12 (18 March) of 2024. ‘NC 19-020’ had its highest yield during week 13 (25 March) of 2024, and during week 14 (1 April), it produced significantly more marketable fruit than all other selections. ‘NC 20-099’ and ‘NC 21-033’ had

their highest marketable yields during week 16 (15 April) of 2024 (Figure 2.2, Table B1).

‘Albion’ had the largest average fruit size at 19.8 g which was significantly larger than ‘NC 21-033’ (12.6 g) (Table 2.2).

### **Primary Fruit Chemistry**

‘Albion’ had the highest average pH (3.67), significantly higher than ‘NC 19-020’ (3.55) and ‘NC 20-099’ (3.50). On the other hand, ‘NC 21-033’ had the highest average TA at 47% which was significantly higher than all other selections. Additionally, ‘NC 21-033’ had the highest average TSS at 10.9, and this was also significantly higher than all other selections (Table 2.3). TSS varied across the selections and over the course of the season, but ‘NC 21-033’ had a significantly higher average TSS than all other selections during weeks 11 (11 March), 17 (22 April), and 18 (29 April) of 2024 (11.9, 11.8 and 10.9, respectively). ‘NC 19-020’ had its peak TSS during week 3 (15 January), and ‘NC 20-099’ peaked at 12.2 during week 6 (5 February) of 2024. ‘Albion’ and ‘NC 21-033’ had their highest average TSS (10.8 and 13.7, respectively) during week 10 (4 March) of 2024. Lastly, ‘NC 22-004’ had its highest average TSS at 10.2 during week 14 (1 April) of 2024 (Table B2).

### **Fruit Firmness**

For fruit firmness, ‘NC 20-004’ had the highest average first peak force (165.6 g), second peak force (203.9 g) and total force (548.2 g/sec) and was significantly higher than all other selections in all three categories (Table 2.4). The total force (TF) varied across cultivars and over the course of the season, but ‘NC 22-004’ had a significantly higher average TF than all other selections during weeks 11 (11 March) (617.5 g/sec) and 15 (8 April) (627.8 g/sec). ‘Albion’ showed its highest average TF (517.5 g/sec) during week 10 (4 March). ‘NC 19-020’ and ‘NC 21-033’ had their highest average TF (422.4 g/sec and 421.9 g/sec, respectively) during week 12

(18 March), and ‘NC 20-099’ and ‘NC 22-004’ had their highest average TF (482.4 g/sec and 671.4 g/sec, respectively) during week 14 (1 April) (Table B3).

For the first peak force (FPF), ‘Albion’ (146.7 g) and ‘NC 21-033’ (132.0 g) had their highest FPF at the beginning of the testing period and seemed to decline as time went on. On the other hand, ‘NC 19-020’ (109.9 g), ‘NC 20-099’ (143.0), and ‘NC 22-004’ (201.0) peaked in FPF later in the testing period. Additionally, ‘NC 19-020’ and ‘NC 21-033’ consistently showed lower FPF levels, with averages of 102.3 g and 109.9 g, respectively, over the entire season (Table B4). The second peak force (SPF) results showed that ‘NC 19-020’ (124.6 g) and ‘Albion’ had their highest SPF during the first half of the testing period. Conversely, ‘NC 20-099’ (178.0 g), ‘NC 21-033’ (184.3 g), and ‘NC 22-004’ (290.9 g) showed their highest SPF values within the last three weeks of the testing period (Table B5).

## **Discussion**

In greenhouse production, the controlled environment can be used to help alleviate some of the major challenges faced by traditional outdoor strawberry production, including labor costs, pest and disease pressures, and adverse weather conditions (Samtani et al., 2019; Hoffmann et al., 2024). Greenhouse production also allows for the management of important environmental factors such as temperature and photoperiod, which are both influential for the flowering and fruiting capacity of strawberries (Durner et al., 1984; Garcia & Kubota, 2017). Our findings highlight the potential of certain NC State strawberry breeding selections to perform well in a controlled environment greenhouse setting.

Hanson et al. (2006) showed a positive correlation between crown diameter and fruit yield in various strawberry cultivars grown in high tunnels. Our findings partially corroborate

this, as initial crown diameter measurements closely reflected the average total yield for the season; selections with larger crown diameters produced higher yields than those with smaller diameters. However, the end-of-season crown diameter data did not exhibit a strong correlation with yield. This discrepancy could be due to the method we used, which involved measuring only the diameter of the largest crown rather than all of the crowns collectively—a difference that becomes more pronounced over time. Additionally, neither the initial nor the end-of-season crown number showed a clear relationship with the overall yield of the selections. The foliar dry mass results were generally consistent with the total yield results, except for the selection ‘NC 20-099,’ which had significantly more dry mass than all other selections but fell in the middle of the group for yield. While vegetative growth is important for supporting high fruit yields, it's crucial to balance vegetative and reproductive growth to ensure that resources are used effectively for optimal fruit production (Albregts & Howard, 1986). This indicates that ‘NC 20-099’ was a vigorous selection that did not efficiently allocate resources to reproduction.

Our yield data showed significant differences among the selections, with ‘NC 19-020’ demonstrating particularly high yields, even outperforming the cultivar Albion. Additionally, ‘NC 19-020’ produced the largest fruits, which is advantageous for both market preference and ease of harvest. This aligns with previous research indicating that genetic factors play a major role in determining yield potential (Hancock et al., 2008). Most of the selections did not produce substantial yields during the first several weeks of the harvest period, especially ‘NC 20-099’ which did not produce any fruit until week 11 of 2024 (11 March), indicating that it’s not suitable for greenhouse production. The differences observed in the yield patterns of the selections also demonstrate the complex interaction between genetics and environmental factors,

emphasizing the need for targeted breeding programs to develop cultivars suited for specific conditions (Durner et al., 1984; Garcia & Kubota, 2017).

Strawberry flavor is an intricate characteristic of the fruit, influenced by sugars, acids (amino and organic), and aromatic compounds. The total sugar content plays a crucial role in flavor and can fluctuate depending on the cultivar and the time of the year (Haynes, 2024). TA is a measure of the non-volatile organic acids present in a sample. Historically, the acceptable sugar level, or total soluble solids (TSS) and TA were 7.0% and 0.8%, respectively. However, in more recent years, consumer preferences have shown that the minimum TSS should increase to 9.0%, while the TA should remain around 0.8%.

The primary chemistry results revealed significant differences in the fruit quality attributes of pH, total acidity (TA), and total soluble solids (TSS). The pH values ranged from 3.5, indicating higher acidity, to 3.67, indicating lower acidity. pH is an important component of flavor, as acidity inversely affects the perceived sweetness of strawberry fruit (Cordenunsi et al., 2003). The TA varied more widely across the selections, ranging from 0.29% to 0.47%. Higher TA levels contribute to the tartness of the fruit and influence the overall flavor balance (Kader, 1999). Notably, 'NC 21-033' exhibited a moderately high pH (less acidic) but also had the highest TA, suggesting a unique flavor profile for this selection. TSS is another vital quality parameter, correlating with perceived sweetness and overall fruit flavor, significantly affecting the marketability of strawberries, especially in North Carolina's local fresh markets (Hoffmann et al., 2024; Kader, 1999). A TSS of 7.0 is generally considered the minimum acceptable level for strawberry fruit (Kader, 1999). All selections exceeded this threshold except 'NC 19-020,' which fell below it, indicating that it may not be suitable for greenhouse production. TSS is critical for flavor and overall marketability, making it an essential factor in evaluating the potential of

different strawberry selections. Overall, 'NC 21-033' had a moderate pH, and the highest TA and TSS of all the selections indicating that it has high-quality flavor which could be useful for future breeding.

Fruit firmness is an important quality attribute for strawberry selection. Research has shown that harvesting at peak firmness can enhance both shelf life and consumer satisfaction (Kader, 1999; Vicente et al., 2009). The variability in firmness observed among the selections highlights the importance of including this trait in breeding objectives. 'NC 22-004' consistently demonstrated high firmness across all measures, while 'NC 19-020' and 'NC 21-033' showed lower firmness levels. Firmness has practical implications for production and marketability. For instance, selections with higher firmness, such as 'NC 22-004,' may be preferred for markets that require a longer shelf life, whereas softer cultivars like 'NC 21-033' might be better suited to local fresh markets. This differentiation emphasizes the need for breeding programs focused on developing cultivars that meet diverse market requirements.

The findings of this study demonstrate significant differences among the advanced selections in terms of yield, fruit quality, and firmness, emphasizing the importance of genetic selection in optimizing strawberry production in greenhouse environments. 'NC 19-020' was shown to produce the highest yields and large fruit sizes. The primary chemistry results showed that 'NC 21-033' exhibited a unique flavor profile with the highest TA and TSS. However, 'NC 19-020' fell below the acceptable TSS threshold, indicating potential limitations for its marketability based on sweetness. Fruit firmness results showed that 'NC 22-004' consistently demonstrated high firmness across all measures, while 'NC 19-020' and 'NC 21-033' had lower firmness levels. Overall, the results underscore the complex interaction between genetic factors and environmental conditions, emphasizing the need for targeted breeding programs to develop

cultivars that meet specific production and market needs. This study provides valuable insights for breeding decisions and future research directions, contributing to the ongoing efforts to develop resilient, high-yielding, and flavorful strawberry cultivars for North Carolina growers.

## TABLES

Table 2.1. Average crown diameter, crown number, and foliar dry mass of strawberry cultivar Albion and four NC State advanced selections grown in a greenhouse and sampled monthly from October 2023 – January 2024 and at the end of the season (EOS).

Selection	Crown Diameter (mm)	Crown Number	EOS Crown Diameter (mm)	EOS Crown Number	Foliar Dry Mass (g)
Albion	12.8 ± 0.31 <sup>i</sup>	1.8 ± 0.09 <sup>ii</sup> b <sup>iii</sup>	21.5 ± 0.56 a	4.2 ± 0.31 b	27.5 ± 2.5 <sup>iv</sup> b
NC 19-020	14.1 ± 0.32	2.2 ± 0.11 a	19.9 ± 0.85 abc	5.1 ± 0.30 b	29.3 ± 1.6 b
NC 20-099	26.9 ± 14.2	2.0 ± 0.11 ab	21.3 ± 1.00 ab	7.6 ± 0.68 a	95.8 ± 12.9 a
NC 21-033	12.2 ± 0.32	1.6 ± 0.10 b	18.4 ± 0.43 bc	4.2 ± 0.24 b	21.6 ± 1.3 b
NC 22-004	12.5 ± 0.29	1.9 ± 0.11 ab	17.8 ± 0.93 c	5.5 ± 0.39 b	27.3 ± 1.9 b

<sup>i</sup> Average crown diameter ± standard error

<sup>ii</sup> Average crown number ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons; columns with no letters showed no significant differences.

<sup>iv</sup> Average foliar dry mass ± standard error

Table 2.2. Components of yield. Average total marketable yield, non-marketable yield, and fruit size of strawberry cultivar Albion and four NC State advanced selections grown in a greenhouse.

Selection	Marketable (g/lm)	Non-Marketable (g/lm)	Marketable (g/plant)	Non-Marketable (g/plant)	Fruit Size (g)
Albion	2496 ± 61 <sup>i</sup> a <sup>ii</sup>	467 ± 21	312.0 ± 21.4 <sup>iii</sup> a	58.4 ± 7.4	19.8 ± 0.97 <sup>iv</sup> a
NC 19-020	2800 ± 129 a	813 ± 43	350.0 ± 45.5 a	101.6 ± 15.2	19.5 ± 1.43 a
NC 20-099	1870 ± 107 ab	751 ± 59	255.0 ± 39.5 ab	102.4 ± 21.7	16.6 ± 1.88 ab
NC 21-033	1155 ± 44 b	519 ± 21	157.5 ± 16.2 b	70.7 ± 7.7	12.6 ± 0.54 b
NC 22-004	1767 ± 44 ab	404 ± 14	252.5 ± 16.7 ab	57.8 ± 5.4	17.9 ± 1.19 a

<sup>i</sup> Average total yield in grams per linear meter ± standard error

<sup>ii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons; columns with no letters showed no significant differences.

<sup>iii</sup> Average total yield in grams per plant ± standard error

<sup>iv</sup> Average marketable fruit size ± standard error

Table 2.3. Primary postharvest chemistry: average pH, total acidity (TA), and total soluble solids (TSS) of strawberry cultivar Albion and four NC State advanced selections.

Selection	pH	TA	TSS
Albion	3.67 ± 0.02 <sup>i</sup> a <sup>ii</sup>	0.38 ± 0.01 <sup>iii</sup> b	9.3 ± 0.20 <sup>iv</sup> b
NC 19-020	3.55 ± 0.03 bc	0.29 ± 0.01 d	6.6 ± 0.19 d
NC 20-099	3.50 ± 0.04 c	0.42 ± 0.01 b	9.4 ± 0.37 b
NC 21-033	3.63 ± 0.02 ab	0.47 ± 0.01 a	10.9 ± 0.27 a
NC 22-004	3.61 ± 0.03 abc	0.33 ± 0.01 c	8.1 ± 0.19 c

<sup>i</sup> Average pH ± standard error

<sup>ii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons

<sup>iii</sup> Average total acidity (TA) ± standard error

<sup>iv</sup> Average total soluble solids (TSS) ± standard error

Table 2.4. Average firmness of strawberry cultivar Albion and four NC State advanced selections grown in a greenhouse.

Cultivar	FPF (g)	SPF (g)	TF (g/sec)
Albion	121.9 ± 4.1 <sup>i</sup> b <sup>ii</sup>	125.8 ± 3.7 <sup>iii</sup> bc	410.1 ± 11.2 <sup>iv</sup> b
NC 19-020	102.3 ± 3.8 c	105.8 ± 3.6 c	362.6 ± 11.4 bc
NC 20-099	103.5 ± 4.2 c	144.0 ± 6.7 b	384.0 ± 15.9 b
NC 21-033	109.9 ± 4.4 bc	140.2 ± 7.4 b	296.2 ± 11.7 c
NC 22-004	165.6 ± 5.7 a	203.9 ± 9.6 a	548.2 ± 23.3 a

<sup>i</sup> Average first peak force ± standard error

<sup>ii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Mean comparisons are within the same column and year.

<sup>iii</sup> Average second peak force ± standard error

<sup>iv</sup> Average total force (total area under the curve) ± standard error

## FIGURES



Figure 2.1. Photos taken of each selection on 25 March, 2024. A) Albion. B) NC 19-020. C) NC 20-099. D) NC 21-033. E) NC 22-004.

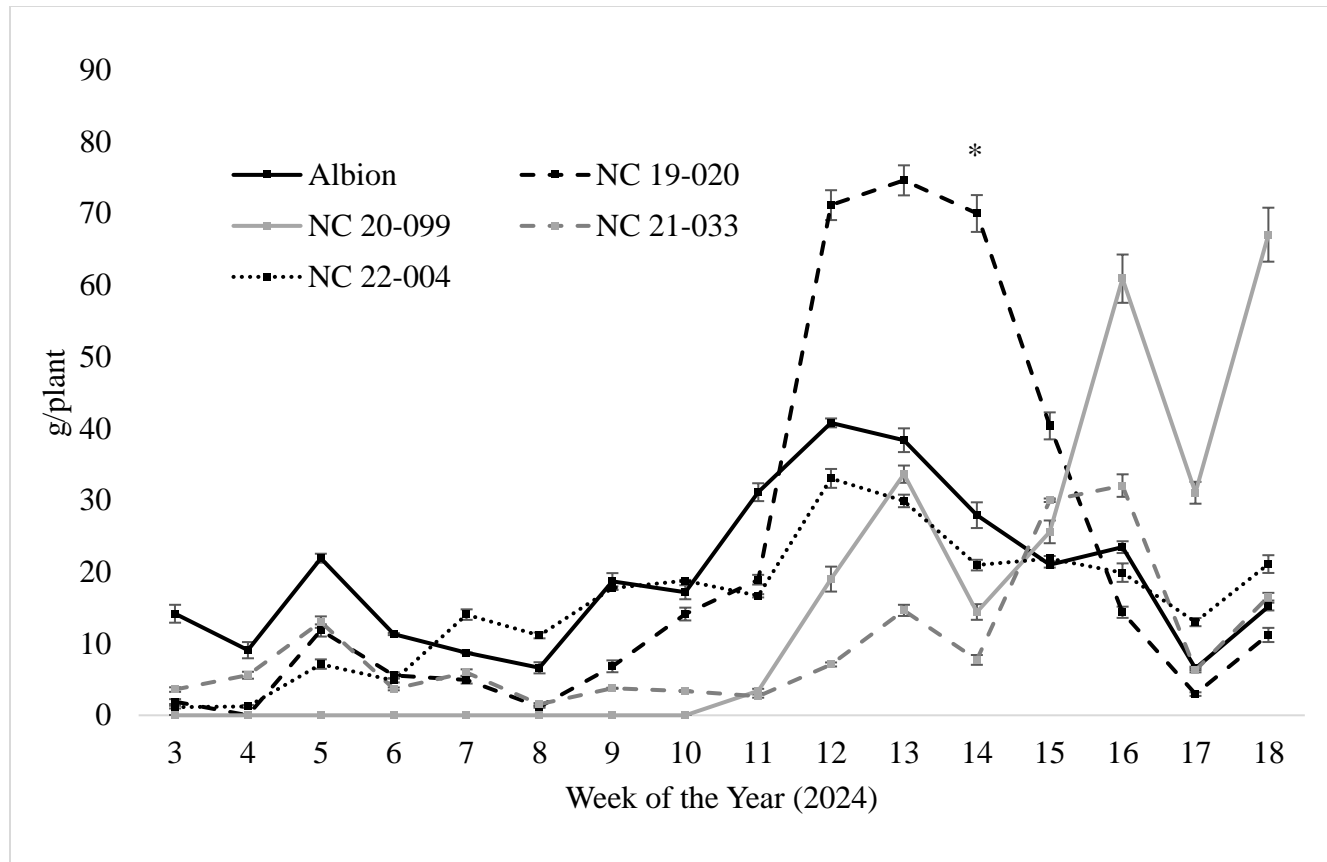


Figure 2.2. Weekly total marketable yield (g/plant). \* Indicates a significant difference between all selections ( $\alpha \leq 0.05$ ).

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## APPENDICES

## Appendix A

Table A1. Weekly average yield (g/plant) of seven greenhouse-grown strawberry cultivars.

2022-2023							
Week <sup>i</sup>	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
48	$1.0 \pm 0.1$ <sup>ii</sup> $b$ <sup>iii</sup>	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$3.3 \pm 0.3$ $a$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$
49	$1.8 \pm 0.3$ $b$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$6.1 \pm 0.3$ $a$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$
50	$5.6 \pm 0.5$ $a$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$7.8 \pm 0.3$ $a$	$0.9 \pm 0.2$ $b$	$0.0 \pm 0.0$ $b$
51	$2.9 \pm 0.3$ $ab$	$0.7 \pm 0.2$ $ab$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$	$4.5 \pm 0.5$ $a$	$0.0 \pm 0.0$ $b$	$0.0 \pm 0.0$ $b$
1	$43.0 \pm 2.1$ $a$	$37.2 \pm 1.7$ $ab$	$0.0 \pm 0.0$ $c$	$11.7 \pm 1.7$ $bc$	$36.8 \pm 0.6$ $ab$	$39.0 \pm 1.2$ $a$	$26.5 \pm 1.6$ $ab$
2	$10.8 \pm 0.5$ $a$	$14.5 \pm 0.7$ $a$	$0.0 \pm 0.0$ $a$	$8.9 \pm 1.7$ $a$	$6.1 \pm 0.3$ $a$	$10.6 \pm 0.9$ $a$	$7.6 \pm 0.7$ $a$
3	$11.8 \pm 0.2$ $ab$	$21.0 \pm 1.3$ $a$	$0.85 \pm 0.2$ $b$	$16.3 \pm 0.9$ $a$	$8.1 \pm 0.4$ $ab$	$18.9 \pm 0.5$ $a$	$17.0 \pm 0.8$ $a$
4	$13.9 \pm 0.3$ $ab$	$14.3 \pm 1.3$ $ab$	$1.2 \pm 0.2$ $b$	$16.6 \pm 1.4$ $a$	$9.6 \pm 0.4$ $ab$	$10.4 \pm 0.6$ $ab$	$4.7 \pm 0.6$ $ab$

Table A1. (continued)

5	$8.4 \pm 0.3$ a	$7.4 \pm 0.6$ a	$0.0 \pm 0.0$ a	$8.3 \pm 0.8$ a	$3.3 \pm 0.4$ a	$0.4 \pm 0.1$ a	$7.4 \pm 0.5$ a
6	$5.3 \pm 0.5$ ab	$2.1 \pm 0.2$ bc	$0.0 \pm 0.0$ c	$1.1 \pm 0.3$ bc	$1.0 \pm 0.3$ bc	$3.5 \pm 0.01$ bc	$9.1 \pm 0.3$ a
7	$21.9 \pm 0.5$ ab	$19.8 \pm 1.0$ ab	$10.4 \pm 0.9$ b	$25.6 \pm 1.4$ ab	$17.7 \pm 0.7$ ab	$21.3 \pm 1.1$ ab	$28.8 \pm 0.7$ a
8	$17.9 \pm 0.4$ c	$21.8 \pm 0.6$ abc	$8.3 \pm 0.4$ d	$18.1 \pm 0.6$ c	$20.9 \pm 0.7$ bc	$30.7 \pm 0.4$ a	$30.2 \pm 0.4$ ab
9	$13.9 \pm 0.8$ cd	$23.7 \pm 0.4$ bc	$6.2 \pm 0.2$ d	$10.6 \pm 0.6$ d	$24.2 \pm 0.8$ bc	$40.2 \pm 0.6$ a	$31.6 \pm 1.0$ ab
10	$10.7 \pm 0.9$ bcd	$21.5 \pm 0.8$ bc	$5.3 \pm 0.4$ d	$5.5 \pm 0.5$ d	$8.3 \pm 0.5$ cd	$37.0 \pm 0.8$ a	$24.7 \pm 1.4$ ab
11	$9.6 \pm 0.4$ ab	$2.1 \pm 0.3$ b	$2.4 \pm 0.2$ b	$4.0 \pm 0.5$ b	$5.2 \pm 0.5$ b	$10.6 \pm 1.1$ ab	$16.7 \pm 0.7$ a
12	$7.5 \pm 0.5$ bc	$6.9 \pm 0.4$ bc	$1.4 \pm 0.4$ c	$7.2 \pm 0.3$ bc	$2.5 \pm 0.4$ c	$15.2 \pm 0.2$ ab	$18.6 \pm 1.2$ a
13	$23.0 \pm 0.8$ bc	$13.9 \pm 0.5$ c	$21.9 \pm 0.6$ bc	$26.3 \pm 0.9$ bc	$17.8 \pm 1.0$ bc	$39.2 \pm 2.3$ ab	$51.6 \pm 1.5$ a
14	$111.3 \pm 3.2$ ab	$93.0 \pm 4.7$ b	$180.6 \pm 4.7$ a	$128.1 \pm 3.4$ ab	$152.2 \pm 3.2$ ab	$112.6 \pm 2.9$ ab	$113.0 \pm 1.7$ ab
15	$66.3 \pm 2.8$ ab	$103.1 \pm 2.8$ a	$106.6 \pm 2.8$ a	$104.0 \pm 4.7$ a	$85.5 \pm 3.1$ ab	$103.0 \pm 1.5$ a	$48.3 \pm 0.3$ b

Table A1. (continued)

16	100.7 ± 1.6 a	143.8 ± 3.5 a	137.4 ± 3.5 a	156.7 ± 5.9 a	130.1 ± 3.1 a	131.0 ± 2.6 a	39.7 ± 0.8 b
17	51.2 ± 0.2 ab	86.2 ± 1.2 a	68.0 ± 1.2 a	85.5 ± 5.5 a	70.9 ± 0.8 a	52.3 ± 1.5 ab	12.5 ± 0.5 b
18	18.2 ± 0.9 ab	19.9 ± 0.8 ab	25.0 ± 1.4 ab	34.4 ± 2.0 a	34.8 ± 0.9 a	27.3 ± 0.4 ab	12.4 ± 0.3 b
19	11.2 ± 1.2 a	4.3 ± 0.2 a	8.3 ± 0.4 a	10.3 ± 1.0 a	9.8 ± 0.7 a	11.4 ± 0.8 a	9.6 ± 0.4 a
20	12.0 ± 0.9 ab	1.5 ± 0.3 b	9.9 ± 0.6 ab	6.9 ± 0.7 ab	14.5 ± 1.4 ab	10.2 ± 0.4 ab	16.2 ± 0.4 a
21	9.7 ± 0.5 b	1.4 ± 0.3 b	6.0 ± 0.8 b	4.3 ± 0.6 b	10.9 ± 0.3 b	6.1 ± 0.4 b	22.1 ± 0.7 a
2023-2024							
Week	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
48	19.2 ± 0.4 a	6.2 ± 0.3 bc	3.5 ± 0.6 bc	0.0 ± 0.0 c	8.0 ± 0.5 b	2.7 ± 0.4 bc	0.0 ± 0.0 c
49	11.7 ± 0.2 a	7.3 ± 0.9 ab	5.7 ± 1.1 ab	0.0 ± 0.0 b	6.5 ± 0.4 ab	2.9 ± 0.7 ab	0.3 ± 0.1 b
50	8.0 ± 0.4 b	15.2 ± 0.7 a	1.0 ± 0.3 bc	0.0 ± 0.0 c	5.7 ± 0.6 bc	0.0 ± 0.0 c	0.0 ± 0.0 c

Table A1. (continued)

51	$14.2 \pm 0.6$ b	$32 \pm 0.5$ a	$5.8 \pm 0.9$ bc	$0.0 \pm 0.0$ c	$11.8 \pm 0.6$ bc	$11.1 \pm 1.5$ bc	$6.7 \pm 0.6$ bc
1	$21.4 \pm 0.6$ ab	$28.2 \pm 0.5$ a	$12.8 \pm 1.2$ bc	$0.0 \pm 0.0$ c	$15.8 \pm 1.0$ bc	$15.8 \pm 1.4$ abc	$13.2 \pm 1.1$ abc
2	$13.7 \pm 0.6$ a	$9.2 \pm 0.5$ ab	$5.1 \pm 0.7$ bc	$0.0 \pm 0.0$ c	$6.0 \pm 0.7$ abc	$6.0 \pm 0.4$ abc	$3.3 \pm 0.3$ bc
3	$12.7 \pm 0.1$ a	$9.0 \pm 0.8$ a	$6.4 \pm 0.8$ a	$3.9 \pm 0.4$ a	$9.7 \pm 0.5$ a	$9.7 \pm 0.5$ a	$16.3 \pm 1.4$ a
4	$11.1 \pm 0.5$ a	$14.0 \pm 0.9$ a	$10.7 \pm 0.8$ a	$4.5 \pm 0.3$ a	$13.7 \pm 0.6$ a	$13.7 \pm 0.8$ a	$8.0 \pm 0.6$ a
5	$21.1 \pm 0.8$ ab	$24.7 \pm 1.0$ ab	$16.8 \pm 0.4$ bc	$11.9 \pm 1.1$ bc	$34.4 \pm 0.4$ c	$34.4 \pm 0.7$ a	$20.6 \pm 0.6$ ab
6	$10.7 \pm 0.2$ bc	$21.1 \pm 1.3$ ab	$13.5 \pm 0.2$ bc	$4.0 \pm 0.3$ c	$32.1 \pm 0.3$ c	$32.1 \pm 1.1$ a	$10.8 \pm 0.7$ bc
7	$12.2 \pm 0.3$ abc	$21.2 \pm 0.9$ a	$16.4 \pm 0.7$ abc	$7.0 \pm 0.6$ bc	$3.7 \pm 0.4$ c	$16.2 \pm 0.9$ ab	$10.8 \pm 0.1$ abc
8	$5.6 \pm 0.6$ c	$6.4 \pm 0.4$ c	$12.7 \pm 0.5$ bc	$15.8 \pm 0.8$ abc	$2.8 \pm 0.3$ c	$22.1 \pm 1.3$ ab	$23.7 \pm 1.1$ a
9	$20.1 \pm 0.7$ c	$29.0 \pm 0.7$ bc	$32.3 \pm 2.7$ c	$31.9 \pm 1.0$ abc	$19.5 \pm 1.0$ c	$52.7 \pm 0.8$ a	$43.2 \pm 1.1$ ab
10	$27.1 \pm 1.1$ ab	$32.1 \pm 1.9$ ab	$22.1 \pm 1.2$ b	$33.1 \pm 1.3$ ab	$24.8 \pm 1.8$ ab	$52.1 \pm 2.3$ a	$30.2 \pm 1.0$ ab

Table A1. (continued)

11	21.3 ± 1.2 ab	20.9 ± 1.2 ab	18.4 ± 1.7 b	27.8 ± 0.3 ab	36.3 ± 0.6 a	38.7 ± 0.8 a	29.6 ± 1.2 ab
12	32.3 ± 0.8 bc	37.0 ± 0.4 bc	27.7 ± 1.9 c	50.6 ± 0.9 ab	62.2 ± 1.2 a	46.2 ± 1.3 ab	42.5 ± 1.0 b
13	38.2 ± 1.9 b	30.9 ± 1.7 b	25.3 ± 2.4 b	77.4 ± 2.2 ab	48.8 ± 3.0 ab	28.1 ± 1.3 b	40.3 ± 2.1 ab
14	34.7 ± 1.0 b	27.6 ± 1.2 bc	10.1 ± 0.9 c	70.9 ± 2.1 a	71.4 ± 2.0 a	18.5 ± 1.5 bc	24.3 ± 1.0 bc
15	32.2 ± 1.3 ab	21.0 ± 1.4 b	13.4 ± 0.9 b	57.9 ± 2.6 a	60.6 ± 1.5 a	16.3 ± 0.5 b	24.9 ± 2.0 b
16	20.4 ± 1.3 abc	35.0 ± 1.4 a	8.0 ± 0.2 c	26.1 ± 1.2 ab	31.9 ± 1.0 ab	19.8 ± 0.2 abc	14.3 ± 1.0 bc
17	9.7 ± 0.8 ab	9.1 ± 0.4 ab	3.2 ± 0.4 c	2.5 ± 0.2 bc	11.8 ± 0.4 a	5.9 ± 0.2 abc	5.2 ± 0.2 abc
18	16.3 ± 0.6 ab	29.8 ± 1.6 a	8.3 ± 0.5 b	11.0 ± 1.1 b	20.6 ± 0.1 ab	13.7 ± 0.6 ab	19.4 ± 1.0 ab

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average weekly yield (g/plant) ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test ( $P < 0.05$ ) for multiple comparisons. Comparisons are within each week, across all cultivars.

Table A2. Weekly average total soluble solids (TSS) of seven greenhouse-grown strawberry cultivars.

2023							
Week <sup>i</sup>	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
7	9.0 ± 0.31 <sup>ii</sup>	8.0 ± 0.64	7.2 ± 0.00 <sup>iii</sup>	8.2 ± 0.19	8.9 ± 0.33	9.5 ± 0.93	8.8 ± 0.32
8	6.9 ± 0.27	7.4 ± 0.21	5.9 ± 0.00	6.8 ± 0.13	7.1 ± 0.14	7.0 ± 0.13	6.7 ± 0.78
9	6.9 ± 0.07 a <sup>iv</sup>	5.9 ± 0.20 bc	4.8 ± 0.12 d	5.6 ± 0.15 c	6.1 ± 0.20 bc	6.5 ± 0.04 ab	6.9 ± 0.05 a
10	6.4 ± 0.13 a	6.8 ± 0.22 b	n/a	n/a	5.6 ± 0.05 ab	5.8 ± 0.19 ab	6.3 ± 0.17 a
11	7.9 ± 0.00 a	n/a	n/a	n/a	6.1 ± 0.00 b	6.8 ± 0.15 b	8.2 ± 0.13 a
12	9.5 ± 0.66 a	7.0 ± 0.00 b	6.3 ± 0.00 ab	n/a	n/a	8.1 ± 0.23 b	8.1 ± 0.30 ab
13	6.4 ± 0.29 ab	6.7 ± 0.22 b	5.3 ± 0.38 ab	5.6 ± 0.17 ab	6.3 ± 0.48 ab	6.8 ± 0.12 a	6.8 ± 0.18 a
14	4.2 ± 1.08 b	4.6 ± 0.11 ab	6.1 ± 0.36 ab	5.5 ± 0.19 ab	6.4 ± 0.15 a	6.0 ± 0.21 ab	6.6 ± 0.09 a
15	6.1 ± 0.20 ab	4.0 ± 0.20 d	4.8 ± 0.17 cd	4.8 ± 0.21 cd	5.5 ± 0.19 bc	5.4 ± 0.07 bc	6.9 ± 0.18 a

Table A2. (continued)

16	7.8 ± 0.06 b	5.4 ± 0.12 c	7.4 ± 0.36 b	7.6 ± 0.15 b	7.7 ± 0.30 b	6.6 ± 0.40 bc	9.6 ± 0.31 a
17	8.1 ± 0.21 ab	6.9 ± 0.47 b	8.8 ± 0.41 a	8.0 ± 0.36 ab	8.6 ± 0.45 ab	8.1 ± 0.23 ab	9.2 ± 0.36 a
18	8.3 ± 0.18 ab	7.6 ± 0.44 ab	8.0 ± 0.36 ab	8.3 ± 0.23 ab	7.5 ± 0.22 ab	7.1 ± 0.10 b	8.8 ± 0.44 a
19	8.7 ± 0.19	8.2 ± 0.65	8.6 ± 0.40	8.5 ± 0.05	9.2 ± 0.69	7.8 ± 0.55	9.3 ± 0.23
20	8.3 ± 0.12 a	n/a	6.7 ± 0.10 ab	5.4 ± 0.60 b	7.2 ± 0.21 ab	7.4 ± 0.49 ab	8.4 ± 0.72 a
21	7.3 ± 0.32 ab	n/a	6.1 ± 0.60 b	5.2 ± 0.00 b	7.2 ± 0.54 ab	6.6 ± 0.00 ab	9.0 ± 0.14 a
2024							
Week	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
1	9.8 ± 0.32	10.4 ± 0.13	9.5 ± 0.22	n/a	9.8 ± 0.36	10.1 ± 0.52	10.0 ± 0.35
2	10.2 ± 0.17	n/a	n/a	n/a	10.3 ± 0.0	n/a	n/a
3	10.6 ± 0.53	10.5 ± 0.00	10.5 ± 0.35	n/a	10.1 ± 0.2	9.5 ± 0.0	8.7 ± 0.20

Table A2. (continued)

4	10.2 ± 0.2	10.5 ± 0.60	10.1 ± 0.00	n/a	9.9 ± 0.95	9.9 ± 0.0	9.1 ± 0.00
5	9.6 ± 0.31 a	9.7 ± 0.44 a	8.7 ± 0.17 ab	6.9 ± 0.13 c	8.7 ± 0.4 ab	9.0 ± 0.36 ab	8.3 ± 0.14 bc
6	9.8 ± 0.05	9.6 ± 0.31	9.5 ± 0.38	8.4 ± 1.0	8.4 ± 0.45	8.8 ± 0.23	9.2 ± 0.17
7	9.2 ± 0.23 ab	10.3 ± 0.60 a	8.7 ± 0.20 abc	7.2 ± 0.40 c	7.9 ± 0.0 bc	8.9 ± 0.41 abc	8.4 ± 0.28 bc
8	9.1 ± 0.13 a	9.6 ± 0.40 a	8.9 ± 0.44 ab	7.4 ± 0.21 c	7.5 ± 0.15 bc	9.1 ± 0.36 a	8.6 ± 0.29 abc
9	7.9 ± 0.35 abc	8.4 ± 0.30 ab	9.3 ± 0.46 a	6.5 ± 0.30 c	7.1 ± 0.19 bc	8.0 ± 0.45 abc	7.9 ± 0.14 abc
10	10.5 ± 0.34 a	10.6 ± 0.31 a	10.0 ± 0.21 ab	7.7 ± 0.20 c	8.9 ± 0.60 abc	10.0 ± 0.49 ab	8.8 ± 0.29 bc
11	8.8 ± 0.49 a	9.0 ± 0.52 a	9.2 ± 0.26 a	6.7 ± 0.29 b	6.8 ± 0.15 b	9.7 ± 0.62 a	9.4 ± 0.38 a
12	9.2 ± 0.60 a	7.8 ± 0.38 ab	9.0 ± 0.33 a	5.9 ± 0.19 c	6.5 ± 0.20 bc	8.3 ± 0.55 a	8.3 ± 0.20 a
13	9.6 ± 0.18 abc	9.1 ± 0.49 abc	11.3 ± 0.65 a	7.6 ± 0.43 c	8.1 ± 0.17 bc	10.5 ± 0.92 ab	9.8 ± 0.59 ab
14	10.2 ± 0.36 ab	8.9 ± 0.73 abc	11.1 ± 0.55 a	7.3 ± 0.37 c	7.9 ± 0.23 bc	11.1 ± 0.47 a	10.3 ± 0.76 ab

Table A2. (continued)

15	9.2 ± 0.81	7.9 ± 0.36	9.3 ± 1.1	7.5 ± 0.41	8.1 ± 0.25	7.9 ± 0.19	9.4 ± 0.34
16	7.4 ± 0.20 ab	6.4 ± 0.22 b	7.7 ± 0.47 ab	7.2 ± 0.56 ab	7.0 ± 0.12 ab	6.4 ± 0.48 b	8.3 ± 0.19 a
17	9.2 ± 0.45 ab	7.9 ± 0.20 b	10.0 ± 0.72 a	7.8 ± 0.35 b	9.0 ± 0.21 ab	8.7 ± 0.12 ab	10.0 ± 0.20 a
18	9.2 ± 0.38 a	8.6 ± 0.23 ab	10.1 ± 0.31 a	6.6 ± 0.30 c	7.4 ± 0.06 bc	10.1 ± 0.59 a	8.9 ± 0.38 ab

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average total soluble solids (TSS) ± standard error

<sup>iii</sup> Standard error of '0.00' indicates the data is only from one replicate, so there is no standard error.

<sup>iv</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test ( $P < 0.05$ ) for multiple comparisons. Comparisons are within each week, across all cultivars.

Table A3. Weekly average fruit firmness of seven greenhouse-grown strawberry cultivars as measured by the total force (TF) (g/sec) required to puncture through the fruit.

Week <sup>i</sup>	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
2	540.7 ± 41 <sup>ii</sup> bc <sup>iii</sup>	846.6 ± 71 a	749.6 ± 75 ab	n/a	560.8 ± 39 bc	725.0 ± 84 ab	348.3 ± 34 c
3	658.7 ± 35 bc	865.9 ± 52 a	792.7 ± 81 ab	829.9 ± 116 ab	531.2 ± 33 cd	729.6 ± 44 ab	358.7 ± 19 d
4	617.3 ± 44 b	795.9 ± 52 a	586.0 ± 30 b	547.8 ± 38 bc	591.2 ± 64 b	696.0 ± 34 ab	368.5 ± 25 c
5	439.3 ± 23 a	591.2 ± 41 a	457.1 ± 53 a	560.0 ± 51 a	430.6 ± 28 ab	566.8 ± 34 a	266.9 ± 19 b
6	439.3 ± 33 c	765.4 ± 56 a	516.0 ± 48 bc	511.5 ± 70 bc	444.3 ± 20 c	660.4 ± 35 ab	349.7 ± 22 c
7	451.7 ± 21 b	649.3 ± 46 a	531.4 ± 41 ab	606.0 ± 42 ab	540.3 ± 58 ab	552.3 ± 39 ab	295.4 ± 18 c
8	534.9 ± 51 a	602.5 ± 45 a	619.9 ± 42 a	700.5 ± 64 a	522.9 ± 62 ab	573.5 ± 38 a	345.2 ± 16 b
9	489.2 ± 30 bc	793.2 ± 59 a	615.6 ± 26 b	631.3 ± 41 b	619.4 ± 32 b	601.2 ± 33 b	347.8 ± 16 c
10	417.8 ± 19 bc	593.6 ± 43 a	542.2 ± 43 ab	537.6 ± 30 ab	538.8 ± 54 ab	425.9 ± 17 bc	286.2 ± 14 c
11	339.3 ± 14 cd	584.6 ± 43 a	516.4 ± 57 ab	464.2 ± 21 abc	376.8 ± 23 bc	430.9 ± 16 bc	239.1 ± 12 d

Table A3. (continued)

12	433.6 ± 24 ab	504.0 ± 31 a	403.2 ± 23 b	480.3 ± 30 ab	427.2 ± 18 ab	428.7 ± 23 ab	237.5 ± 13 c
13	305.0 ± 18 cd	495.9 ± 19 a	375.3 ± 30 bc	428.7 ± 23 ab	365.9 ± 19 bc	405.8 ± 20 b	230.1 ± 13 d
14	589.2 ± 40 b	797.1 ± 53 a	555.0 ± 48 bc	674.1 ± 31 ab	569.2 ± 42 bc	413.5 ± 41 c	240.6 ± 11 d
15	398.9 ± 20 bc	580.1 ± 42 a	399.2 ± 27 bc	549.3 ± 37 a	429.1 ± 23 b	399.0 ± 26 bc	292.0 ± 21 c
16	316.1 ± 24 b	492.1 ± 49 a	285.0 ± 58 b	364.4 ± 39 ab	342.0 ± 32 b	374.0 ± 42 ab	208.8 ± 16 b
17	340.7 ± 17 cd	725.3 ± 37 a	310.3 ± 39 cd	458.2 ± 47 bc	368.1 ± 16c d	493.1 ± 28 b	286.4 ± 11 d
18	299.3 ± 28 bc	480.5 ± 52 a	351.6 ± 31 abc	353.9 ± 34 abc	296.9 ± 14 bc	397.1 ± 30 ab	254.2 ± 17 c

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average total force (total area under the curve) in g/sec ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all cultivars.

Table A4. Weekly average skin firmness of seven greenhouse-grown strawberry cultivars as measured by the first peak force (FPF) (g) required to puncture through the skin of the fruit.

Week <sup>i</sup>	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
2	135.5 ± 12 <sup>i</sup> bc	193.8 ± 9 a	182.1 ± 17 ab	n/a	166.7 ± 16 ab	140.5 ± 15 abc	92.8 ± 10 c
3	164.9 ± 10 bc	229.1 ± 15 a	219.3 ± 15 ab	138.1 ± 6 cd	150.3 ± 17 cd	159.2 ± 11 cd	115.0 ± 7 cd
4	167.8 ± 9 bc	229.2 ± 13 a	176.2 ± 10 b	132.3 ± 6 bc	163.5 ± 16 bc	159.7 ± 9 bc	126.5 ± 8 c
5	103.6 ± 5 bc	174.1 ± 14 a	131.2 ± 11 b	112.5 ± 7 bc	131.6 ± 7 ab	116.2 ± 6 bc	83.5 ± 5 c
6	120.3 ± 9 bc	190.7 ± 13 a	141.3 ± 9 bc	96.9 ± 5 c	128.1 ± 7 bc	145.7 ± 7 b	103.8 ± 9 c
7	109.4 ± 8 ab	142.3 ± 12 a	141.4 ± 15 a	135.5 ± 9 ab	146.9 ± 15 a	131.3 ± 7 ab	95.6 ± 5 ab
8	146.3 ± 12 a	136.5 ± 12 ab	154.6 ± 14 a	136.6 ± 12 ab	134.1 ± 9 ab	143.1 ± 7 a	100.7 ± 5 b
9	118.2 ± 6 bc	168.1 ± 11 a	144.4 ± 8 ab	116.0 ± 8 bc	138.5 ± 6 ab	138.2 ± 7 ab	89.7 ± 6 c
10	118.0 ± 7 abc	148.4 ± 11 ab	151.7 ± 7 a	107.6 ± 9 c	126.6 ± 10 abc	114.7 ± 6 bc	101.5 ± 7 c
11	99.6 ± 6 bc	149.2 ± 12 a	136.8 ± 12 a	98.0 ± 6 bc	98.0 ± 6 bc	130.0 ± 5 ab	83.5 ± 5 c

Table A4. (continued)

12	97.2 ± 6 ab	108.6 ± 6 a	113.0 ± 7 a	99.2 ± 8 ab	101.9 ± 6 ab	105.7 ± 6 a	76.5 ± 4 b
13	92.7 ± 6 ab	119.8 ± 7 a	115.1 ± 9 a	109.3 ± 8 a	107.3 ± 6 a	107.3 ± 6 a	75.7 ± 4 b
14	131.4 ± 7 ab	149.8 ± 9 a	138.3 ± 13 ab	110.8 ± 8 b	121.6 ± 7 ab	100.6 ± 7 bc	74.0 ± 5 c
15	102.2 ± 7 ab	137.2 ± 12 a	116.9 ± 13 ab	98.0 ± 9 b	102.5 ± 4 ab	125.0 ± 9 ab	90.9 ± 7 b
16	81.5 ± 8 bc	116.0 ± 10 ab	85.9 ± 18 abc	127.5 ± 12 a	93.1 ± 9 abc	98.1 ± 9 abc	70.4 ± 8 c
17	79.1 ± 4 c	130.8 ± 9 a	76.7 ± 8 c	93.3 ± 20 bc	98.9 ± 4 bc	120.2 ± 10 ab	86.6 ± 3 c
18	85.4 ± 7	102.7 ± 13	106.1 ± 8	104.8 ± 10	90.6 ± 6	104.9 ± 5	72.8 ± 5

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average first peak force (force required to puncture fruit skin) in g ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all cultivars.

Table A5. Weekly average fruit flesh firmness of seven greenhouse-grown strawberry cultivars as measured by the second peak force (SPF) (g) required to puncture through the inner flesh of the fruit.

Week <sup>i</sup>	Albion	Brilliance	Camino Real	Fronteras	Monterey	Sweet Sensation	Sweet Charlie
2	152.3 ± 13 <sup>ii</sup> abc <sup>iii</sup>	209.3 ± 17 a	206.7 ± 32 ab	n/a	137.6 ± 9 bc	162.3 ± 24 abc	96.0 ± 6 c
3	210.4 ± 14 abc	250.1 ± 10 a	235.8 ± 27 ab	132.2 ± 10 cd	178.4 ± 12 bc	185.2 ± 9 bc	88.5 ± 5 d
4	203.4 ± 15 a	216.5 ± 15 a	184.3 ± 9 a	142.0 ± 19 ab	167.4 ± 13 a	193.3 ± 13 a	104.0 ± 7 b
5	149.9 ± 11 a	139.5 ± 8 a	135.7 ± 9 a	109.1 ± 6 ab	123.7 ± 12 a	150.4 ± 8 a	72.5 ± 5 b
6	144.6 ± 12 bc	211.2 ± 17 a	172.0 ± 16 abc	119.5 ± 22 bc	147.1 ± 11 bc	186.9 ± 16 ab	112.3 ± 11 c
7	167.2 ± 10 ab	201.2 ± 15 a	192.6 ± 19 a	126.2 ± 8 bc	165.5 ± 17 ab	161.1 ± 10 ab	78.0 ± 5 c
8	183.1 ± 22 a	194.0 ± 16 a	192.7 ± 14 a	181.8 ± 13 a	166.3 ± 30 ab	175.3 ± 14 a	90.2 ± 5 b
9	152.3 ± 11 c	219.8 ± 14 a	200.1 ± 9 ab	166.9 ± 11 bc	165.8 ± 9 bc	178.4 ± 11 abc	89.7 ± 5 d
10	124.4 ± 6 bc	182.2 ± 13 a	179.3 ± 15 a	153.3 ± 10 ab	138.1 ± 16 ab	137.4 ± 7 ab	85.3 ± 5 c
11	110.2 ± 7 cd	200.3 ± 16 a	181.2 ± 20 ab	148.2 ± 13 abc	118.1 ± 10 cd	141.8 ± 8 bc	73.2 ± 3 d

Table A5. (continued)

12	161.1 ± 13 ab	190.5 ± 16 a	157.4 ± 12 ab	171.2 ± 12 ab	133.1 ± 9 b	142.8 ± 11 ab	82.3 ± 6 c
13	120.6 ± 9 c	196.6 ± 8 a	139.6 ± 13 bc	158.5 ± 7 b	122.1 ± 9 c	149.7 ± 9 bc	78.8 ± 4 d
14	200.4 ± 13 bcd	304.0 ± 21 a	214.3 ± 18 bc	240.3 ± 10 b	171.0 ± 10 cd	141.6 ± 17 d	68.7 ± 3 e
15	147.3 ± 11 b	207.1 ± 15 a	142.0 ± 14 b	208.0 ± 12 a	139.0 ± 11 b	142.5 ± 12 b	98.3 ± 9 b
16	129.0 ± 12 ab	183.0 ± 17 a	143.1 ± 57 ab	179.3 ± 17 a	144.2 ± 11 ab	130.0 ± 15 ab	86.2 ± 11 b
17	128.7 ± 8 c	309.9 ± 19 a	133.8 ± 20 bc	206.4 ± 26 b	131.7 ± 8 c	207.9 ± 16 b	107.2 ± 6 c
18	113.3 ± 12 bcd	175.5 ± 18 a	134.7 ± 15 abc	151.5 ± 16 ab	88.0 ± 5 cd	160.7 ± 14 ab	78.9 ± 5 d

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average second peak force (force required to puncture fruit skin) in g ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all cultivars.

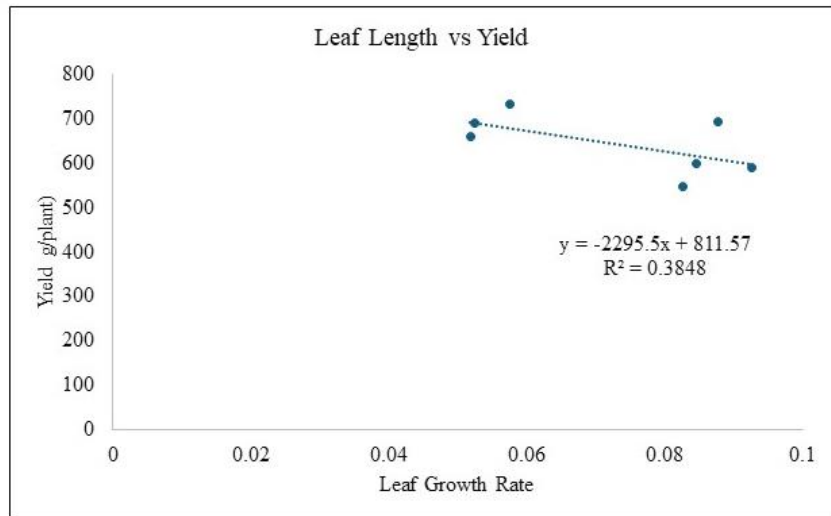
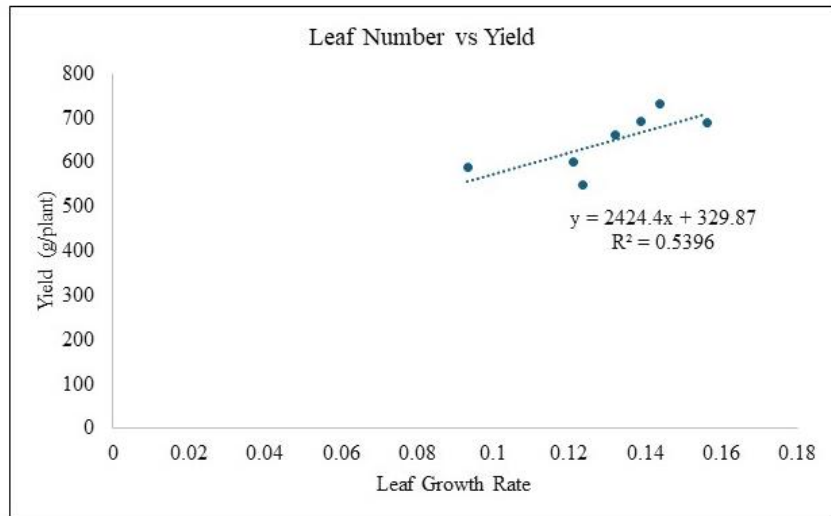


Figure A1. Leaf number growth rate and leaf length growth rate compared to total yield of seven greenhouse-grown strawberry cultivars.

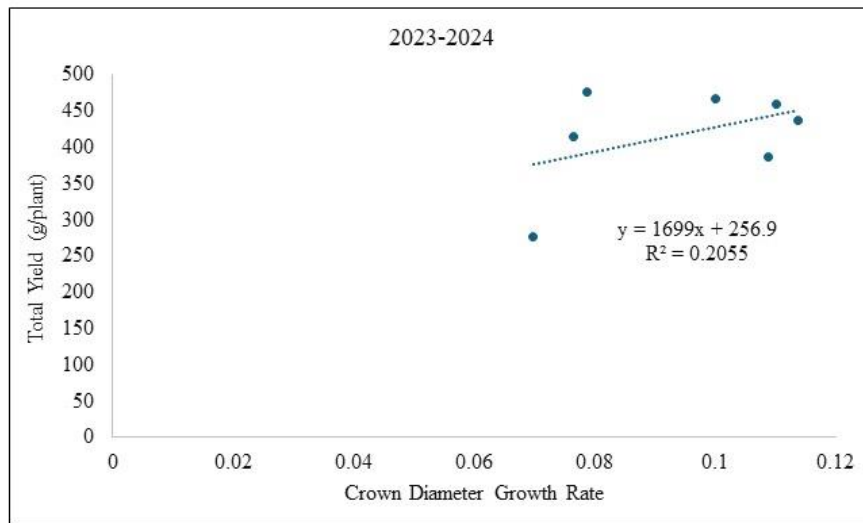
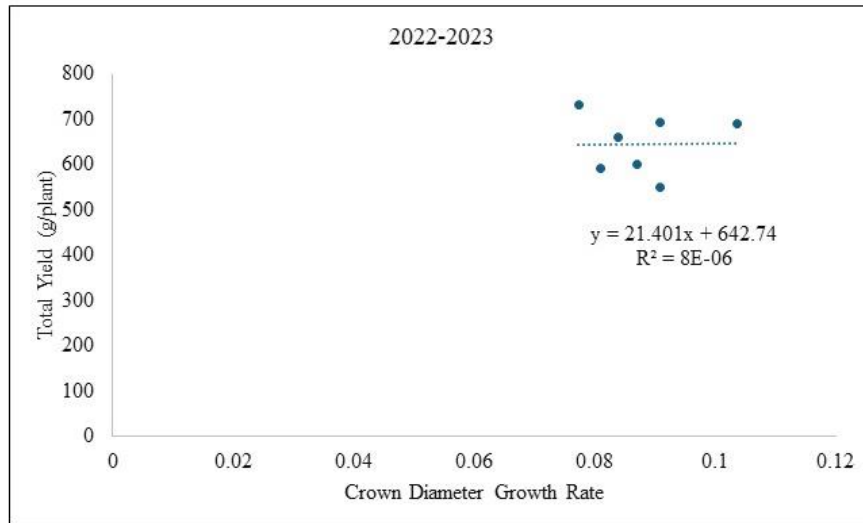


Figure A2. Crown diameter growth rate vs total yield of seven greenhouse-grown strawberry cultivars.

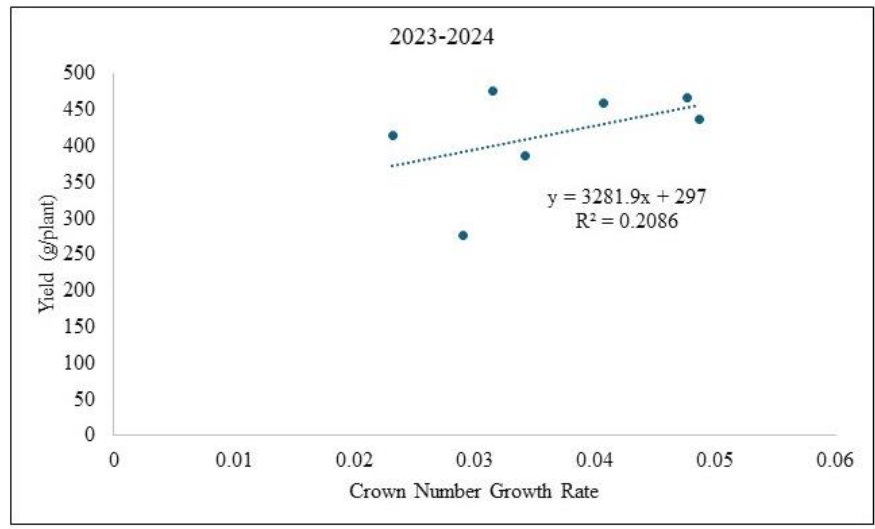
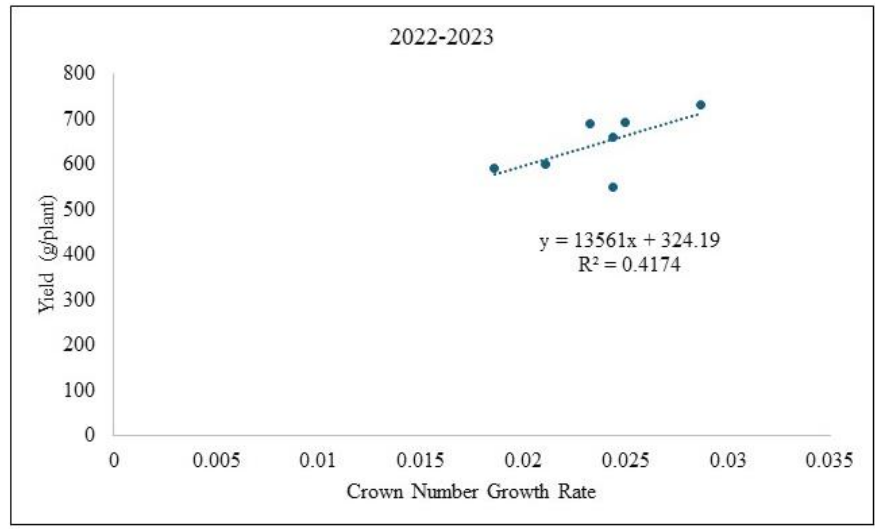


Figure A3. Crown number growth rate vs total yield of seven greenhouse-grown strawberry cultivars.

## Appendix B

Table B1. Weekly average yield (g/plant) of strawberry cultivar Albion and four NC State advanced selections.

Week <sup>i</sup>	Albion	NC 19-020	NC 20-099	NC 21-033	NC 22-004
3	14.2 ± 1.2 <sup>ii</sup>	1.9 ± 0.3	0.0 ± 0.0	3.6 ± 0.3	1.1 ± 0.2
4	9.1 ± 1.1	0.0 ± 0.0	0.0 ± 0.0	5.6 ± 0.5	1.2 ± 0.2
5	21.9 ± 0.6 a <sup>iii</sup>	11.8 ± 0.8 ab	0.0 ± 0.0 b	13 ± 0.8 ab	7.1 ± 0.7 ab
6	11.3 ± 0.1 a	5.6 ± 0.4 ab	0.0 ± 0.0 b	3.7 ± 0.2 b	4.9 ± 0.3 b
7	8.7 ± 0.1 ab	5.0 ± 0.5 ab	0.0 ± 0.0 ab	6.0 ± 0.5 ab	14.0 ± 0.7 a
8	6.6 ± 0.8	1.2 ± 0.1	0.0 ± 0.0	1.5 ± 0.2	11.1 ± 0.4
9	18.7 ± 1.2 a	6.8 ± 0.8 ab	0.0 ± 0.0 ab	3.8 ± 0.1 ab	17.8 ± 0.2 ab
10	17.2 ± 1.0 a	14.1 ± 0.9 ab	0.0 ± 0.0 ab	3.4 ± 0.1 ab	18.8 ± 0.1 a
11	31.1 ± 1.2 a	18.9 ± 0.7 ab	3.4 ± 0.3 b	2.7 ± 0.2 b	16.7 ± 0.2 ab
12	40.8 ± 0.6 ab	71.2 ± 2.1 a	19.0 ± 1.7 b	7.1 ± 0.3 b	33.0 ± 1.3 b
13	38.4 ± 1.7 ab	74.6 ± 2.1 a	33.6 ± 1.2 b	14.6 ± 0.8 b	29.9 ± 0.9 b
14	27.9 ± 1.8 b	70.0 ± 2.6 a	14.4 ± 1.1 b	7.7 ± 0.7 b	21.0 ± 0.7 b
15	21.0 ± 0.4	40.4 ± 1.9	25.6 ± 1.6	30.0 ± 0.2	21.9 ± 0.4
16	23.5 ± 0.8	14.4 ± 0.8	60.9 ± 3.4	32.0 ± 1.6	19.9 ± 1.3
17	6.5 ± 0.2 b	3.0 ± 0.3b	31.0 ± 1.5 b	6.3 ± 0.3b	13.0 ± 0.6 ab
18	15.2 ± 0.5 ab	11.2 ± 1.0 b	67.0 ± 3.8 ab	16.5 ± 0.5 ab	21.1 ± 1.2 ab

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average weekly yield (g/plant) ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are made within each week, across all selections.

Table B2. Weekly average total soluble solids (TSS) of strawberry cultivar Albion and four NC State advanced selections

Week <sup>i</sup>	Albion	NC 19-020	NC 20-099	NC 21-033	NC 22-004
3	9.9 ± 0.90 <sup>ii</sup>	9.3 ± 0.00		10.9 ± 0.00	
4	10.3 ± 0.00			11.6 ± 0.35	
5	9.4 ± 0.40 a <sup>iii</sup>	6.2 ± 0.35 b		9.0 ± 0.43 a	
6	9.6 ± 0.35 b	6.9 ± 0.20 c	12.2 ± 0.9 a	8.8 ± 0.05 bc	
7	8.3 ± 0.80				7.3 ± 0.12
8	8.1 ± 0.17 b	6.6 ± 0.20 c		11.5 ± 0.32 a	8.1 ± 0.17 b
9	8.5 ± 0.38 b	6.6 ± 0.12 c		12.2 ± 0.00 a	8.4 ± 0.52 bc
10	10.8 ± 0.47 ab	8.3 ± 1.05 b		13.7 ± 1.2 a	8.0 ± 0.40 b
11	8.7 ± 0.21 b	5.2 ± 0.13 c	8.8 ± 0.05 b	11.9 ± 0.65 a	8.1 ± 0.20 b
12	8.5 ± 0.72 ab	5.1 ± 0.26 c		10.9 ± 0.00 a	7.0 ± 0.17 bc
13	10.6 ± 0.55 ab	6.2 ± 0.09 c	11.0 ± 0.45 ab	11.7 ± 0.00 a	8.9 ± 0.35 b
14	11.4 ± 1.02 a	7.4 ± 0.26 b	9.6 ± 0.87 ab	10.6 ± 0.53 a	10.2 ± 0.38 ab
15	8.8 ± 0.09	7.8 ± 0.28	9.9 ± 1.19	10.3 ± 0.83	8.3 ± 1.05
16	7.4 ± 0.09 abc	6.4 ± 0.23 bc	7.8 ± 0.68 ab	8.7 ± 0.03 a	5.9 ± 0.07 c
17	9.9 ± 0.30 b	6.9 ± 0.10 d	7.6 ± 0.27 cd	11.8 ± 0.33 a	8.4 ± 0.26 c
18	8.4 ± 0.32 b	5.6 ± 0.35 c	9.4 ± 0.15 b	10.9 ± 0.23 a	8.1 ± 0.44 b

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average total soluble solids (TSS) ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all selections.

Table B3. Weekly average fruit firmness of seven greenhouse-grown strawberry cultivars as measured by the total force (TF) (g/sec) required to puncture through the fruit

Week <sup>i</sup>	Albion	NC 19-020	NC 20-099	NC 21-033	NC 22-004
10	517.5 ± 28 <sup>ii</sup> a <sup>iii</sup>	352.3 ± 16 b		297.0 ± 28 b	511.1 ± 44 a
11	392.1 ± 25 b	408.0 ± 38 b	392.7 ± 23 b	276.2 ± 42 b	617.5 ± 50 a
12	422.8 ± 16	422.4 ± 19	422.0 ± 34		422.0 ± 25
13					
14	451.6 ± 27 b	359.8 ± 19 b	482.4 ± 56 ab	334.9 ± 39 b	671.4 ± 83 a
15	375.2 ± 26 b	331.1 ± 30 b	362.3 ± 32 b	347.1 ± 22 b	613.2 ± 59 a
16	384.0 ± 33		446.1 ± 62	341.5 ± 28	
17			364.4 ± 30 b	272.2 ± 32 b	627.8 ± 35 a
18	283.8 ± 23 ab	251.9 ± 28 ab	293.6 ± 25 ab	215.4 ± 16 b	388.7 ± 46 a

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average total force (TF) ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all selections.

Table B4. Weekly average skin firmness of seven greenhouse-grown strawberry cultivars as measured by the first peak force (FPF) (g) required to puncture through the fruit.

Week <sup>i</sup>	Albion	NC 19-020	NC 20-099	NC 21-033	NC 22-004
10	146.7 ± 14 <sup>ii</sup> a <sup>iii</sup>	96.7 ± 6 b		132.0 ± 25 ab	163.0 ± 12 a
11	125.1 ± 12 b	101.5 ± 14 b	119.2 ± 21 b	123.3 ± 20 b	196.5 ± 13 a
12	115.7 ± 7 ab	107.1 ± 6 b	116.9 ± 11 ab		141.2 ± 8 a
13					
14	125.6 ± 9 ab	101.8 ± 6 b	143.0 ± 12 ab	104.6 ± 19 ab	164.7 ± 17 a
15	127.1 ± 11 b	109.9 ± 11 b	106.2 ± 8 b	123.7 ± 8 b	201.0 ± 16 a
16	124.4 ± 7		110.2 ± 14	123.0 ± 8	
17			86.6 ± 6 b	89.3 ± 7 b	152.1 ± 3 a
18	89.6 ± 9 ab	77.4 ± 12 b	75.6 ± 7 b	89.2 ± 7 b	127.2 ± 13 a

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average first peak force (TF) ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all selections.

Table B5. Weekly average fruit flesh firmness of seven greenhouse-grown strawberry cultivars as measured by the second peak force (SPF) (g) required to puncture through the fruit.

Week <sup>i</sup>	Albion	NC 19-020	NC 20-099	NC 21-033	NC 22-004
10	129.1 ± 9.3 ab	87.2 ± 5 b		76.3 ± 8 b	147.9 ± 21 a
11	111.9 ± 9.1 b	105.1 ± 10.3 b	125.3 ± 9 b	88.5 ± 19 b	189.2 ± 15 a
12	137.1 ± 6.8	124.6 ± 6	131.3 ± 14		154.3 ± 10
13					
14	145.1 ± 10.3 b	108.9 ± 6 b	169.6 ± 22 b	144.3 ± 20 b	251.7 ± 30 a
15	120.5 ± 9.6 b	106.4 ± 10 b	138.4 ± 14 b	160.1 ± 14 b	249.5 ± 25 a
16	119.9 ± 11		178.0 ± 30	184.3 ± 22	
17			142.1 ± 13 b	167.6 ± 18 b	290.9 ± 14 a
18	101.9 ± 10 b	70.6 ± 8 b	123.0 ± 11 b	104.0 ± 9 b	182.4 ± 26 a

<sup>i</sup> Week of the year (week 1 starts January 1<sup>st</sup>)

<sup>ii</sup> Average second peak force (SPF) ± standard error

<sup>iii</sup> Results of one-way ANOVA (alpha-level = 0.05) followed by post-hoc Tukey's Honestly Significant Difference (HSD) test (P < 0.05) for multiple comparisons. Comparisons are within each week, across all selections.