Improving yield, quality and economic potential of strawberries grown in high tunnels for Kansas

by

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Abstract

Interest in spring day-neutral strawberry production in high tunnels is increasing in the Midwest. Although day-neutral cultivars have a much longer fruiting period than June-bearing cultivars, it is not clear if they will thrive in the summer climatic conditions in Kansas. High temperatures can reduce fruit yield and quality, potentially resulting in poorer fruit marketability and profitability for growers. A recent study at Kansas State University saw that heat-tolerant cultivars could be grown in high tunnels in Kansas when shade cloth was used. Different colored plastic mulches could also be used to change the soil temperature and light intensity, which can help to improve productivity and fruit quality. The goal of this thesis was to determine the best color for plastic mulch for a high tunnel system in regard to productivity, fruit quality, and profitability. A split-plot randomized complete block design was used in trials conducted at the Kansas State University Olathe Horticulture Research and Extension Center in 2020 and 2021. Six plastic mulches (black, white, black stripe, silver, red, and green) were employed, as well as two-day neutral cultivars, ‘Albion’ and ‘Portola’. Throughout the season, soil temperature, UV-A, and UV-B were measured in each plastic plot. All input costs were recorded throughout the growing season to calculate the production budget and profitability of the production system based on crop price and marketability. Three harvests were analyzed for quality, and mature fruit (90% to 100% red) and fruit yield was measured by harvesting strawberry plants twice per week. At harvest and for up to four days of storage, visual quality, respiration, flesh firmness, color, soluble solids content (SSC), titratable acidity (TA), and SSC/TA ratio were measured as well as nutritional quality (total phenolic, antioxidant, and anthocyanin). In our study, total and marketable strawberry fruit yields were greater in 2020 than 2021. In comparison to the (standard) black mulch, the silver mulch had a higher fruit yield, likely due to a reduced

temperature range and lower UV-B irradiation capacity ($P<0.0001$). Strawberries grown with silver mulch had 38 % and 33% higher total and marketable fruit weight per plant, respectively ($P<0.0001$). The 'Portola' plants grown with the green mulch had 7% higher marketability compared to the ones grown with black plastic mulch. 'Portola' showed significantly higher total (1.68 lb/plant) and marketable (1.04 lb/plant) yield compared to 'Albion', which produced 1.08 lb/plant and 0.76 lb/plant, respectively ($P< 0.0001$). Strawberry size, soluble solid content, SSC/TA ratio, color, firmness, and total anthocyanin content were not affected by plastic mulch color. 'Albion' fruit grown with silver mulch had greater TA, FRAP and total phenolics than those grown with black mulch when measured at harvest ($P < 0.0001$). In contrast, 'Portola' fruit grown with the black plastic mulch had the greatest FRAP concentration (1020 mol 100 g-1) compared to the other plastic mulch. According to our findings, the use of silver mulch enhanced yield for both cultivars and antioxidant content for 'Albion.' The economic analysis revealed that silver mulch was also the most profitable mulch for 'Albion', while the black stripe mulch performed the best for 'Portola', which had the lowest breakeven prices of $2.18/lb and $1.92/lb, in 2020. The average percent marketability ([marketable fruit yield / total fruit yield] x 100) observed in our trials was 69.4 %, which is estimated to provide $870/1000ft^2 in net revenue at $2.80/lb. When the selling price was projected at $3.02/lb for 'Portola' and $4/lb for 'Albion', it was estimated that the profit was equal to the investment cost (100% ROI). The results of this work indicate that the use of silver and other reflective mulches may be a low-cost way to effectively increase strawberry yield and quality. The economic analysis also suggests that the production of day-neutral strawberries can be a profitable enterprise for high tunnel growers in the region. As growers integrate this crop into their production system, careful consideration to the cultivar, growing methods, and marketing will be critical for success.

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Chapter 1 - Literature Review

Introduction

Strawberries are native to North America and wild *Fragaria (Rosaceae*) species grow across the northern hemisphere and specifically in the southern part of North America. For millennia, humans have consumed the fruits of wild *Fragaria* species (Pauketat et al., 2002). The modern cultivated strawberry species (*Fragaria* ×*ananassa)* originated in the 18^{th} century in Europe, evolved through hybridization between species *F. virginiana* and *F. chiloensis* found in North and South America (Luby et al., 1992; Salamone et al., 2013).

Strawberries are widely cultivated as hybrid plant in the *Fragaria* genus (Hummer et al., 2011). Because of its distinct aroma, gleaming red color, juicy texture, and sweetness, this is now one of America's most popular fruits. The flesh of a strawberry is derived from adjacent tissue rather than the ovary, making it an accessory fruit (Hummer et al., 2011). Strawberry plants generate a short stem known as a "crown." The ideal crown numbers range between 5-6, up to 6 crowns will result in higher fruit yields and larger fruit size. However, high temperatures can promote crown development (>6), which leads to smaller fruits (Poling, 2012). Petioles develop circularly around the crown and the leaf blades are divided into 3 leaflets, called a “trifoliate”. This “trifoliate” responsible for photosynthesis, requiring water and CO_2, and transfer the carbohydrates from the leaf to storage, for consumption (Hancock, 1999). The pistils are conic-shaped stems called the “receptacle”. The receptacle is fertilized and matured into a strawberry. Achenes are the seed-like structures outside the berry with ovules that would eventually become seedlings. Strawberry plants produce runners, which also known as stolons. These runners are eventually form their own roots and produce a clone plant. When runners begin to dry out and shrivel after, new roots have start to be established themselves in the soil. As a result, propagating strawberry plants from runners is the most common practice (Maughan et al., 2015), as genotype is produced by the runner plant, which multiplies from the mother plant and has the same genetic makeup as the mother plant.

Strawberry Production in the US

Strawberries ranked as third high-value fruit crop in the U. S. with an overall $3.5 billion dollars market value (USDA NASS, 2020). Strawberries are the most popular fruit in the U.S. based on grocery store sales of fresh fruit (Nielsen, 2015). In the United States, fresh strawberry consumption per capita was 8.5 pounds in 2021 (Shahbandeh, 2022). This trend is due to the year-round availability of strawberries from both domestic and imported sources, as well as the adoption of improved varieties (Samtani et al., 2019).

A growing emphasis on healthy eating could be driving up consumer demand for strawberries (USDA ERS, 2016). Berries are high in fiber, vitamins, minerals, and other bioactive substances, all of which are essential for optimal nutrition and the development of the body's defenses against chronic illnesses (Nile and Park, 2014). The health advantages of berries are promoted by various grants, such as those funded by the "Farmers Market and Local Food Promotion Program" to encourage good eating habits (USDA, 2015). Despite being one of the world's leading strawberry producers (Wu et al., 2015), the United States has been importing fresh strawberries since 2012 to meet rising demand (USDA, ERS, 2017). California and Florida accounted for 98% of total strawberry production in the U.S. in 2018 (USDA, NASS, 2018). In 2020, the United States produced 1.16 million tons of strawberries. The United States is not only the world's biggest strawberry producer, but it is also the world's fourth largest importer of fresh strawberries, with a record 961 million pounds imported in 2020. Imports of strawberries supplement the domestic supply, particularly during the winter months. During the winter and early spring, nearly all fresh strawberry imports to the United States (99%) come from Mexico. Strawberry imports cost the United States totaled $830 million dollars in 2021, with Mexico accounting for $820.6 million dollars of the total (USDA, 2021). The fact that climate has a substantial impact on strawberry production in terms of location and site is one of the most compelling reasons for relying on imported strawberries (Rysin et al., 2015).

Based on the flowering and fruiting characteristics of the strawberry plants in the U.S, June bearing, and day neutral strawberry cultivars are the most popular (Darrow and Waldo, 1934; Gu et al., 2017). June-bearing cultivars are often cultivated in an annual or perennial system with matted rows covered in black plastic and produce fruit for several weeks in early summer (Hoover et al., 2017; Solomon et al., 2013). While everbearing strawberries usually produce three phases of flowers and fruit during the spring, summer and fall (Wolford and banks, 2016). Day-neutral strawberries can bloom and produce fruit throughout the spring, summer, and fall, due to the light insensitivity. Fresh bare root transplanting or plug planting with 30–40 cm spacing with a single drip line in the center is the most common production approach for day-neutral and everbearing strawberry cultivars in the United States (Dittmar et al., 2012; Whitaker et al., 2020). Bareroot transplants are a cheaper than purchasing rooted strawberry plugs (Demchak et al., 2021). However, strawberry plug plantings are another viable planting strategy that allows for greater root establishment of transplants while requiring less irrigation and achieving higher yields (Jin et al., 2017; Li et al., 2017). In California and Florida, day-neutral cultivars are chosen for their longer growing season and higher yield. Whereas in the Midwest, June-bearing varieties are primarily planted commercially in an annual hill production metod with plastic mulch to avoid extreme heat condition (Rowley et al., 2011).

Strawberry Production in Kansas

The June-bearing strawberry cultivar is the most commonly grown cultivar in the Kansas. They're usually cultivated as either an annual raised bed or short-term perineal matted row cropping system, with 20-inch plant spacing in the fall, and harvested in mid-May to June, before the summer heat starts. (Kadir et al., 2006). Kansas has been limited to low yielding June-bearing cultivars with short growing seasons to avoid hot summer (Hoover et al., 2016; Petran et al., 2017). Climatic conditions such as late spring frosts, low winter temperatures, and short growing seasons can negatively influence production performance and fruit quality (Carroll et al., 2016). Due to spring frost and extreme heat, early spring day neutral production was not successful in Minnesota (Hoover et al., 2016; Petran et al., 2017). In 2016, researchers at Olathe Horticulture Research and Extension Center (OHREC) found that some of the day-neutral strawberry cultivars can be successfully grown in an annual raised bed production method in high tunnels with evaporative cooling to reduce the heat load in the summer (Gude et al., 2018). Day-neutral strawberries are typically sold through direct selling, such as U-pick or farmers markets, for $2.50 to $3.50 per pound in the Midwest (Klodd et al., 2021). As a result, higher production and fruit quality are critical for growers in Kansas to secure a larger price premium for off-season strawberries (Heidi et al., 2018).

Quality Attributes

Strawberry fruit quality is a major factor in consumer preference and willingness to pay a higher price (Stevens et al., 2011). High-quality characteristics include bright, glossy, crimson color with green calyx with distinctive seeds pattern displayed on the outside of the fruit (Nuns et al., 2009). Strawberry quality is determined by a complex balance of many sensory attributes, including appearance (red color, in fruit size and shape, freedom of defect), texture, sweetness (sugar-acid ratio) and flavor (phenolics, and aroma volatiles) (Jouquand et al., 2008).

Fruit appearance, such as surface color and glossiness with a fruit size larger than 3 cm and >12 g by weight and free from any form of defect are critical indicators for consumer choice. Fruit should be fully ripe and red colored (90-100%), with Croma level redness (a*) and lightness (L*) ranges between 25-40 (Whitaker et al., 2020), without white or green tips. Calyx color should remain green and healthy, also a bright glossy appearance is an indication of freshness and absence of water loss (Bordelon et al., 2013).

Texture is another parameter for strawberry quality. Immature or unripe fruit texture can be hard and not juicy (Brummell, 2006). Texture changes take place mainly due to reduced cellular turgor pressure, and a breakdown of the pectin-rich middle lamellae layer of the cell wall that holds adjacent cells together, resulting in a decline in firmness (i.e., softening) of the fruit tissue. The overripe fruit is mushy, whereas underripe fruit is crisp. Research study have indicated that there is a negative association between the traits of 'firmness' and 'overripe,' therefore strawberries that are considered 'overripe' are softer (Jouquand et al., 2008). According to another study, lower strawberry firmness correlates with higher fruit decay scores, also the degree of quality decline can be a cultivar-specific response. Commercial California cultivars like 'Selva' and 'Parker', for example, have significantly more fruit firmness when fully red than

'Chandler', 'Santana', 'Pajaro', and 'Douglas' (Kader, 1999). The standard strawberry fruit firmness ranges between 2-5 (N), depending on the cultivars (Whitaker et al., 2020).

Strawberry flavor is a combination of numerous taste and aroma compounds. Strawberry fruit sweetness is mostly determined by the ratio of sugars (sucrose, glucose, and fructose) to organic acids (primarily citric and malic acids) (Jouquand et al., 2008; Montero et al., 1998). For strawberries, the acceptable SSC, TA, and SSC/TA ratios are 6-7%, 0.67-1.00%, and 8-15%, respectively (Whitaker et al., 2020). High acid and low sugars produce a tart strawberry, while high sugars and low acids induce a bland taste. Low sugar and low acid content lead to a tasteless strawberry (Gündüz et al., 2014; Kader, 1999). Volatile compounds are essential for both aroma and the overall flavor of strawberries. Strawberry flavor intensity is highly connected with the combined influence of thirty-one volatile chemicals (organic compounds that have high vapor pressure and low solubility e.g., esters, mostly methyl and ethyl esters) (Jouquand et al., 2008). According to Michael (2014), certain esters, terpenes, and furans are most linked to the intensity of fresh strawberry flavor. "Strawberry flavor intensity" and total concentration of fresh strawberry volatiles have a strong relationship (Joucand et al., 2011). A sensory panel assessed strawberry cultivars with vivid red color and a balance of acidity and sugars as having high flavor quality, according to Sistrunk and Morris (1985). The strong flavor of some cultivars can lead to increased customer preference and, in turn, market pricing.

Strawberries are a nutrient-dense fruit that contain key health-promoting phytochemicals like antioxidants, which may help to lower the risk of chronic diseases including inflammation and cancer (Yang et al., 2011). They also contain dietary fiber, B vitamins, folic acid, vitamins C and E, folate, and potassium, as well as non-nutrient compounds like polyphenols (Basu et al., 2014; Giampieri et al., 2016). This fruit has become popular throughout the world as part of a well-balanced diet that contributes to human health due to its low caloric content (only 35 calories per 100 grams) and nutrient density (Giampieri et al., 2014).

Strawberries also have phytonutrient knowns as antioxidant. Strawberry fruits have higher antioxidant capacity (2 to 11 times) than apples, peaches, pears, grapes, tomatoes, oranges, or kiwifruit (Giampieri et al., 2014; Scalzo et al., 2005). Antioxidant-rich foods aid to reduce the oxidation of low-density lipoproteins in humans, which is connected to oxidative stress-induced aging. Anthocyanin, is another potent antioxidant in strawberries, outperforms ascorbate, glutathione, and other well-known antioxidants for promoting many health benefits (Skrovankova et al., 2015). Anthocyanins are water-soluble flavonoids pigments that, depending on the pH of the fruit, can change red, purple, or blue. Strawberries' red hue comes from anthocyanidin glycosides, pelargonidin 3-glucoside, and cyanidin 3-glucoside (Timberlake and Bridle, 1982). Elagic acid is the most common phenolic component in strawberries, accounting for most of the total phenolic content (Huang et al., 2012). In strawberries, flavanols account for 11% of the phenolics (Häncook et al., 1999). Many studies reported that depending on the strawberry cultivars, total antioxidant (FRAP), total phenolic, and total anthocyanin content are usually ranging above 200 (μmol 100 g^{-1}) (FRAP), TP 100 (mg 100 g^{-1}), and Antho. 60 (mg100 g^{-1}FW) respectively (Gude et al., 2021; Rekika et al., 2005). Strawberries have high levels of vitamin C and phenolic compounds which makes them have effective antioxidant potential, therefore the role of strawberries in human health and disease prevention is an active biochemistry research area (Romandini et al., 2013). According to a number of studies, strawberries may protect people's hearts by reducing low-density lipoprotein (LDL) levels and enhancing lipid profiles, antioxidant status, and platelet function (Alvarez- Burton-Freeman et al., 2004; Giampieri et al., 2014).

Handling Requirements and Shelf-life

The quality of strawberry fruit is directly affected by the harvest and handling techniques. Preharvest factors including climatic conditions, cultural practices, genetic variability, and postharvest handling can affect the overall strawberry fruit quality (Ahamed, 2017). Optimally, strawberries should be harvested in the early morning when temperatures are at or below 25 $^{\circ}$C and after dew drops have dried (Kader, 1999). Strawberries can be harvested with or without the calyx using a sharp knife or gently pinching the stem without touching the fleshy part of the strawberry (Herris et al., 2007). Fruits are usually harvested slightly under-ripe and firmer for commercial purposes because they are less likely to rot, transport better, and to maintain longer shelf life (Wang et al., 2009). Gentle handling is recommended, any damaged fruit should be decarded immediately to prevent postharvest disease infection like botrytis (Wang et al., 2000). Harvested fruits need to be placed in large plastic crates or clamshells on picking carts and transported immediately from the field to the collection area or packhouse with a cooling truck (Taghavi et al., 2021). Commercial strawberries are generally packaged in the field and transported promptly to a cooling facility, and pre-cooled with frost air cooling technology.

Cooling slows the metabolism of harvested fruit and extends the shelf life. To maintain fruit quality and achieve a longer shelf life, fruit should be immediately stored in forced air-cooling area or in a refrigerator at a temperature range of 0 to 4 $^{\circ}$C (Lee et al., 2021; Winardiantika et al., 2015). When fruits are stored at an ideal temperature and humidity (0-1 $^{\circ}$C and 90-% humidity), strawberries have a shelf life of 5-8 days. But this can vary depending on the cultivar (Nunes, 2009). In the industry carrier transport refrigeration technology is typically used in refrigerated trucks, trailers, rail cars, or marine containers with a stable temperature of

2 °C to retain freshness and quality during transportation (Thompson and Singh, 2015). However, due to its non-climacteric character, this strategy can have a negative impact on fruit quality and taste (Kader, 1999). Because as they are harvested at a slightlly immature stage, these berries often respire more at harvest and storage because they contain much lower quantities of sugars and acids than ripe berries (Wang et al., 2009; Symons et al., 2012).

In comparison to immature fruit, fully developed fruit has a higher anthocyanin content, according to research (Wang et al., 2009). Strawberries collected at (90-100 % red) mature stage can generate optimum pigment during storage under favorable temperature-dependent conditions, and in some cases, light can help to speed up the pigment creation process (Kalt et al., 1993). In addition, due to increased temperature fluctuations and longer storage times, the biochemical breakdown of strawberry fruit appearance is faster. When the storage temperature is over 4 °C, the higher rate of fruit deterioration is more obvious (Octavia et al., 2017). The fragile flesh of the strawberries can easily be bruised or wounded along the postharvest handling chain, from harvesting to shipment, which can make these fruits more vulnerable to fungal pathogens such as gray mold. Botrytis cinereal is the most common postharvest disease in strawberries (Jin et al., 2017; Romanazzi et al., 2016). Researchers have demonstrated that that UV radiation (Jin et al., 2017), edible coatings (Feliziani et al., 2015), essential oils (Li et al., 2017), and heat (Jin et al., 2017) can prevent postharvest illnesses and extend strawberry shelf life.

Factors Affecting Quality

Biotic factors including the presence of pest and/or disease can significantly affect the quality of strawberry fruit. Strawberry pests and disease are important biotic factors that influence fruit quality. Spider mites (*Tetranychus* sp.), strawberry aphids (*Chaetosiphon fragaefolii*), thrips (*Frankliniella occidentalis*), tarnished plant bugs, sap beetles (*Nitidulidae*), field crickets (*Gryllus* sp.), and a variety of moths and butterflies (*Lepidoptera*) are all common strawberry pests can cause significant yield and quality loss in strawberry (Vafaie and Porter, 2014). Fruit that is damaged by tarnished plant bug (TPB) nymph feeding becomes deformed and has small fruit size (Klodde et al., 2021). Among all disese grey mold (*Botrytis cinerea*), powdery mildew (*Podosphaera aphanis*), and anthracnose (*Colletotrichum* sp.) disease result in the most potential yield loss in strawberries.Gray mold rot appears as tan to brown soft areas or blotches that are covered with a powdery mold that make the fruit completely unmarketable (Giesbrecht and Ong, 2014).

Abiotic factors including environmental conditions such as temperature, light intensity, soil type and cultural practice all have an influence on strawberry fruit quality.

Effect of Temperature in Strawberry Fruit Quality

Temperature not only affects the strawberry plant growth, but also affects the fruit quality by changing the cellular components of the fruit. Strawberries grown at different temperatures (day/night) has a noticeable difference in antioxidant activity and total flavonoid content. For example, during fruit growth, a relatively cool temperature increased fruit firmness (Anagnostou et al., 1993), whereas high temperature growing conditions (25/30 ˚C) can dramatically boost antioxidant activity, as well as anthocyanin and total phenolic content (Wang et al., 2009). Temperature fluctuations during the preharvest period can affect the rate of nutrient absorption and metabolism, color development, and firmness of strawberries (Kader, 1999). Research has shown that day/night temperature fluctuation (30/18 ˚C) reduced plant growth and fruit quality of the strawberry varieties 'Earliglow' and 'Kent' (Fragaria ananassa Duch).The higher temperature differential between day and night (30/18 ˚C), increased the concentration of malic acid in fruits, and reduced citric acid and ellagic acid in strawberry fruit. Strawberry fruit become highly acidic and lower in soluble solids when the day/night temperature ranges between (30/ 22 ˚C) during production (Wang et al., 2000).

One of the most critical variables in strawberry storage quality is proper temperature management after harvest, which includes quick cooling and keeping the pulp temperature low (Jin et al., 2011; Kader, 1991). Strawberries should be stored at a temperature of 0-2 ˚C and a relative humidity of 95% to avoid moisture loss and to restore the increased water content within the cell walls (Harris, 2007). Strawberry postharvest shelf life can be extended up to seven days if stored at 0 ˚C, according to USDA (Mitcham, 2007). However, after seven days of storage even at 0 ˚C, Ayala-Zavala et al. (2004) found a tendency of considerable declines in strawberry anthocyanin and soluble solid content. Storage temperature (together with time and condition) affects the stability of phenolic antioxidants in fruits during storage (Giampieri et al., 2014). Furthermore, total phenolic and antioxidant capacity rose or remained stable for up to 5 days at 5 and 10 ˚C, regardless of taste or smell deterioration (Ayala-Zavala et al., 2004). According to Hernández-Munoz et al. (2008), as strawberries lose moisture during storage, sugar concentration rises, resulting in higher soluble solid content. Therefore, it is very important for strawberries to ensure proper temperature during production, at harvest and storage for better quality fruit.

Effect of Light Intensity/ UVA and UVB on Strawberry Quality

Different levels of light intensity can influence the overall strawberry fruit quality. The different production methods can alter the amount of light exposed to the crop. Altering light intensity and light quality by using different plastic mulches may affect crop growth, yield, color and firmness phytochemical accumulation in the strawberries (Bacci et al., 1999; Taghavi et al., 2021). Low light intensity during development and harvest can result in a considerable drop in the concentration of taste chemicals (hexenal, hexanal, ethyl methyl butyrate, and methyl butyrate) in the fruit. Low light reduces the glossiness of strawberry fruit, resulting in a higher proportion of albino fruit, according to Sharma, (2006). Strawberries cultivated in greater light contain more ascorbic acid, according to Wang et al. (2009). The most common reason for smaller strawberry fruits is a lack of light (Osman et al., 1994). Darker red and firm fruit may result from increased UV exposure during the growing stage and after harvest (Warner et al., 2018). Higher UV-B light exposure, on the other hand, can affect fungal infection on strawberry fruit in the field or during storage, with no association to other climatic variables (Nechet et al., 2015). Strawberry fruits grown under UV-A + UV-B film had higher levels of anthocyanin and phenolic content (cyanidin 3-glucoside, quercetin 3-glucuronide, and kaempferol 3-glucoside) than those grown under UV-blocking film in the high tunnel (Tsormpatsidis et al., 2007). Oppositely, Josuttis et al. (2010) found that phenolic contents in strawberries were unresponsive with changes in UV under different UV screening films even in standard physiological conditions (Josuttis et al., 2010; Tsormpatsidis et al., 2007). Therefore, it can be concluded that optimum light intensity is important to maintain fruit quality. Also, greater UV-B exposure can have a more detrimental effect than UV-A to the plant.

Genetics

According to research strawberry plant genetics also has a strong influence on fruit maturity and quality (Taghavi et al., 2019). Capocasa et al. (2017) showed that the genotypic effect of strawberries on nutritional quality outweighs the effect of growth conditions. The authors found that genetic factors have a direct impact on strawberry texture, whereas environmental influences simply affect the manifestation of textural qualities. Strawberry cultivars differ in terms of overall texture and rate of softening. Research showed that total organic acid content in strawberry is affected by genotype (Winardiantika et al., 2015), while vitamin-C content differs among strawberry cultivars. According to Nelson et al. (1972), ascorbic acid levels of 60 to 80 mg/100 g can be enhanced through breeding. Malic acid content, on the other hand, appears to be genotype independent (Winardiantika et al., 2015). Fruits' major anthocyanin concentration (pelargonidin 3-glucoside) can also differ between cultivars. For example, the cultivar ‘Fern’ had more anthocyanins and better color than ‘Selva’ (Anagnostou et al., 1993). Podoski (1998) found that cultivar ‘Carlsbad’ was the firmest and ‘Rosalinda’ was the softest, confirming that firmness is primarily determined by cultivar. Cultivar did not have a substantial impact on TA, according to Anagnostou et al. (1993). The relative distribution of phenolic chemicals, on the other hand, varies with genotype. According to Anttonen et al. (2006), flavanol content might vary up to 4-fold amongst cultivars, with modest changes related to growth conditions. As a result, a variety of cultivars can be used for a number of purposes. ‘Toyonoka’, for example, is firmer and more suited to distant markets, whilst ‘Oso Grande’ is appropriate for fresh eating and has high nutritional value (Cordenunsi et al., 2002).

Agricultural Practices

Different agricultural practices defined as pre-harvest factors can influence the overall fruit quality. Soil types, fertilization, composts, and mulching can impact the total nutritional composition, including ascorbic acid content, and antioxidant activity of harvested fruit, by regulating the water and nutrient delivery to the plant (Wang et al., 2000). Several studies have shown that fruits cultivated at different times of the year have varied in flavors (Watson et al., 2002). When compared to irrigating at 300 hPa. (Hectopascal Pressure), field research indicated that irrigating at 200 hPa resulted in higher production rate and better fruit quality. Also, research has shown that more heavily irrigated plots had lower fruit firmness but greater fruit size (Hapula and Salo, 2007). Strawberries grown in low-organic-matter and low-cation-exchange-capacity sandy soil with elevated Calcium (Ca), magnesium (Mg), and Nitrogen (N) level can increase ascorbic acid density of fruit than plants without supplemental fertilizer (Wang, 2006). Alternation of strawberry soil pH range (6–6.5) can affect the overall mineral uptake and plant growth yield, and fruit quality reported by Hakala et al. (2010). According to Singh (2007), preharvest Calcium sprays on the plants can improve the darker fruit color during storage. Different production systems (open fields, tunnels, and greenhouses) can alter strawberry n productivity and quality via varying polyphenol content levels (Saltveit et al., 2011). Strawberries cultivated in the open field had a greater total phenolic content than those produced in high tunnels. (Pincemail et al., 2012). Therefore, ideal cultural practices play an important role to ensure better berry quality.

Strawberry Production in High Tunnels

High tunnels (HTs) are a type of unheated greenhouse with a moderate level of environmental protection that is used to extend the growing season and increase crop yield (Pool et al., 2014). Utilizing high tunnel production system is becoming more useful, especially in the Midwest to combat unfavorable climatic condition for specialty crop production. High tunnels can extend the growing season for strawberries (Kadir et al., 2006; Rowley et al., 2011) by protecting them from early season frost events and promoting early season growth (Demchak and Hanson, 2010; Karlsson and Werner, 2011; Kadir et al., 2006; Rowley et al., 2011). High tunnels provide an evenly distributed diffused light environment that provides lower leaves with a powerful photosynthetic ability, as well as increased plant growth rates and heat retention, reducing plant stress (Heidi et al., 2018). It has been reported that light is reduced by <10% by the plastic layer of high tunnels. Low (10 mol/m^2 /day) day light intensity in late fall, winter, and early spring can limit crop growth even if temperature is adequate (Bruce et al., 2019). As a cool season crop extreme light condition can increase tunnel temperature higher than optimum >24°C can restrict the strawberry plant growth and yield (Petran et al., 2017). Thus, placing a shade cloth over HTs during mid-summer is a common practice to reduce extreme heat and light for strawberry production. However, low light condition in the HTs can reduce berry size, less glossy fruit and albino fruit (Osman et al., 1994; Sharma, 2006). Therefore, maintaining optimum light condition for strawberries grown under HTs is important to ensure better fruit quality.

Significantly higher yields (Werner, 2018; Rowley et al., 2011) and better berry quality with a longer shelf life are the common advantages of high tunnel growing (Nes et al., 2017). As a result, the high tunnel's season extension capability may provide growers with early and late season berry production opportunities at premium pricing, (Black et al., 2010; Rowley et al., 2015). Adopting day-neutral cultivars (‘Albion’, ‘Seascape’; San Andreas and ‘Evi-2’) and June bearing cultivar (‘Chandler’, ‘Earlyglow’, Strawberry Festival’) grown in high tunnel becoming more popular in the Midwest. Depending on the cultivar, strawberries can be sensitive to variables like late spring frosts, low winter minimum temperatures, and short growing seasons (Carroll et al., 2016). HTs day-neutral cultivars are usually planted in mid -March, fruit and production can last up to 5-6 months (Gude et al., 2018; Rowley et al., 2011). In HT June-bearing varieties, the harvest season can extend only for 3-5 weeks (up to late June) (Kadir et al., 2006).

The University Tennessee, University of Kentucky and Mississippi State University reported the utilization of high tunnel for off season day-neutral strawberry production. Their HTs system has adapted for June bearing cultivars including ‘Radiance’, ‘Camino real’, ‘Chandler’ and ‘Strawberry Festival’ for better yield during warmer conditions in the HT. They also adapted day-neutral strawberries (Albion’ and ‘San Andreas,’) cultivars in the tunnels in late summer that allows the berries to get in two cropping seasons — the first in late fall and the second in early spring. The late season, fall harvest begins in November and continues until around the end of December and production season resumes in late March or early April. The above studies indicate the seasonal extension ability of HTs (early and late season) to give more crop protection, higher yields and better fruit quality, amd to maximize the profit of $3/ quart (2.08 lb) for high tunnel strawberries. However, the high tunnel construction cost $2.95 per square foot, land preparation, higher labor requirement for raised bed preparation, and installation of plastic mulch and a drip irrigation become challenging to cover the investment by

1-2 years, without offseason and high value crop rotation practices (Lalk et al., 2020; Kaiser et al., 2019).

In 2018, Kansas State University researched six day-neutral cultivars grown under high tunnels in Kansas, which was a successful production system as it offered optimum growing conditions for certain day-neutral cultivars even in early frost spring based on yield and crop quality analysis (Gude et al., 2018; Gude et al., 2021). However, it is unclear how the higher construction/maintenance costs of the high tunnel itself factors into the overall profitability day-neutral strawberry production in high tunnels. Sydorovych et al. (2013) provided a cash flow analysis for organic heirloom tomatoes that predicted that the structure could be paid for in one to two years.

Plastic Mulch

Before plastic mulch introduced commercially, natural mulches, (e.g straw, wood shavings, tree leaves, cotton gin waste, rice or buckwheat hulls) were commonly used to retain soil organic matter and also to provide food for soil-borne organisms like earthworms and soil biota (Dorn et al., 2011). However, because of their high carbon-to-nitrogen (C/N) ratio, organic mulches (such as grain straw) can contaminate the soil with weed seeds and deplete the seedbed nitrogen. Organic mulches are said to lower soil temperature in the early spring, and don’t always result in increased yields, according to some research (Subrahmaniyan et al., 2008).

Plasticulture is a crop-growing technology that uses plastic mulch films to cover the soil, as well as drip irrigation (Lamont et al., 2017). Professor Emmert at the University of Kentucky developed plastic mulch as a cost-effective crop management technology in 1950 (Anderson and Emmert, 1994; Jensen, 2004). White, black mulch (complete opacity), silver black stripe or white center black stripe mulch (bicolor), photo selective mulch (brown or green) and red are most popular plastic mulches used in fruit and vegetable cultivation (Paul, 2019). Plastic mulch can warm the soil, conserve moisture, and prevent weed growth and nutrient leaching. Plastic mulching, on the other hand, permits crops to be grown even in the early spring season by warming the soil up to three weeks ahead of normal crop growth.

Despite having all the above benefits, plastic mulches are resistant to hydrolysis and microbial decomposition (Stevens, 2002). Therefore, it remain in the soil as microplastic fragments for decades without adequate disposal. Numerous studies reported that plastic waste accumulats in nature, posing a significant threat to terrestrial and aquatic wildlife when it reaches the food chain (Barnes et al., 2009;Duis and Coors, 2016; Sivan, 2011, Rilling, 2012). Also, plastic disposal activities on farm can be a laborious and costly task (Steinmetz et al., 2016). Therefore, biodegradable plastic mulch is another important form of plastic mulch used in agricultural production system (Kasirjan and Nogouajio, 2012). It is mostly used for short-cycle crops (90 days) and degrades completely into natural compost at the end of the growing season (Wang et al., 2006). Although biodegradable mulch is environmentally friendly, its high cost and risk of a sudden rupture keeps its use only for high-value crops with limited planting areas (Greer et al., 2003). However, multiple university research trials, found that biodegradable plastic mulches outperformed polyethylene mulch in terms of weed control, soil temperature, and crop yields (Ghimire et al., 2018).

Effect of Colored Mulch on Soil Temperature in Different Crops

Use of plastic mulch for vegetable production has been used commercially since the 1960s (Lamont, 2005). Also, there are many kinds and colors of plastic mulches available in the market and been used for many horticultural crops. However, the use of different kinds and colors of plastic depends on the crop variety, weather, and soil condition. Different color plastic mulch alters the microclimate around the crop by modifying the radiation level (absorptivity vs. reflectivity) which ultimately affects the surface temperature of the mulch cover and consequently the underlying soil temperature (Filipović, 2016). Black mulch reflects minimum short-wave (UV-B) radiation (10%) and absorbs the highest radiation (90%) compared to any other colored mulch (Teasdale, 2001). Black plastic mulch prohibits light transmittance to the soil, which can raise the plant soil root zone temperature 3-5 °C, and results in effective weed suppression, earlier crop maturity and higher yields in many fruit crops e.g., strawberries. Therefore, it is widely used for horticultural crops including tomatoes, peppers, eggplant, and melons. Dark-colored mulches like black or red usually have 5 °C higher soil surface temperature increase or decrease than clear or white mulch (Sakamoto et al., 2016; Tara et al., 2000; Zhang et al., 2011).

Even in high tunnels, different colored plastic mulches display varying thermal and radiation properties. The use of red plastic can increase strawberry fruit size and improve quality (Shuikhy et al., 2015). White mulch absorbs 51% of shortwave (UV- A and UV-B) radiation, reflects 48% into the air, and conducts only 1% of the radiation into the soil. According to a study it can make a gentle decrease in soil temperature 0.1 °C at 1-inch depth or -0.7 °C at a 4-inch depth as compared to bare soil (Tarara, 2000). Tarara (2000) also found that soil moisture levels influence the low absorption rate, and a higher rate of light reflection resulting in a cooler soil temperature than bare ground.

Studies have suggested that metalized stripe mulch is capable of reducing summer soil temperatures like white mulch and can improve summer plant growth and strawberry yields (Albregts et al., 1993; Deschamps and Agehara, 2019; Hutton et al., 2007). Silver stripe mulch was found to be beneficial for reducing pest incidences, such as cucumber bugs, in cucumber and squash plants, according to a Virginia Tech study (Daz-Pérez, 2010; Tarara, 2000;). According to a Pennsylvania State University study, red plastic can increase tomato and eggplant productivity, while silver mulch can increase pepper fruit yield by 20% when compared to black plastic (Ahmed et al., 2017; Andino and Motsenbocker, 2004). Brown and green mulches are primarily infrared transmitting (IRT) plastic mulches, which have the ability to hasten maturity and enhance fruit size of the peppers harvested compared to the black, yellow and blue plastic mulch treatments (Lamont et al., 2015).

Effect of Mulch Color on Strawberry Plant Growth, Yield and Quality

Standard black plastic mulch use is more common in commercial vegetable and berry production. Microclimatic variations can affect strawberry fruit yield and quality via the thermal and radiation characteristics of colored plastic, which vary depending on geographic location and gentype (Descamps and Agehara, 2019). When compared to red mulch, a 0.2 °C increase in soil temperature beneath black mulch can reduce strawberry productivity by up to 15% in high temperature regions like Florida (Kasperbauer, 2001). Therefore, white mulch is even more beneficial for strawberry cultivation in hotter areas. White mulch is commonly utilized to increase total phenolic and ellagic content in strawberries due to their sensitivity to high temperatures whereas strawberries cultivated with brown mulch had the highest total anthocyanin level which increases over high temperature and stress condition (Hughes et al., 2013; Pandey et al., 2015). In comparison to the black mulch, increased reddish orange and red color mulch exposure improved strawberry fruit color (chroma), ascorbic acid, soluble solid content, yield per plant, and fruit size (Anttonen et al., 2006). According to Miao et al. (2016) strawberries grown with the red and yellow tinted plastic contained much more total anthocyanin content (TAC). Strawberries grown with reflective silver mulches had significantly increased total levels of ellagic and ascorbic acid in compared with strawberries grown with black mulches (Atkinson et al., 2006). In certain studies, fruit grown with green mulch was found to have lower fruit quality criteria than black mulch (e.g., color, sugar, and acid) (Zhang et al., 2011). So, it is evident that color plastic mulch has a great influence over strawberry yield and fruit quality.

Economic of Colored Mulches

Plastic mulches' economic benefit and cost effectiveness are heavily dependent on the crop type as well as local or regional preconditions such as selling opportunities, average wages, and water availability. Plastic mulching has been found to be economically beneficial, particularly in arid climates, for the sale and distribution of seasonal fruits (Steinmetz et al., 2016). Plastic mulch is widely utilized for high-value specialty crops such as asparagus and strawberries (Heißner et al., 2005; Stevens et al., 2011) to accelerate fruit growth and output in order to bring off-season products to market as soon as possible, which improves crop prices and profitability. Water savings (up to 25%) and reduced labor costs for weed and pest management are the most major economic advantages of plastic mulch, according to many studies (Ingman et al., 2015). A standard black plastic cost between $135 and $154 per roll for a 4 ft 4,000-ft x 1.25

mil roll (Velandia et al., 2018). However, with large volume discounts, growers can often reduce plastic mulch costs. In contrast, Xie et al. (2005) reported that infra-red and reflective mulch prices can be higher, which can decrease overall profit for small scale production systems. The economic analysis of different color plastic mulches, demonstrate that using silver mulch in watermelon production yielded the higher compared to black and red plastic mulch (Bajpai and Rao, 2017). End-of-seasonplastic mulch removal and disposal can add extra labor and disposal costs (Ghimire et al. 2018). Narva (2011), reported that plastic mulch for melon production increased annual expenditures by about 6% while doubling revenue, resulting in a more than 5-fold profit increase. Plastic mulch disposal fees ($20-$100) can be varied in different states (Velandia et al., 2018) and., total labor and machine costs involving removal and disposal activities could negatively impact the overall profitability of the system (Schonbeck,1998). In addition, scholarly literature on economic costs and benefits analysis of plastic mulches is lacking, making it difficult to completely comprehend the cost benefits of this production system (Steinmetz et al., 2016).

Importance of Local Food Production in the United States

Freshness, support of the regional economy, and taste were the top three reasons for buying local goods, according to a Food Market Institute survey in the United States in 2014 (FMI, 2014). Much research indicates that fresh fruits, e.g., strawberries can lose 30-50% of their nutritional components (antioxidant, anthocyanin and soluble solid) after 5-7days of storage or transportation even with a temperature 0 ˚C, depending on the type of produce (Ayala-Zavala et al., 2004; Gil et al., 2006; Lantz et al., 2010). By minimizing the distance that food travels, local food production has the potential to deliver fresh and healthy food to urban areas. Despite the fact that there are several definitions of local food, the USDA defines it as "the direct or intermediated marketing of food to consumers that is produced and delivered within a small geographic area" (Low et al., 2011). There is no pre-determined distance, but it suggests that the food was grown within a few miles (an eight-hour trip) of the selling point, or that it was produced in the same city or state (Martinez, 2010). Food traveling fewer than 400 miles from its origin is defined as a "locally or regionally produced agricultural food product" by the 2008 Farm Act (Martinez, 2010). Regardless of the various definitions of local food, as per capita local food consumption increased over the last decade and local produce sales increased by roughly 8% (USDA-NASS, 2015). Local and regional food producer participation and sales are growing, thus local producers are using both direct-to-consumer (e.g., farmers' markets) and intermediate marketing channels to sell their products (e.g., sales to institutions or regional distributors) (USDA-NASS, 2009). The USDA Local Food Marketing Practices Survey, reported that, local producers had $8.7 billion in local food sales in 2015 (Martinze, 2010). Furthermore, the 2018 Farm Bill, which has been bolstered by the Agricultural Act of 2014 and the Local Agriculture Market Program (LAMP) in the 2018 Farm Bill, significantly strengthens federal policies on local food systems (Martinez, 2010, USDA, 2021). According to the USDA's Agriculture Marketing Service and the 2015 Census of Agriculture, strengthening the local food system can provide a new source of employment and income while also helping to reduce energy and greenhouse gas usage (USDA-NASS, 2015; Low et al., 2011). As a result, local food production might have potential to not only provide food and nutritional security, but also promote better public health in metropolitan areas across the country (USDA-NASS, 2015, Pirog et al., 2018).

In 2017, more than 167,000 farms in the United States produced and sold food locally, generating $8.7 billion in revenue (USDA NASS, 2017). According to a USDA analysis, vegetables, fruit, and nuts account for the majority (60%) of all local food sales, with only 8% of total sales made through strictly direct-to-consumer channels (Low et al., 2017, USDA-NASS, 2017). Furthermore, vegetables, fruit, and nuts ranked first in terms of local food production and sales. Small farms with yearly sales of $50,000 or less account for up to 81% of local food sales. Furthermore, more than half of all small-scale Direct-to-Consumer Sales (DTC) enterprises are located near metropolitan and peri-urban areas, which account for 89% of all DTC sales (Low et al., 2015; USDA-NASS, 2012). In addition, between 2007 and 2012, the USDA found a 20% greater company survival rate in DTC farms, as well as an average 10% increase in local food sales (USDA-ERS, 2012; Low et al., 2011). This data estimates that local food production might have potential to achieve food security in urban areas. However, food and nutritional security concerns are not only the reason for the growing interest in local food in the U.S.; rather, different environmental movements catalyzed the acceptance of this interest (Pirog et al., 2009). Local food production can support local food production and economy during unexpected situation like the recent pandemic crisis in 2019 and onwards. Local farmers were able to ensure higher distance between customers and open space in direct selling conditions, rather than an enclosed retail store which was a cause of more concern. Therefore, the marketing method like pick-your-own farms saw >20% higher increase in customer (USDA, 2021). However, COVID-19 wreaked havoc on the US food supply chain, exacerbating the country's food shortage with food supply chain challenges. In 2020, the USDA responded by providing food through its local Farmers/Producers to Families Food Box Initiative, a $6 billion program designed to combat local food insecurity and help food delivery companies affected by pandemic-related disruptions

(USDA food supply chain, 2020). Therefore, local strawberry production is important to support the local food system in a crisis period.

Local Food Production in Kansas

Local food production and direct marketing of fruits and vegetables have been increasing at double-digit rates over the previous decade. According to the 2017 Census of Agriculture, direct-to-consumer (DTC) marketing of fruits and vegetables had marginal growth over nominal gross sales in 2007 (13.5%) increased up to 16 % from 2007-2017, with median DTC sales of $122,000 or less in the Midwest and South (Low et al., 2017). However, according to projections, even after the pandemic, this growth might reach 19.2 % in 2020. (Goldy et al., 2020). The Midwest states are dominated by monocrop cereal crop production, leaving smaller-scale farmers to diversify production through DTC channels. The Environmental Working Group (EWG) showed that in 8 states of the Midwest (Illinois, Iowa, Kansas, Minnesota, Nebraska, North Dakota, South Dakota and Texas) farmers received more than $41 billion subsidy payments for local crop production (USDA, 2020). According to the 2017 US agriculture census, Kanas is currently using only 14, 000 acres out of 45 million acres of land to produce fruits and vegetables. This represents market value of nearly $27 million dollars, from 1,089 producers while only 3 % of all farms in Kansas sell produce directly to the consumer. According to a survey conducted at the 2014 Great Plains Growers Conference, 70% of vegetable growers in Kansas have an average farm size of < 25 acres and 38% had only been cultivating for 5 years or less. As a result, neither Kansas nor Missouri is among the top five states in terms of direct local food sales, although metropolitan areas such as Kansas City, Lawrence, Topeka, and Wichita are seeing an increase in the local food market. According to food hub feasibility studies completed for the Kansas City metro area in 2015, the value of unfulfilled demand for local fruits and vegetables in the Kansas City region was estimated to be more than $150 million (Flaccavento et al., 2014; Greater Kansas City Food Hub Working Group, 2015). This study also examined grower and customer interest in local food sales, finding that 43 % of growers within a 250-mile radius wanted to sell apples, melons, and berries as the most popular fruit crops. However, berry production was at a minimum in the bordering counties (KC Food Hub Feasibility Study, 2015). One of the most difficult problems for small-scale local fruit producers, according to this report, is to satisfy and maintain this high-volume customer demand with consistent quality via direct-to-consumer operations. To compete with the vast variety of fresh food offered year-round at big supermarkets. Therefore, direct-to-consumer producers must diversify their production with controlled environments and storage facilities.

Challenges and Opportunities of Local Food Production

Local food production can be very difficult since the majority of it happens on small farms (1-5 acres). Small-acreage growers often struggle to meet intermediate expectations such as large volume, consistent quality, on-time delivery, off-season crop demand, growth management, price negotiation, and financial access (FAO 2017). Other factors, such as the scale and type of the operation's involvement in the local food system, can have a detrimental impact on small-scale local food production (Brinkley et al., 2021).

The establishment of food hubs can overcome the challenge for small farm owners to aggregate numerous farmers' products in a coordinated distribution and storage location. As a result, growers are no longer required to invest in on-farm infrastructure, marketing, or distribution (Fischer et al, 2013). Moreover, the Local Food Promotion Program from the 2018

Farm Bill offered $50 million to assist urban, indoor, and other non-traditional agricultural production (USDA, 2018). Also, these indoor farming technology-based production might solve the challenge to meet the greater needs of off season high value crops in a moderate volume consistently from small local farms. Martinze et al. (2010) noted that maintaining communication between different small growers and purchasers (e.g., restaurant operators) might be a major difficulty. However, the utilization of several local supply chains made local marketing systems more complicated to track food safety aspect and increase the chance of a food-borne pathogen outbreak in fresh produce. Employing the FDA Food Safety Modernization Act (FSMA) regulatory requirement and voluntary Good Agricultural Practices (GAP) certification can help local growers ensure that they maintain microbiological food safety for fresh produce even at the small farm level (Retinour et al., 2019). But this certification and audits for small farm sometimes cost thousands of dollars of investment, which makes small farms producers more economically strained. Yet, off-season berry production can give farmers higher economic returns because of ready local market demand, including a willingness to pay a higher premium price. According to a study, locally grown produce that is food safety GAPs certified can provide 30% higher economic incentives for local berry growers. Managing the post-harvest temperature of berries and using good handling practices not only helps control the growth of microbial pathogens on the fruit surface, but also minimizes shrinkage, which adds a value of 30% higher economic incentives and higher consumer preference for safe produce from local growers (Woods et al., 2012).

The Natural Resource Conservation Service (NRCS) started supporting the building of HTs in 2009, with the purpose of boosting environmental stewardship and extending the supply and benefits of local foods. According to research from Virginia Polytechnic Institute and State

University, high tunnel use on farms is increasing near places where local produce is in high demand. According to Meyer and O'Rourke (2021), HT production improves economic viability by allowing a farmer to earn money not only by extending the growing season but also by increasing on-farm crop biodiversity throughout the year, without traditional temperature constraints. The production of high value crops in crop rotation can receive a significant return on a small land area. Another research suggest that high tunnels can offer seasonal extension for warm season crops (e.g, tomato, egg plant, cucumber etc.) and winter harvesting opportunity (baby salad greens, lettuce, spinach etc.) and high value specialty crop protection for small fruit e.g. strawberries and raspberries, which can allow local and regional market sales year-round (Biernbaum, 2006). A study at Kansas State University demonstrated a successful day-neutral strawberry production system in HTs that could provide off-season strawberries to the local market (Gude et al., 2018). Michigan State University also successfully trialed baby leaf salad greens, tomato, and bell pepper in high tunnels with Community Supported Agriculture (CSA) farmers (Biernbaum, 2006). Overall, HTs production systems can increase profit margins during seasonally low production windows and can make meaningful contributions to economic sustainability for farms and markets. Therefore, it is apparent that high tunnels play a significant role for farmers and consumers to benefit from local production, distribution and sale of fruits and vegetables (Meyer and O'Rourke, 2015).

Economics of Strawberry Production for Local Markets

The lower Midwest region, which includes Illinois, Indiana, Kansas, Missouri, Nebraska, and Ohio, produces around 1451 acres of strawberry on 1347 farms, yielding about 14.4 million pounds per year on average (USDA, NASS 2012). Due to comparatively very low strawberry production rate in the central United States, in-season strawberries cost $4.95/lb, whereas early-season strawberries cost $6.60/ lb. (Maughan et al., 2015). As a result, since 2013, day-neutral strawberry research under high tunnel production started to increase significantly in the Midwest region to increase local strawberry production. In the southwestern growing region of the US, Utah State University reported that the higher net returns of early strawberry production were contingent on cultivar-specific early yield enhancement from high yielding cultivars like 'Seascape,' as well as to utilize the direct selling through local markets. Also, using HTs for specialty crop have become popular to extend the crop production season for better local market prices for growers. However, the profitability of HT crop production can vary by location, crop and production method (Rowly et al., 2011). Research has showed that to maintain HT strawberry production in North Carolina, as profitable enterprise, growers need to have a breakeven price of more than $1.28/lb (Ballington et al., 2008). The initial investment and maintenance costs can be a barrier to growers to achieve higher profit only from local strawberry production in the Midwest. Higher production rates therefore play a major role for strawberry profitability. A relatively small, (>15%) yield increase in HT strawberry production can result in net profit of $0.56/ft^2$ compared to open field strawberries (Galinato and Walter,2013). Rodriguez et al. (2012) conducted a sensitivity test to predict the value and numbers of years to recover the total cost for HT vs open field blackberry production. The overall gross return was high for existing HT blackberries compared to open field even with a greater investment than growing blackberries in the open field. Therefore, it is evident that high yielding day-neutral strawberry cultivars have the potential to become an economically profitable crop in the Midwest with a high price premium (Maughan et al., 2015; Rowley et al., 2011).

Research Objective

In the United States and in Kansas, local food consumption has consistently increased over time. In the Midwest consumers are willing to pay $5 per pound for better quality day-neutral strawberries, which has a positive impact on the local economy (Maughan et al., 2015). However, in Kansas locally grown strawberry growers are relatively scarce and utilize systems that only provide fruit for 3-4 consecutive weeks. As a result of the shortage of locally grown strawberries, especially in early spring, and late fall, production of strawberries in Kansas already has a high-demand market. In 2018, a research report from Kansas State University (Gude et al., 2018) examined six day-neutral strawberry cultivars with 'Portola' recommended as the highest yielding cultivar. 'Albion' and 'Evie-2' displayed better fruit quality. Both higher yield and better fruit quality are important for growers to ensure overall profitability and sustainability of local strawberry production in Kansas. Thus, combining different colored plastic mulch with existing high tunnel technology is hypothesized to improve yield and fruit quality of day-neutral strawberries, beyond only a cultivar response. Colored plastic mulch use along with HTs may help to sustain the availability of off-season strawberry market and also diversify the HT cropping system with other high value crops to ensure higher revenue throughout the season. Therefore, we hypothesized that the microclimatic alteration capacity of different color mulch might optimize the soil temperature and light conditions to improve fruit yield and quality, and thus the system's economics. To our knowledge, no strawberry production system has investigated the effectiveness of black stripe mulch along with five different plastics mulches on early spring soil warming and summer soil cooling along with color wavelength of plastic mulch.

Therefore, the objectives of this study are to investigate the effect of different color plastic mulches (black, white, black stripe, silver, red, and green) on:

(1) microclimatic alteration and strawberry production of two day- neutral cultivars in terms of total and marketable yield;

(2) strawberry fruit physical, organoleptic, and nutritional quality at harvest and during storage;

(3) identify the most suitable plastic mulch that could help improve yield and fruit quality for the two spring-planted day-neutral cultivars that we are studying;

(4) evaluate the economic viability of cultivating day-neutral strawberries in a HT plasticulture systems in Kansas;

(5) determine the most economically viable plastic mulch based on production budget to improve the yield and fruit quality of spring-planted day-neutral cultivars;

(6) provide growers with information to examine different revenue scenarios based on price and percent marketability.

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Chapter 2 - Effect of Different Mulches on Yield and Fruit Quality of Day-neutral Strawberries Grown in High Tunnel in Kansas

Abstract

Strawberry (*Frangaria x ananassa*) is a high-value crop extensively grown in the USA. Day-neutral cultivars are insensitive to daylight and may provide growers with higher crop yields and a longer production season. High tunnel (HTs) production systems provide a cost-effective way for annual crops to be grown under poly films and/or shade cloth. The use of different colored plastic mulches in a high tunnel production system with varied temperatures and light intensity could alter yield and fruit quality. This study was conducted to identify the most appropriate color plastic mulch in a high tunnel production system as it relates to yield and fruit quality at harvest and after four days in storage. The experiment was conducted at the Kansas State University, Olathe Horticulture Research and Extension Center in 2020 and 2021 using a split-plot, randomized complete block design (n=4). We evaluated six plastic mulches (black, white, black stripe, silver, red, and green) and two day-neutral cultivars, 'Albion' and 'Portola'. Soil temperature, UV-A and UV-B was measured above each plastic mulch. Mature fruit (90% to 100% red) were harvested twice weekly to determine total and marketable yield (fruit with no defects) and three harvests were evaluated for fruit quality. Respiration rate and overall visual quality of fruit was monitored every 24hrs during storage. Flesh firmness, color, soluble solids content (SSC), titratable acidity (TA), and SSC/TA ratio of the fruit were assessed at harvest and every other day for up to four days of storage at 3 $^{\circ}$C with 90% relative humidity (RH). Fruit nutritional quality including total phenolic (TP), antioxidant (FRAP), and anthocyanin (Antho.) was evaluated at harvest and on day four. In our study, total and marketable strawberry yields were greater in 2020 than 2021. Plastic mulch color had an interaction with total and marketable yield only in 2020, while there was no effect in 2021. In comparison to the (standard) black mulch, the silver mulch had a higher fruit yield, likely due to a reduced temperature range and lower UV-B irradiation capacity (P<0.0001). Both cultivars grown with silver mulch had 38 % and 33% higher total and marketable fruit weight per plant, respectively (P<0.0001). ‘Portola’ showed significantly higher total (1.68 lb/plant) and marketable (1.04 lb/plant) yield compared to ‘Albion’, which produced 1.08 lb/plant and 0.76 lb/plant, respectively ($P < 0.0001$). The ‘Portola’ plants grown with the green mulch had 7% higher marketability compared to the ones grown with black plastic mulch. In 2020, strawberry size, soluble solid content, SSC/TA ratio, color, firmness, and total anthocyanin content were unaffected by plastic mulch color. ‘Albion’ fruit grown with silver mulch had greater TA, FRAP and TP than those grown with black mulch at harvest (P<0.0001). In contrast, ‘Portola’ fruit grown with the black control mulch had the greatest FRAP concentration (1020 mol 100 g^{-1}) compared to the other plastic mulch. According to our findings, silver mulch enhanced yield for both cultivars and antioxidant content for ‘Albion.’. Therefore, based on crop productivity and fruit quality assessment, silver mulch can be a potential mulch to improve strawberry yield and fruit quality in high tunnel production.

Introduction

In 2020, the United States produced 2.5 billion pounds of strawberries that had a worth $3.5 billion (USDA-NASS, 2020). The fresh market value of strawberry production in the United States is second only to commercial apple production (USDA-NASS, 2014). Fresh strawberry consumption per capita in the United States reached 7.12lb per person in 2020 (Shahbandeh, 2021). The low caloric content (35 calories per 100 grams) and nutrient richness make this fruit a healthy food selection for consumers (Giampieri et al., 2014). Strawberries provide an essential source of health-promoting nutrients including minerals, vitamins, and fiber to the human diet. The phytochemicals contribute to the characteristic fruit color, texture, and flavor of strawberries, and have active antioxidants which can curb the risk of many chronic diseases (Wolf et al., 2008; Yang et al., 2011). Anthocyanins are water-soluble flavonoids, the most active antioxidant in strawberries (Mattioli et al., 2020). Vitamin C and phenolic compounds are antioxidants, which could leads to the potential role of strawberry consumption as age related disease prevention (Romandini et al., 2013).

In 2017, it was estimated that 91% of strawberries in the U.S. were produced in California (USDA-NASS, 2018). Therefore, distribution of strawberries within the U.S. relies on long-distance transportation (USDA- NASS, 2017). So, fruits are harvested before reaching full maturity to ensure a longer shelf life. However, strawberries are a non-climacteric fruit, so they do not ripen after harvest. Harvesting less mature fruit can slow the development of phytochemicals as well as the anthocyanins, sugar, and acid content after harvesting. Serrano et al. (2009) reported that strawberry flavor and antioxidant content declined when fruit were harvested at a less mature stage (>75% red). Wang et al. (2009) reported that when fruit was harvested immature, their soluble solid content (SSC), titratable acidity (TA), and sugar content was 5-20 % lower than mature fruit. For optimal fruit quality, berries are suggested to be harvested at the fully mature stage (Serrano et al., 2009; Wang et al., 2009). Storage can also negatively impact the abundance of important phytochemicals, including antioxidants (Gil et al., 2006; Lantz et al., 2010). Ayala-Zavala et al. (2004) reported that there is a trend of significant decreases in strawberry anthocyanin and soluble solid content after five to seven days of storage, even at 0 ˚C.

Locally grown strawberries, on the other hand, provide to the consumer with high-quality fruit because they can be harvested at full maturity and are immediately available to consumers without the need for storage and transportation. In 2014, the Food Market Institute survey in the U.S. found that consumers who support local food rank the most in importance traits as are freshness, taste and boosting the local economy (FMI, 2014). In the United States, local food consumption has risen steadily over time. Local food sales in the United States increased by more than 140% between 2008 and 2014, reaching almost $12 billion, with a prediction of a further 66 % increase until 2019 (USDA, 2017). More specifically, in 2015 it was projected that there was $156 million unmet demand for locally grown fruits and vegetables in the Kansas City metropolitan area (KC Food Hub Feasibility Study, 2015). This report also showed that berries was one of three highest in demand fruit crops in Kansas identified by local growers and buyers; however, there was very small percent of production acreage used for berry production (KC Food Hub Feasibility Study, 2015). Because Kansas relies primarily on seasonal strawberries imported from California and Florida, which are only available for a limited period. As a result, locally grown strawberries, especially early spring, and late fall production of strawberries in Kansas already have a high market demand that can avoid price revenue loss by avoiding national production peak that occurs with the current June-bearing production practices. Therefore, growing strawberries in Kansas has potential to address unmet demand for local food production and achieve better price premium for local grower with reasonably higher yield and fruit quality (KC Food Hub Feasibility Study, 2015).

Growing strawberries in Kansas, however, may be challenging due to the harsh weather and growing conditions. As a result, strawberry growers in Kansas prefer fall-planted June-bearing strawberry cultivars with plasticulture systems that avoid the high summer temperatures during July and August (Demchak et al., 2010; Kadir et al., 2006). In the Midwest, June-bearing cultivars are commonly produced because they reach maximum production from mid-May to mid-June before warm summer temperatures (>29 ˚C) restrict their growth (Durner et al., 1984; Demchak.et al., 2010). The production peak of June-bearing cultivars coincides with the national production peak, reducing the price premium that local grower receive for this crop (Juaron and Klein, 2011; Rowley et al., 2011). Day-neutral cultivars that fruit throughout the season could provide a solution to this challenge for Midwest growers (Herrington et al., 2007; Wu et al., 2015). Due to the photoperiod insensitivity, day-neutral strawberries, can continue to grow and produce fruit as long as temperatures remain between 7 to 25 ˚C, allowing growers to have off-season (early spring - fall) crops that offer higher premium prices compared to fall-planted cultivars (Tarara, 2000).

Early spring temperatures are often too low for successful plant establishment and root growth, which needs a soil temperature of ~12.6 ˚C to survive (Poling, 2012). Therefore, open field day-neutral strawberry production in the Central U.S. could be restricted due to severe weather, cool temperatures in the spring, early fall frosts, and diurnal temperature changes in the spring and fall. The implementation of HTs can help overcome these climactic obstacles so regional growers can achieve better yields and increase profitability from strawberry production (Maughan et al., 2015). HTs can extend the time for optimal growing temperatures for strawberries in the Midwest region by allowing seasonal extension (Gude et al., 2018; Kadir et al., 2006), and protection from early end-of-season frost events (Demchak and Hanson, 2013; Karlsson and Werner, 2011). Studies reported that high tunnel day-neutral strawberry production has a long harvest period (5-6 months, late-May to mid-December) with higher total yields (0.75 to 1.25 lbs/plant) than HT June-bearer strawberries, which last for 3-5 weeks with total yield of 0.43lbs/plan to 0.65lbs/ plant (Kadir et al., 2006; Petran et al., 2017). Due to the 5–12 °C warmer soil temperatures in high tunnels, strawberry production can begin five weeks prior to open-field (Kadir et al., 2006). Also, the shade cloth can be used to reduced light under high tunnels delivers a better photosynthetic ability and lower heat stress influence better plant growth, fruit yield, and quality when day-neutral cultivars grown in HTs. (Gude et al., 2018; Heidi et al., 2019; Demchak, 2009).

A previous study at Kansas State University Olathe Horticulture Research and Extension Center showed that certain cultivars of day-neutral strawberries can provide ample fruit yield when grown in a HT in Kansas (Gude et al., 2018). This research reported 'Portola' as the highest yielding cultivar whereas 'Albion' (0.90lb/plant) and 'Evie-2' (1.30lb/plant) maintained better fruit quality during storage compared to the rest of the cultivars tested (Gude et al., 2018; Gude et al., 2021).

During the hot summer growing season, a HT can get extremely warm with heat being trapped in the tunnel. During late June and early August, Kansas is often hotter than >29 °C (Enz et al., 2014). Temperatures over 29 °C have been shown to reduce berry size and fruit weight and overall yield (Kumakura and Shishido, 1994). Plant growth and fruit quality, such as firmness, sugar content, and aroma, are also inhibited at temperatures above 29 °C (Hellman and Travis, 1988; Lantz et al., 2010). Strawberry flower initiation and development can also be delayed by temperatures above 20-24 °C (Poling, 2012; Phelps, 2014; Petran et al., 2017), and can lower fruit firmness and SSC content (Gündüz and ¨Ozdemir, 2010; Ordidge et al., 2010; Vo´ca et al., 2007).

In addition to shade cloth, another way that the microclimate in the high tunnel can be further manipulated is by plastic mulch. Plastic mulch colors that affect thermal and radiation properties can be selected with the goal of improving fruit yield and quality. Previous research has reported that the color of the plastic mulch can suppress weed growth, improve plant growth and productivity in both annual and perennial crops (Weber, 2003). Using this microclimatic alteration technique via dark colored plastic mulch may help plant growth by keeping the soil temperatures warm enough. Alternatively, light colored mulches can make the soil cool because of the higher reflective ability (Poling, 2012; Hunter et al., 2012).

Environmental factors (sunlight, day-night temps) have a significant impact on strawberry fruit quality and postharvest life (Sistrunk and Morris, 1985). Phytonutrient content and strawberry fruit quality can be affected by light intensity (Taghavi et al., 2019). Higher ultraviolet (UV) light exposure can make fruit smaller, firmer, and darker than fruit grown in a UV-blocking film (Ordidge et al., 2012; Tsormpatsidis et al., 2010). Higher temperature fluctuations (day/night) can influence the antioxidant activity and flavonoid concentration in strawberries (Anagnostou et al., 1995). Dark-colored mulches absorb heat and transport it to the soil surface, raising the overall soil temperature around the plant root zone in strawberry crop (Díaz-Pérez et al., 2005; Lamont, 2005; Tarara, 2000). Except black, colored plastic mulch including red, yellow, green, blue, and white have been reported to affect the fruit quality and bioactive compounds but have no effect on the average individual fruit weight of strawberries (Miao et al., 2017). Todic et al. (2008) found that red plastic mulch significantly increased soluble solid accumulation in strawberries. A study at Pennsylvania State University demonstrated that silver mulch can result in a 20% increase in fruit yield of peppers compared to black plastic (Ahmed et al., 2017; Andino and Motsenbocker, 2004).

Silver and white plastic mulch keep the soil cool and can influence the microclimate and also repel insect pests (Csizinszky et al., 199; Hutton et al., 2007). Utilizing a silver mulch with black striped, helps promote soil warming during early establishment. The silver part of the mulch can cool the soil root zone and minimize symptoms of insect-transmitted viruses. This effect has been shown to increase the bell pepper yield (Csizinszky et al., 1999; Díaz-Pérez, 2010; Hutton and Handley, 2007). Metalized striped mulch was reported as the most efficient mulch reducing soil temperatures reflected by photosynthetically active radiation for strawberries grown in the open field (Descamps and Agehara, 2019).

Based on the existing literature, there is a critical need to learn more about how day-neutral strawberryqaulity and production in HTs could be affected by various plastic mulch types. Therefore, we conducted an experiment with day-neutral strawberry cultivars in 2020 and 2021 with plastic mulch in the high tunnel. A previous study with day-neutral strawberry production (Gude et al., 2018) identified ‘Portola’ as the highest-yielding cultivar (Gude et al., 2018) and ‘Albion’, which maintained better fruit quality compare to ‘Portola’(Gude et al., 2021). More specifically, the objectives for this study were to examine the effect of different color plastic mulches (black, white, black stripe, silver, red, and green) on: (1) microclimatic alteration and strawberry total and marketable fruit yield; (2) strawberry fruit physical, organoleptic, and nutritional quality at harvest and during storge; and (3) selecting suitable plastic mulch that could help improve yield and fruit quality for ‘Portola’ and ‘Albion’ strawberry plants grown in a HT.

Materials and Methods

Experimental Design and Plant Materials

This study was performed at the Kansas State University Olathe Horticulture Research and Extension Center (OHREC) 2020. Strawberries were grown within a one (24' x 200') bay of three-season multi-bay high tunnel (96' x 200'). A 30% shade cloth was applied once daytime temperatures were consistently around 29 $^{\circ}$C. The trial was organized as a split-plot, randomized complete block design with four replicates. The main plots were the six-plastic mulch (black, white, black stripe, silver, red, and green) and the sub-plots were the two cultivars being tested (Fig. 1). All plots were re-randomized for the trial conducted in 2021 and it was conducted in a different bay of the same multi-bay HT to ensure a crop rotation. The black, red, and green color 1.0 mil embossed plastic mulch (Grower's Solution, Cookeville, TN) and three biodegradable plastic mulches including silver, black stripe, and white (Film Organic, Laval, Canada) were used for our trail both years. All the plastic mulches were intended to have no UV blocking effect. Black plastic mulch was considered as the control for this experiment as it is more-commonly used in HTs for strawberry production and in previous studies (Gude et al., 2018). 'Albion' and 'Portola' (*Fragaria x ananassa*) were selected based on yield and quality potential from previous study of Gude et al. (2018). In both years, the trials included three rows with twelve plots per row (48 plots total), and 30 plants in each plot. A buffer zone of 20 plants (4ft) were included at the ends of each bed and to prevent any undesired bias from microclimate effects related to being at the ends of the tunnel and/or bed. Spacing of 36 inches between main plot (plastic mulch) and 12 inches between sub plot (cultivar) maintained as buffer zone to reduce inter plot interference.

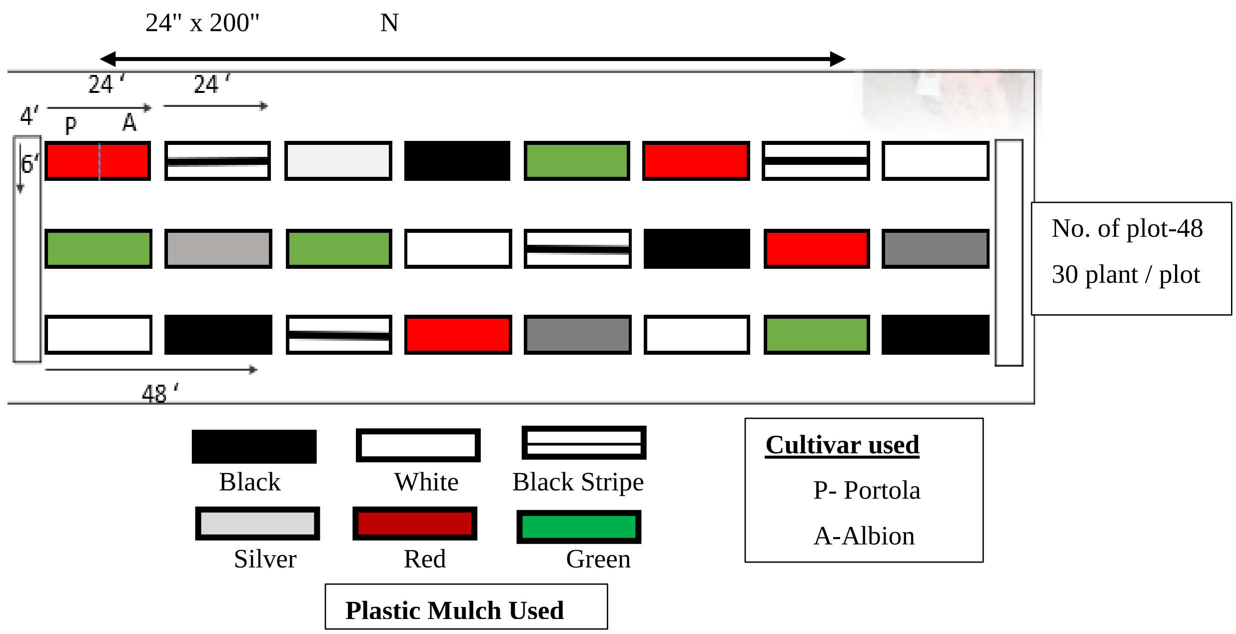

Figure 2.1. The 2020-2021 plot map experimental design

The trial consisted of 48 plots (24' length) and organized as a randomized complete split-plot design with six plastic mulches treatments (black, white, black stripe, silver, red, and green) with two day-neutral cultivars 'Albion' and 'Portola'. Plastic mulches are the main plots and cultivars as the sub-plots. The trial was located at the Olathe Horticulture Research and Extension Center (OHREC) on three rows in a three-season high tunnel.

Bed Preparation and Plant Establishment

Three rows of soil raised beds formed by a tractor-driven bed shaper (Rain-Flo 2550; Rain-Flo Irrigation, PA, USA) placed parallel to the length of the tunnel (north and south) and each plastic mulch was installed manually over the soil beds. All six-plastic mulches were installed at once on 1 April in 2020 and 15 March in 2021. The main plots were 25ft long and 3ft wide rows. Each plot (12' in length) had 6' spacing between rows and 12" in-row spacing. Spacing in between main plots were 3ft maintained to reduce inter plot interference. Each sub-plot was planted with 30 plants in three rows of ten plants each, with 12 inches between rows and in-row spacing. In 2020, we observed weed problem in the plots with the red plastic mulch due to light penetration that stimulated weed growth. Therefore, an additional layer of black plastic mulch was installed below the red plastic in 2021.

Growing Methods

Bare-root strawberry plants (Nourse Farms, South Deerfield, MA) were used for the trials in both years. Due to the late winter weather in Kansas in 2020, the bare-root plants were first planted in 2.5-inch pots with potting mix (Fafard 3B; Conrad Fafard, Agawam, MA) and cultivated in a greenhouse for two weeks before being transplanted to the three-season high tunnel. In 2021, bare-root plants were planted directly into the high tunnel. Plants were grown on raised beds with six the polyethylene mulches and irrigated with drip tape with 4 in emitter spacing (Turbo Tape; Jain Irrigation, Fresno, CA). There were two drip tapes per bed, between each row of plants. Between rows, weeds were inhibited with woven fabric mulch, and runners were removed weekly and as needed based on weed pressure and runner growth.

In both years, a custom-blended granular fertilizer mix (31N-16P-16K) was incorporated into the beds prior to planting at a rate of 50 lbs nitrogen/acre (broadcast). The trials were planted on 2 April in 2020 and 19 March in 2021. In both years, strawberry plants were fertigated with 2 applications of potassium nitrate [13.5N-0P-46.2K (Haifa Chemicals, Haifa Bay, Israel)] and 1 application of calcium nitrate [15.5N-0P-0K (Yara North America, Burton, OH)] in rotation. The application rate was 10 lbs./acre (broadcast) nitrogen for both products and were provide four, six, and eight weeks after planting.

Monitoring Microclimate in the HT

Soil temperature was monitored with data logger (EL-USB-1) from 5 April to 10 October in 2020 and 9 April to 13 October in 2021. Data loggers placed randomly in the center of bed in three of the four replications of each plastic mulch treatment plots at a depth of 4 inches. EL-USB-1 data loggers encased in a weatherproof, stainless-steel shell designed for recording soil temperature recorded soil temperatures every 30 minutes (EL-USB-1; LASCAR Electronics, Erie, PA).

The total growing season for both years was divided into three seasons—early, mid, and late—to evaluate the soil temperatures during cool and warm temperatures for each plastic mulch treatment. In 2020, early season was presented as (5 April to 6 June), mid-season (7 June to 8 August), and late season (9 August to 10 October) for 2020. The data collected from 2021 was separated into: early season (9 April to 10 June), mid-season (11 June to 12 August), and late season (13 August to 13 October). The seasonal separation by 8 weeks, into early mid and late season help us to determine each plastic mulch compatibility to ensure proper monitoring of the soil temperature (12.5-24 $^{\circ}$C) throughout the strawberry production season to assess the early spring establishing temperature as well as the hot summer severe temperature influence.

To describe the light spectrum reflected from each plastic, radiation measurements were performed for each main plot. Measurements were taken perpendicular to the mulch surface at a height of 10 inches. To measure reflected UV-A and UV-B light, three measurements were taken for each mulch type using a radiometer (ILT5000; International Light Technologies, Peabody, MA, USA) according to the manufacturer’s guidelines. The device reported intensity of ultraviolet light reflected from per square feet of plastic mulch in the wavelength range of 250-

400 nm in units of W/m^2. The measurements were collected twice per season, on 19 Aug and 18 Sept., for both years of the trial. During each measurement day, a UV light reading was collected for three replicate plots from each main plot treatment (one reading at 10am, 1pm, and 4pm). The UV light reflection intensity reading was recorded every 5min and averaged.

Harvesting and Yield Data Collection

Mature red fruit (100% red) were harvested twice weekly and marketable and non-marketable fruit numbers and weight were recorded. Non-marketable fruit were determined based upon the presence of decay, gray mold, and small size (<3 cm diameter), and/or pest damage. In 2020, strawberries were harvested from 8 May to 10 October in 2020. In 2021, strawberries were harvested from 22 April to 13 October.

Evaluating Postharvest Quality

Postharvest quality analysis requires a relatively higher quantity of fruit. Therefore, fruit from each of the four HT trial replications for each treatment were combined and re-distributed into three replications of three fruits per replications for fruit quality analysis. Strawberry fruit were transported in a cooler in open cardboard boxes to the postharvest laboratory at KSU-Olathe for evaluating physical, organoleptic, and nutritional quality on the day of harvest and during storage. Fresh fruit were sorted based on maturity (100% mature), free from visual defects or damage, and uniform size and color. Strawberries were stored at a constant 3 °C and 90-95% relative humidity (RH) in environmental chambers (Forma Environmental Chambers; Thermo Fisher Scientific Inc., Asheville, NC) until the end of their 4 days of storage life. Following the physical and organoleptic quality measurements at harvest, fruit samples were frozen with liquid nitrogen and stored at -20°C only for nutritional quality analysis.

Overall visual quality of strawberry fruit was evaluated non-destructively every 24 hours throughout their storage life (~4 days). Twenty fresh berries with similar maturities per cultivar and treatment were separated for overall visual quality. Overall visual quality was evaluated by using the scale provided by Nunes (2010) with scores from 5 to 1 (5-excellent to 1-very poor).

Moisture loss was recorded daily by weight measurements of the same berries every day. The recorded differences in weight measurements resulted in the final weight loss expressed as the percent weight loss for the cultivars during their storage life as reported by Bourne (1976).

Respiration rate (mg $CO_2 \cdot kg^{-1}h^{-1}$) was recorded using a closed static system as described by Biale and Young (1981). The portable gas analyzer (Model 1900141; Bridge Analyzer, Alameda, CA) to measure CO_2 production with three replications of three fruits per replications was used. Strawberry fruit were kept sealed in air-tight glass jars (0.75L Le Parafait Jars) for 60 minutes prior to the measurements. Measurements were taken every 24 hrs. throughout storage period.

Physical quality was examined in regard to fruit texture and color at harvest and every two days during the 4-day storage period using three replications of three fruits each. Texture was measured destructivelywith a texture analyzer TA-58, TA.XT. plus (Texture Technologies Corp; Scarsdale, NY, USA) using a 3mm diameter cylinder probe. Two measurements were taken on opposite sides of the berry near the shoulder. The texture parameters measured were firmness and resilience as described by Caner (2008). Two color measurements from each shoulder of fruit were evaluated using an A5 Chroma-Meters (CR-400; Minolta Co.; Osaka, Japan). Color results were expressed as CIELAB color system where L* is lightness, a* (greenness to +redness) (Bakker et al., 1986).

Organoleptic quality was assessed by measuring titratable acidity (TA) and soluble solid content (SSC) and was recorded on the day of harvest and every two days over the course of the 4-day storage period. Three replications with three fruit each were taken for every parameter. The fresh berries were macerated and then passed through 2 layers of cheese cloth. The juice was used for TA and SSC measurements. TA was recorded with an automatic titrometer (Compact Titrosampler 862; Metrohm USA Inc., Riverview, FL.) and the results were expressed as % of citric acid equivalent (AOAC International, 1995). SSC was recorded with single drop of juice placed in a refractometer (Reichert Technologies, Depew, New York) and expressed as °Brix.

Nutritional quality including total antioxidant capacity, total phenolics and total anthocyanin were measured on the hydrophilic portions of the fruit samples. Total antioxidant capacity was measured according to Benzie and Strain (1996), with the Ferric Reducing Ability of Plasma (FRAP) method. With a 96-well microplate reader in spectrophotometer at 593nm, absorbance was identified against the trolox positive control and designated as micromolar Trolox equivalent in 100g fresh weight basis (μM TE·100g FW). Total phenolic content was measured according to the Singleton and Rossi (1965) procedure with 96-well microplate reader (Synergy H1; BioTek Instruments Inc., Winooski, VT, USA) at 750nm absorbance. The results are expressed as mg gallic acid equivalent in kg fresh weight basis (GAE·kg FW). Total anthocyanin was measured according to Nunes et al., (2005), procedure with 96-well microplate reader in a spectrophotometer at 520nm absorbance (maximum absorbance for anthocyanins). The results are expressed as mg/100g fresh weight of Pelargonidin-3-gluco- side (PGN).

Statistical Analysis

The growing season for both years has been divided into three season average 60 days in each season to evaluate impact on the early spring coldness, hot summer heat and early fall cool weather on crop production cycle. In 2020, early season was (5 April 2020 to 6 June 2020), mid (7 June 2020 – 8 August 2020) and late season (9 August 2020.- 10 October 2020). In 2021, early season was (9 April 2021 to 10 June 2021), mid (11 June 2021 – 12 August 2021) and late season (13 August 2021- 13 October 2021). It was necessary to separated them in to early mid and late season to determine each plastic mulch compatibility to ensure proper soil temperature (12.6-24 ˚C) throughout the strawberry production season to assess the early spring establishing temperature as well as the hot summer severe temperature influence. The average of 8-weeks maximum and minimum soil temperature, as well as their standard deviation for each plastic mulch treatment, were calculated using excel and divided into early, mid, and late seasons.

For this experiment, there were six plastic mulch treatments (mulch) and two cultivar treatments (cultivar) used. All statistical analysis was performed using a statistical analysis software (SAS version 9.4, SAS INSTITUTE).

UV-A and UV-B data were subjected to PROC GLIMMIX statistical analysis. The fixed effects included the year, month of measurement, and plastic mulch treatment—along with all interactions. The time of day the measurement was taken (10am, 1pm, and 4pm) was considered a blocking factor and was included in the RANDOM statement. There were no significant interactions and no significant differences in the UV data between the two years. But there was a significant effect on UV data based on the month (August and September), so the two months were analyzed separately. The mean separation was performed using the Tukey-Kramer method and significance was established at $P \leq 0.05$.

The effects of different color mulch on yield and marketability are determined from the dates that the plasticulture system was established until the end of the growing year. Percent marketability was calculated as the proportion of marketable fruit as compared to the total yield and were calculated based on fruit weight. Average fruit size was determined in grams as a measurement of strawberry fruit count within the total yield. Fruit yield measurements were subjected to a linear mixed model using PROC GLIMMIX. The fixed effects of the model included year, mulch, and cultivar and all two- and three-way interactions. The blocking factor was included in the RANDOM statement. The yield response variables with significant year main effects or significant interactions with year were analyzed separately by year. The least significant difference (LSD) was used for all mean separation of yield response variables.

Three harvests were evaluated for fruit quality analysis at harvest and during a four-day storage period. To observe the overall *P*-value table of the fixed effects on fruit quality, each fruit quality response variable was subjected a linear mixed model (PROC GLIMMIX) and the fixed effects included cultivar, mulch, year, and time with all possible two- and three-way interactions. The effect of harvest was included as a random effect. For fruit quality assessment on day 0 only, each fruit quality measure was assessed with PROC GLIMMIX with cultivar, mulch, and cultivar x mulch as the fixed effects. To assess fruit quality changes over shelf-life, the two cultivars were also analyzed separately, and the fixed effect of mulch, time, and mulch x time were considered. The mean separation was performed using the Tukey-Kramer method and significance was established at $P \leq 0.05$.

Results

Soil Temperature

In Table 2.1 the soil temperature results are presented as early season (5 April to 6 June), midseason (7 June to 8 August), and late season (9 August to 10 October) for 2020. The data collected from 2021 was separated into: early season (9 April to 10 June), mid-season (11 June to 12 August), and late season (13 August to 13 October).

In our results, soil under the black, red, and green plastic mulch had consistently higher maximum and minimum temperatures compared to the soil under white plastic mulch plot across the whole season. For instance, the average maximum and minimum soil temperature was 8.3 °C and 5.8 °C higher under the green plastic mulch than under the white in both seasons. The average maximum and minimum soil temperatures under the green mulch was also 3.4 °C and 3.2 °C higher than the soil under the black plastic mulch. Across the season, the white mulch had a 4.9 °C and 2.6 °C lower maximum and minimum temperature than black plastic mulch plot. In 2020 and 2021, early season average minimum soil temperature means under all plastics mulch was above 12.4 °C except the soil under white plastic mulch was below <10.5°C. The soil under the silver mulch had less fluctuation between the average minimum and maximum temperature in the mid and late seasons compare to all other plastic mulch. The silver plastic mulch was also able to maintain optimum temperatures (12.5-24.1 °C) in the early, mid, and late season.

Ultraviolet Light Intensity Measurement

The UV measurements were taken over the two experimental years in August and September are presented in Table 2.2. The measurements taken in August had higher UV-A and UV-B irradiance reflection level from the plastic compared to the ones in September. The white and silver plastic mulch had higher UV-A light intensity, but lower UV-B light intensity compared to the black plastic mulch [$P<0.0001$ and $P<0.0001$, respectively (Table 2.2)]. The green plastic mulch had the highest UV-B irradiation compared to the black plastic mulch, regardless of the month. In August, the silver plastic reflected 2.4 times higher UV-A light intensity irradiance and 2 times lower UV-B light irradiance compared to black plastic mulch [$P<0.0001$ (Table 2.2)]. A similar pattern was also observed in the month of September, with the silver plastic mulch reflected a 2.5 times higher UV-A light and a 2 times lower UV-B light reflectance than the black plastic mulch plots. In both months the white plastic mulch plots had the lowest UV- B irradiance, which ranged between 2.28- 2.5 (W/m^2) and was 2 times lower than the black plastic mulch plot ($P<0.0001$). The black stripe and red plastic irradiated similar amounts of UV-A, but significantly lower UV-B light exposure compared to black plastic ($P<0.0001$).

Table 2.1. Maximum and minimum mean soil temperatures (˚C) under different color plastic mulch in a high tunnel in 2020 and 2021 in Olathe, KS.

			2020			
	Black	White	Black Stripe	Silver	Red	Green
	Max (SD)[y]	Max (SD)	Max (SD)	Max (SD)	Max (SD)	Max (SD)
Early Season	23.9[z](0.2)	17.6(-0.3)	25.3(0.4)	18.2(0.1)	24.6(0.4)	25.4(-0.4)
Mid-Season	27.2(0.3)	21.4(0.4)	28.8(0.1)	23.4(0.2)	29.8(-0.3)	31.4(-1.2)
Late Season	20.5(0.1)	18.5(0.5)	20.8(0.3)	19.6(-0.1)	22.3(0.2)	22.9(-0.1)
	Min. (SD)	Min. (SD)	Min. (SD)	Min. (SD)	Min. (SD)	Min (SD)
Early Season	12.3(0.1)	9.2(0.2)	13.8(0.2)	12.4(-0.1)	14.7(-0.1)	15.3(0.3)
Mid-Season	20.1(0.5)	18.1(-0.5)	20.9(-0.5)	19.3(-0.1)	21.6(0.4)	22.3(-0.1)
Late Season	16.3(-0.2)	14.2(0.2)	20.5(0.3)	18.5(-0.5)	19.3(0.2)	20.9(-0.5
			2021			
	Max (SD) [c]	Max (SD)	Max (SD)	Max (SD)	Max (SD)	Max (SD)
Early Season	23.3(0.3)	18.8(0.1)	22.6(-0.1)	19.5(-0.4)	25.9(0.2)	26.1(0.1)
Mid-Season	29.4(-1.2)	23.6(1.4)	28.2(0.4)	24.8(0.2)	32.1(0.3)	35.1(-0.1)
Late Season	20.9(0.7)	15.4(0.4)	21.3(0.2)	19.5(-0.1)	23.5(0.4)	24.3(0.2)
	Min. (SD)	Min. (SD)	Min. (SD)	Min. (SD)	Min. (SD)	Min (SD)
Early Season	12.4(0.2)	10.8(0.3)	13.9(-0.1)	12.7(0.3)	14.5(-0.1)	14.9(0.3)
Mid-Season	20.6(-1.1)	18.5(0.2)	21.2(0.2)	20.3(0.2)	23.4(0.2)	23.8(0.4)
Late Season	15.6(-1.2)	11.4(1.3)	16.4(0.4)	15.7(0.4)	19.3(-0.1)	19.8(0.2)

[z]Values are the means of soil temperature maximums and minimums for three seasons recorded during two consecutive year trial from April to October (2020-2021). Eighteen soil temperature probes added 4 inches below the soil surface, recording temperature in 30 min increments throughout each growing season (3 probes per plastic mulch).
[y]SD = values in parentheses denote the standard deviation for each season max and min temperature.

Table 2.2. Irradiance intensity of ultraviolet (UV-A & UV-B) reflected by different plastic mulch types in a high tunnel in Olathe, KS in 2020 and 2021.

Month	Treatment	UV-A (W/m^2)	UV-B (W/m^2)
August	Black	21.67c	5.30b
	White	42.16b	2.51e
	Black C. Stripe	23.50c	3.61dc
	Silver	52.10a	2.65de
	Red	18.66c	3.69c
	Green	16.55c	6.34a
P-value ^{z}		<0.0001	<0.0001
September	Black	19.23c	4.80b
	White	38.66b	2.28d
	Black C. Stripe	20.33c	3.31c
	Silver	47.50a	2.40d
	Red	16.56c	3.38c
	Green	14.23c	5.58a
P-value		<0.0001	<0.0001

Trial was arranged in randomize split plot design, with following six plastic mulch randomly assigned within the tunnel: black, white, black stripe, silver, red and green
Ultraviolet (UV) light measurements were taken 10 inches above each plastic mulch plot every 5 min, on 18 August and September 19, 2020, and 2021
^{z}Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05
Means followed by the same letter are not significantly different according to Tukey's HSD paired comparisons where α=0.05.

Fruit Yield and Percent Marketability

Table 2.3 provides the probability values for the various analysis of variance (ANOVA) tests to determine the statistical significance of cultivar, mulch color, and year as well as the interaction between the factors. We observed significant cultivar x year and treatment x year interactions for several yield parameters including total and marketable yield (Table 2.3). Therefore, the two years were analyzed separately for these parameters. For the percent marketability of harvested fruit, there was a significant cultivar x treatment effect but no significant year interactions, so the data were pooled across the two years.

Since there was no significant cultivar x treatment interaction for the total and marketable yield parameters, the main effects of mulch type and cultivar are shown in Table 2.4 and Table 2.5, respectively. In 2020, there were significant treatment effects on total and marketable fruit yield but not in 2021 (Table 2.4). In 2020, strawberries grown with silver mulch had significantly higher total fruit yield (lbs/plant) compared to the other plastic mulch treatments. The total and marketable fruit weight harvested per plant was 38 % and 33 % higher for plants grown with silver and black stripe mulch than the black plastic mulch [P<0.0001(Table 2.4)]. Strawberry plants grown with silver mulch produced 35% more total ($P < 0.0001$) and 34% more marketable ($P < 0.0001$) fruit number compared to black mulch (Table 2.4). The other mulch treatments (white, red, green) resulted to similar total and marketable yields (fruit weight/plant) as the plants grown with black plastic mulch (Table 2.4). There were no significant differences in total and marketable fruit size observed between mulch treatments for both production years. Table 2.5 shows that cultivar significantly affected the total and marketable fruit yield as well as marketability in both years. In 2020, 'Portola' produced 5% (by weight) more total yield and 37 % more marketable fruit yield compared to 'Albion' (Table 2.5). In 2020, the 'Portola' plants produced 36% higher total fruit number, and in 2021 'Portola' produced 23% higher fruit number per plant compared to 'Albion' [P<0.0001(Table 2.5)]. In 2021, there were no significant differences observed in total yield, marketable yield, fruit number and fruit size amongst any of the different plastic mulch treatments as compared to the black plastic mulch.

Table 2.6 provides the mean percent of marketable fruit by weight for each cultivar and plastic mulch treatment., 'Albion' produced a significantly higher proportion of marketable fruit than ‘Portola’ with most of the plastic mulch treatments, except red, which resulted in similar marketability between the two cultivars. Also, ‘Portola’ fruit grown with green plastic mulch produced a similar percentage of marketable fruit (71.9 %) as compared to ‘Albion’ fruit grown on any of the plastic types (Table 2.6). For ‘Albion’, plants grown with any of the plastic mulch had a similar percent marketability, but plants grown with the red plastic had significantly lower percent marketability of fruit than those grown with the green mulch. For ‘Portola’, the percent of marketable fruit was similar for plants grown with the black, white, silver, and black stripe (Table 2.6). However, the green mulch produced 7% more marketable fruit compared to those grown with the black control mulch. Strawberries from the ‘Portola’ cultivar grown with red mulch had significantly lower marketability than the ones grown with black plastic mulch [*P*<0.001 (Table 2.6)].

Table 2.3. Probability values for total and marketable fruit yield and percent marketability (by wt.) of two day-neutral strawberry cultivars grown with different color plastic mulch in a high tunnel in Olathe, KS in 2020 and 2021

	Total Fruit Yield ^{y}			Marketable Fruit Yield ^{y}			Marketability ^{y}
	Weight (Lbs./plant)	Number (fruit/plant)	Size (g/fruit)	Weight (Lbs./plant)	Number (fruit/plan)	Size (g/fruit)	Weight (%)
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment	<0.0001	<0.0001	ns	<0.0001	0.0015	ns	0.0001
Cultivar x Treatment	ns	ns	ns	ns	ns	ns	0.0010
Year	0.0037	0.0001	0.0002	ns	ns	ns	<0.0001
Treatment x Year	0.0093	0.0002	ns	ns	0.0281	ns	ns
Cultivar x Year	0.0006	0.003	0.0157	0.0104	ns	0.0438	ns
Treatment x Cultivar x Year	ns^{x}	ns	ns	ns	ns	ns	ns

[z] The experimental design was a split-plot randomized complete block design with four replications: main plots included the use of six plastic mulch (black, white, black strip, silver, red, and green) and sub plots included the use of two-day-neutral cultivars 'Albion', 'Portola', each plot consisted of 30 plants grown in a raised bed row system;100% mature fruit were harvested twice weekly from May to October and all cumulative fruit harvest data from 2020 & 2021 were included in the statistical analysis.

[y]Analysis of variance to determine which factors and interactions between factors affected the total, marketable yield, and fruit marketability percent data from the entire production season were used for this analysis.

[x]Nonsignificant at $\alpha = 0.05$.

Table 2.4. Main effects of different color plastic mulch on total and marketable fruit yield of two day-neutral strawberry cultivars grown in a high tunnel in Olathe, KS, in 2020 and 2021

	Total Fruit Yield [z]			**Marketable Fruit Yield** [z]		
Treatment [y]	Weight (lbs./plant)	Number (fruit./plant)	Size (g/fruit)	Weight (lbs./plant)	Number (fruit/plant)	Size (g/fruit)
			2020			
Black	1.17b	54.64c	9.58	0.77c	31.00c	11.15
White	1.36b	68.02b	9.27	0.92bc	38.00b	10.89
Black C. Stripe	1.64a	76.84b	9.55	1.08ba	43.63b	11.13
Silver	1.89a	88.55a	9.55	1.15a	47.34a	11.09
Red	1.23b	51.06c	9.92	0.77c	29.00c	11.66
Green	1.10b	54.31c	9.00	0.73c	32.69cb	10.68
P-value[x]	<0.0001	<0.0001	ns	<0.0001	<0.0001	ns
			2021			
Black	0.93	42.67	9.99	0.69	29.13	10.92
White	1.08	48.47	10.10	0.77	31.64	11.08
Black C. Stripe	1.11	48.64	10.34	0.83	34.39	11.06
Silver	1.24	56.02	10.02	0.88	36.50	11.09
Red	1.00	44.88	10.08	0.74	30.41	11.03
Green	0.97	44.59	9.86	0.73	32.16	10.54

P-value	ns	ns	ns	ns	ns	ns

[z] Two-day-neutral cultivars 'Albion', 'Portola' fruits were harvested at 100% maturity twice weekly in 2020 and 2021 and marketability was determined by fruit free from disease and pest damage, and rot, total and marketable fruit were counted and weighed each time and values are presented on a per plant basis.
[y]Five different color plastic mulches were (white, black stripe, silver, red, and green) considered as treatment and black standard plastic mulch was the control.
[x]Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05
Means followed by the same letter are not significantly different according to LSD paired comparisons where α=0.05.

Table 2.5. Main effects of cultivar on total and marketable fruit yield of two day-neutral strawberry cultivars grown in a high tunnel in Olathe, KS, in 2020 and 2021

	Total Fruit Yield [z]			Marketable Fruit Yield [z]		
Cultivar[z]	Weight (Lbs./plant)	Number (fruit/plant)	Size (g/fruit)	Weight (Lbs./plant)	Number (fruit/plant)	Size (g/fruit)
2020						
Albion	1.08	55.40	8.85	0.76	34.27	10.19
Portola	1.68	75.75	10.11	1.04	39.58	12.01
P-value[x]	<0.0001	<0.0001	<0.0001	<0.0001	< 0.0001	<0.0001
2021						
Albion	0.93	42.93	9.80	0.73	31.68	10.47
Portola	1.18	52.17	10.32	0.82	33.06	11.44
P-value	<0.0001	<0.0001	<0.0001	ns	ns	<0.0001

[z]Two-day-neutral cultivars 'Albion', 'Portola' fruits were harvested at 100% maturity twice weekly in 2020 and 2021 and marketability was determined by fruit free from disease and pest damage, and rot, total and marketable fruit were counted and weighed each time and values are presented on a per plant basis.
[x]Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05
Means followed by the same letter are not significantly different according to LSD paired comparisons where α=0.05

Table 2.6. Effects of cultivar and plastic mulch on the proportion (%) of marketable fruit produced in a high tunnel in Olathe, KS, in 2020 and 2021

Cultivar	Plastic mulch[z]	Percent marketability weight (%)
Albion	Black	75.19ba
	White	73.60ba
	Black Stripe	75.21ba
	Silver	75.13ba
	Red	71.92bc
	Green	76.96a
Portola	Black	66.36de
	White	64.60e
	Black Stripe	67.50de
	Silver	69.22dc
	Red	60.10f
	Green	71.86bc
	P-value	<0.001

Two-day-neutral cultivars 'Albion', 'Portola' fruits were harvested at 100% maturity twice weekly in 2020 and 2021 and marketability was determined by fruit free from disease and pest damage, and rot, total and marketable fruit were counted and weighed each time and values are presented on a per plant basis.
[z]Five different color plastic mulches were (white, black center strip, silver, red, and green) considered as treatment and black standard mulch was the control.
There was interaction between plastic mulch and cultivar, so we pooled 2020 and 2021 data
Means followed by the same letter are not significantly different according to LSD paired comparisons where α=0.05.
[x]Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05

Fruit Quality

The data in the Table 2.7 represents the effects of six different plastic mulch color and their interactions with cultivar and storage time on the fruit quality parameters.Overall visual quality of the fruit did not significantly affect by plastic mulch. Only respiration rate ($P < 0.05$), moisture loss (%) ($P < 0.0001$) and FRAP ($P < 0.0001$) were significantly affected by the main effect of mulch (Table 2.7). Significant plastic mulch x time x cultivar interactions were observed in TA (%) ($P<0.05$), FRAP ($P <0.0001$), and respiration ($P < 0.05$). Respiration and FRAP were also significantly affected by a plastic mulch x time interaction. Significant plastic mulch x cultivar interactions were evident in FRAP ($P<0.0001$) and TP content only ($P <0.001$). Most of the parameters including anthocyanin content, SSC (%), SSC/ TA, redness (a*) and respiration rate were significantly affected by cultivar x time interactions.

There were no significant effects of plastic mulch on the overall visual quality of both cultivars at the day of harvest and throughout storage time. ‘Albion’ and ‘Portola’ fruit grown with silver plastic mulch had a visual quality score > 4.5 on a scale of 5 compared to black plastic mulch was (>4 out of scale of 5) at the day of harvest (Fig. 2.2 & 2.3).

During storage, we observed significant day and mulch effects in ‘Portola’ for moisture loss (Fig. 2.5). ‘Portola’ fruit grown with green plastic mulch had significantly higher moisture loss compared to the fruit grown with silver plastic on day 2 [$P<0.0001$ (Fig. 2.5)]. There were no significant mulch effects on moisture loss during shelf life for ‘Albion’ (Fig. 2.4). In general, ‘Portola’ had greater higher moisture loss tendency than ‘Albion’ during storage.

Table 2.8 shows the effects of cultivar, mulch treatment, and interaction effects on the respiration rate of fruit from the day of harvest. There were significant cultivar and cultivar x plastic mulch interaction effects for respiration rate of fruit on day 0. For both cultivars, the respiration rate of fruit was not significantly different between the plastic mulch treatments and the black plastic mulch on the day of harvest (Table 2.8). The only significant differences in respiration rate on day 0 attributed plastic treatments was among ‘Portola’ fruit. The ‘Portola’ fruit grown with silver mulch having a significantly lower respiration rate than those grown with the white and red plastic mulches. Overall, ‘Albion’ had significantly lower respiration rates on day 0 than ‘Portola’ ($P < 0.001$). There were no significance differences observed in the respiration rate of ‘Albion’ fruit grown with any of the plastic mulches on the day of harvest or during storage (Table 2.8, Fig. 2.6). There was similar trend for ‘Albion’ during storage, and there were no significant differences observed in respiration of ‘Albion’ fruit grown with the various plastic mulches when compared to the black plastic mulch. However, ‘Portola’ fruit grown with black stripe and green mulch had significantly higher respiration rates compared to the black plastic mulch on the second day of storage. On day four ‘Portola’ fruit still had the lowest respiration rates when grown with silver mulch compared to the red plastic mulch [$P<0.001$ (Fig. 2.7)].

There were no significant mulch x cultivar interactions for fruit texture (N) and color index including redness (a*), lightness (L*) on day 0. The main effects of cultivar and mulch treatment are provided in Table 2.8. ‘Albion’ fruit were significantly firmer and had darker red color on day 0 compared to ‘Portola’ [$P < 0.0001$ (Table 2.9)]. Plastic mulches did not affect fruit firmness for either cultivar during storage (Figures 2.8 & 2.9). ‘Albion’ did not show any significant differences in fruit redness over time with any of the different mulches (Fig 2.10). For ‘Portola’, the redness (a*) value on day 4 was significantly lower than day 0 and day 2 for all plastic mulch except for the black plastic mulch [$P < 0.0001$ (Fig. 2.11)]. There were no significant differences in lightness over any of these treatments at harvest or during shelf life (Fig. 2.12 & 2.13).

For the organoleptic fruit quality traits collected on the day of harvest, TA was only quality traite that was significantly influenced by plastic mulch x cultivar interaction ($P < 0.05$), cultivar ($P < 0.0001$) and time effect ($P < 0.05$) (Table 2.10). On the day of harvest, strawberries from 'Albion' plants had higher ranges of TA (0.76-0.99%) compared to 'Portola' [0.66-0.72% (Table 2.10)]. At day 0, both cultivars produced fruit with similar TA (%) values across all of the plastic mulch types. 'Portola' grown with red mulch produced the same level of TA (%) as 'Albion' grown with the black plastic mulch. However, throughout storage, none of the strawberry cultivars showed any significant differences in TA over time (Fig 2.14 & 2.15) with any of the plastic mulches.

SSC and SSC/TA measured on the day of harvest were only significantly affected by cultivar ($P < 0.0001$). 'Albion' fruit had 31 % higher Brix and 5% greater SSC/TA ratio than 'Portola'. There were no significant changes in the SSC (°Brix) or the SSC/TA after the 4-days of storage for either cultivar grown with the six-plastic mulches (Fig. 2.16, 2.17, 2.18, 2.19).

On the day of harvest, there were significant plastic mulch x cultivar interactions for antioxidant (FRAP) and total phenolics, so the two cultivars were analyzed separately to determine the effects of the plastic mulch treatments on these fruit parameters. (Table 2.11, Fig. 2.20, 2.21, 2.22, 2.23). Anthocyanin content was statistically similar across all treatments and cultivars on the day of harvest (Table 2.12).

Antioxidant content (FRAP) for 'Albion' fruit that were grown with black stripe, silver and green plastic was significantly higher compared to fruit grown with the black plastic at the day of harvest (P<0.0001). The antioxidant content (FRAP) content for 'Albion' fruits grown with black stripe, silver, and green plastic mulches ranged from 1497.2 to 1559.6 µmol 100 g^{-1} and was higher compared to the fruit produced with black plastic mulch, which was 1009.21 µmol 100 g^{-1} [P<0.0001 (Table 2.11)]. After four days of storage, 'Albion' fruit had significantly lower antioxidant capacity (FRAP) when grown with white, black stripe and red plastic mulches compared to the black plastic mulch [P<0.0001 (Fig. 2.20)].

On the day of harvest 'Portola' fruits grown with all the plastic mulches had significantly lower antioxidant (FRAP) content compared to the black plastic mulch (P < 0.0001). After four days of storage, the antioxidant capacity of 'Portola' fruits increased in fruit grown with white, silver, and green plastic mulch, but decreased in fruit grown with the black plastic (Fig. 2.21).

The total phenolic (TP) content of 'Albion' fruit on the day of harvest was not significantly different among the plastic mulches. TP content ranged from 229.40 $mg \cdot 100g^{-1}$ to 178.11 $mg \cdot 100g^{-1}$ (Table 2.11). On the day of harvest 'Portola' fruits grown with green plastic mulch had the lowest TP content compared to fruit from plants grown with black plastic [P<0.05 (Table 2.11)]. During storage, there were no significant effects on total phenolic for either cultivar or amongst all of the plastic mulch treatments (Fig. 2.22, 2.23).

There was no significant cultivar x mulch treatment interaction effect on the anthocyanin content of strawberries on the day of harvest. The main effect of cultivar and mulch treatments are presented in Table 2.12. Anthocyanin levels were unaffected by all the plastic mulch on the day of harvest (Table 2.12) and during storage for both cultivars (2.24 & 2.25). However, 'Albion' fruit had 46% greater anthocyanin content compared to 'Portola' (Table 2.12).

Table 2.7. Probability values for physical, organoleptic, and nutritional fruit quality of two day-neutral strawberry cultivars grown with various plastic mulch (black, white, black stripe, silver, red and green) in a high tunnel in 2020

Quality Parameter	Mul. [z]	Cult.[y]	Time (d)[x]	Mul. x Cult.	Mul. x Time	Cult. x Time	Mul. x Cult. x Time (d)
Overall visual quality	ns[w]	<0.001	<0.001	ns	ns	ns	ns
Moisture loss (%)	<.0001	<0.001	<.0001	ns	ns	<0.001	ns
Respiration (mg CO_2· kg−[1] h−[1])	<0.05	<0.001	<0.001	ns	<0.001	<0.05	<0.05
Flesh Firmness(N)	ns	<0.001	<0.0001	ns	ns	ns	ns
Redness (a*)	ns	<0.0001	<0.0001	ns	ns	<0.001	ns
Lightness(L*)	ns	<0.0001	<0.0001	ns	ns	ns	ns
TA (%)	ns	<0.0001	ns	ns	ns	ns	<0.05
SSC (%)	ns	<0.0001	<0.0001	ns	ns	<0.001	ns
SSC/ TA (%)	ns	<0.0001	<0.001	ns	ns	<0.001	ns
FRAP (μmol·100 g^{-1})	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	ns	<0.0001
TP. (mg·100 g^{-1})	ns	<0.0001	<0.001	<0.001	ns	ns	ns
Antho. (μg 100 g^{-1})	ns	<0.0001	<0.0001	ns	ns	<0.001	ns

A linear mixed model was used to test which factors and interactions had significant effects on the examined quality parameter ($P \leq 0.05$).

[z] Plastic mulch of six different color (black, white, black stripe, silver, red, and green) plastic mulch

[y] Two day-neutral strawberry cultivars ('Albion', 'Portola')

[x] The effect of storage (in days). FRAP, TP, and Antho. were measured only on day 0& 4 while the rest of the parameters were measured on day 0, 2 and 4.

[w] ns: not significant

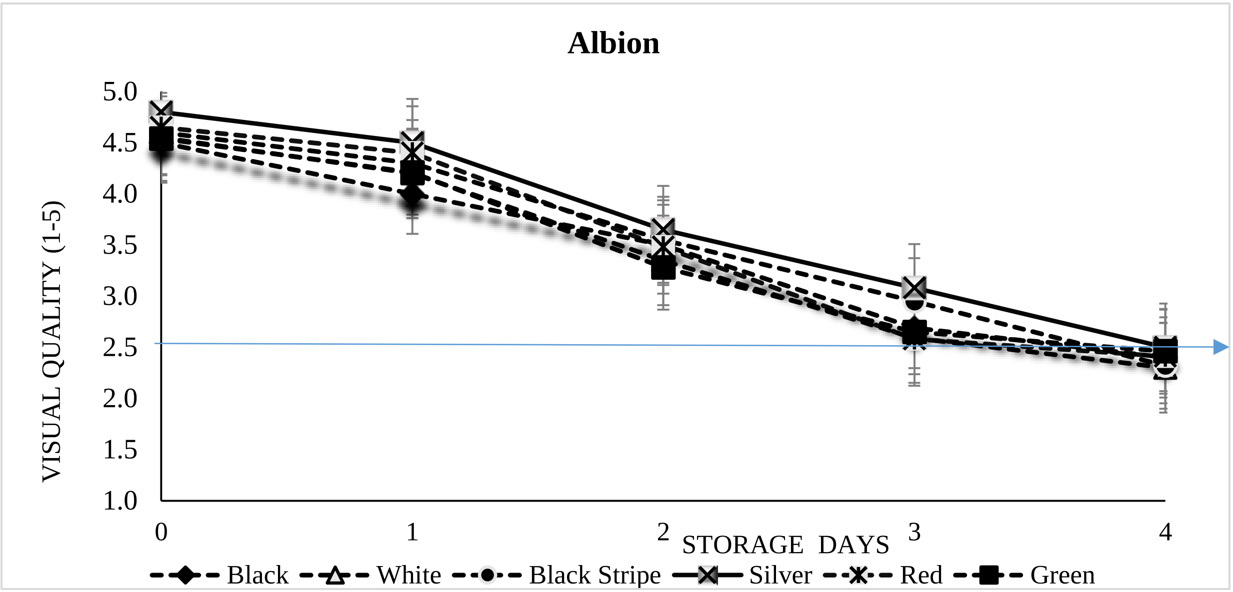

Figure 2.2. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on Overall visual quality of day-neutral strawberries ('Albion') four days of storage at 3 ˚C. Average ('Albion') fruit overall visual quality of fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean. Scored below 2.5, the cultivar was considered unmarketable.

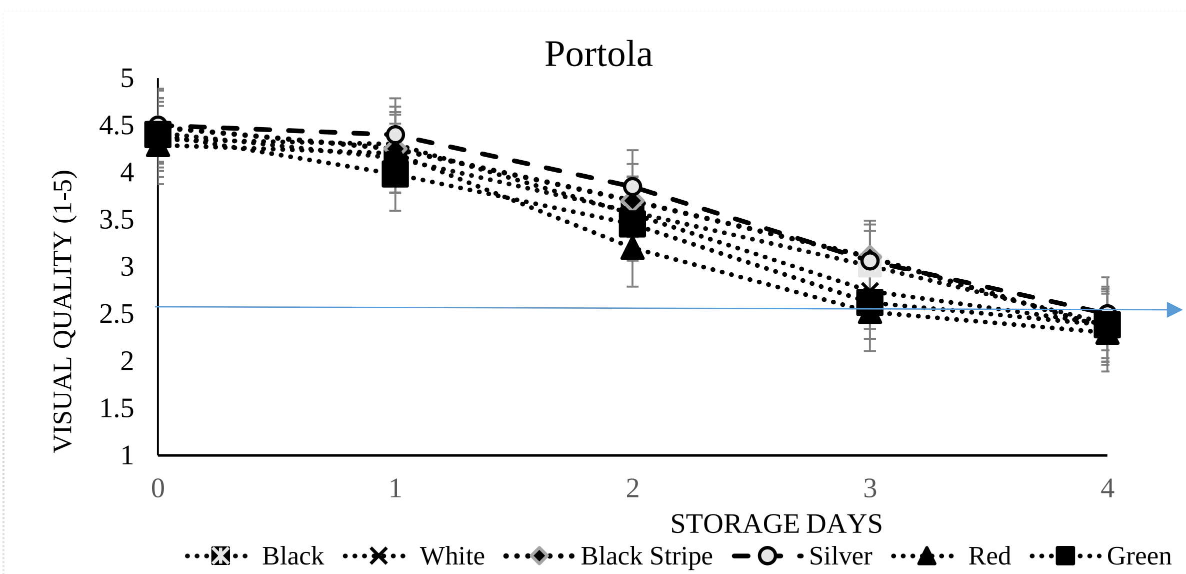

Figure 2.3. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on Overall visual quality of day-neutral strawberries ('Portola') four days of storage at 3 ˚C. Average ('Portola') fruit overall visual quality of fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean. Scored below 2.5, the cultivar was considered unmarketable.

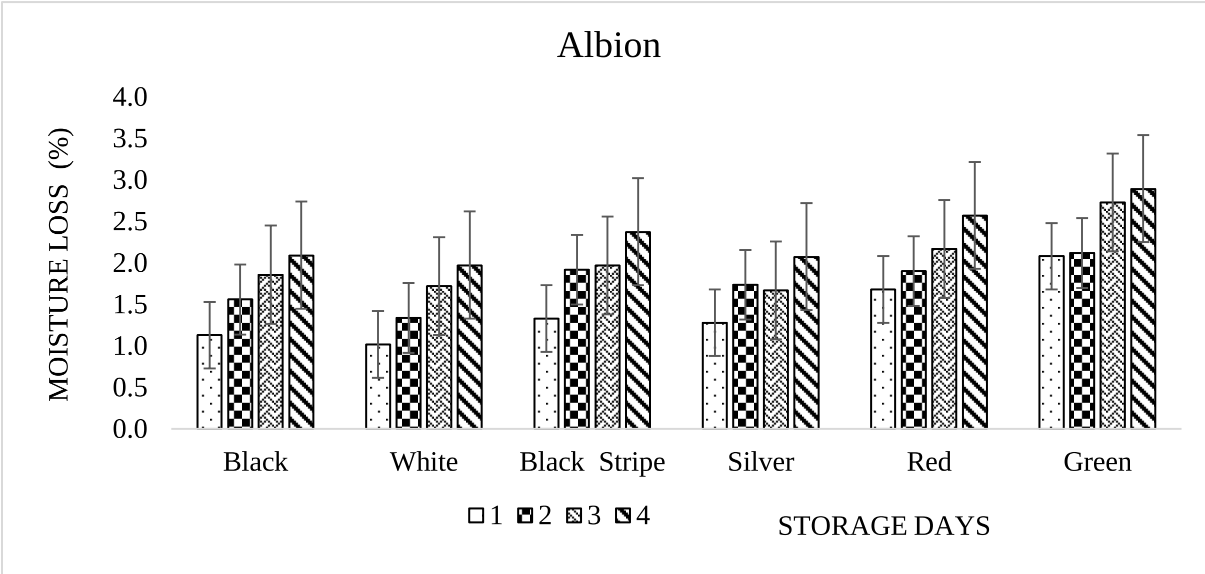

Figure 2.4. Effect of six different types of plastic mulch (black, white, black stripe, silver, red, and green) on the Moisture loss of day-neutral strawberries 'Albion 'over four days of storage at 3 °C. Average ('Albion') moisture loss of fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

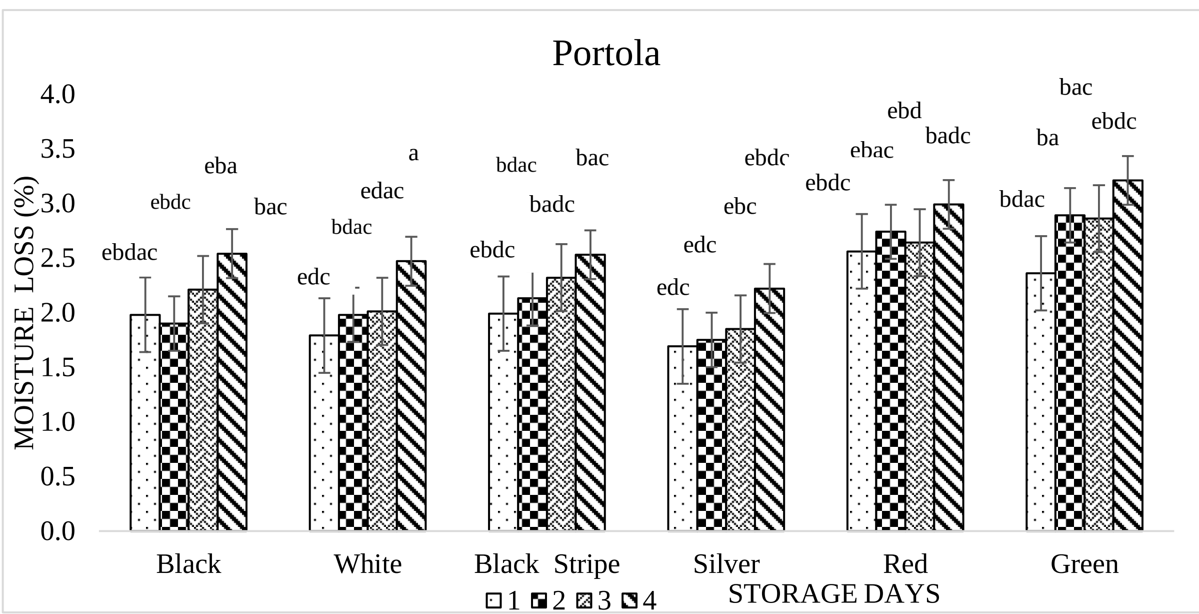

Figure 2.5. Effect of plastic mulch (black, white, black center stripe, silver, red, and green) on the Moisture loss of day-neutral strawberries 'Portola' over four days of storage at 3 °C. Average ('Portola') fruit moisture loss of fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

Table 2.8. Effect of plastic mulches on respiration rate of two day-neutral strawberry cultivars grown in high tunnel measured every 24 h throughout storage at 3 °C in 2020

Cultivar	Plastic Mulch [z]	Respiration (mg CO_2 kg^{-1} h^{-1})
Albion	Black	14.25ba
	White	14.10ba
	Black Stripe	12.83ba
	Silver	13.94ba
	Red	11.89b
	Green	14.90ba
Portola	Black	15.53ba
	White	15.951a
	Black Stripe	14.71ba
	Silver	12.20b
	Red	15.95a
	Green	15.47ba
P-value (Cultivar x Plastic mulch)		0.024
Main Effect: Cultivar		
Albion		13.25a
Portola		14.96b
F-test (Cultivar)		<0.001
Main Effect: Plastic mulch		
Black		14.89
White		15.02
Black Stripe		13.77
Silver		13.07
Red		13.92
Green		15.46
P-value (Plastic mulch)		ns

[z] Plastic mulch (black, white, black center stripe, silver, red and green) and two day-neutral strawberry cultivars (‘Albion’, ‘Portola’) were used

[y]Values represent the LSMEANS of fruit harvested at the 100% ripeness stage from three harvest in 2020. Values are ls means of 9 fruit (3 fruit per rep) over 3 sampling times in growing season (2020 in Olathe, KS). LSMEANS followed by the same letters are not significantly different (P>0.05) according to pairwise comparisons with a Tukey’s adjustment.

[x]Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05.

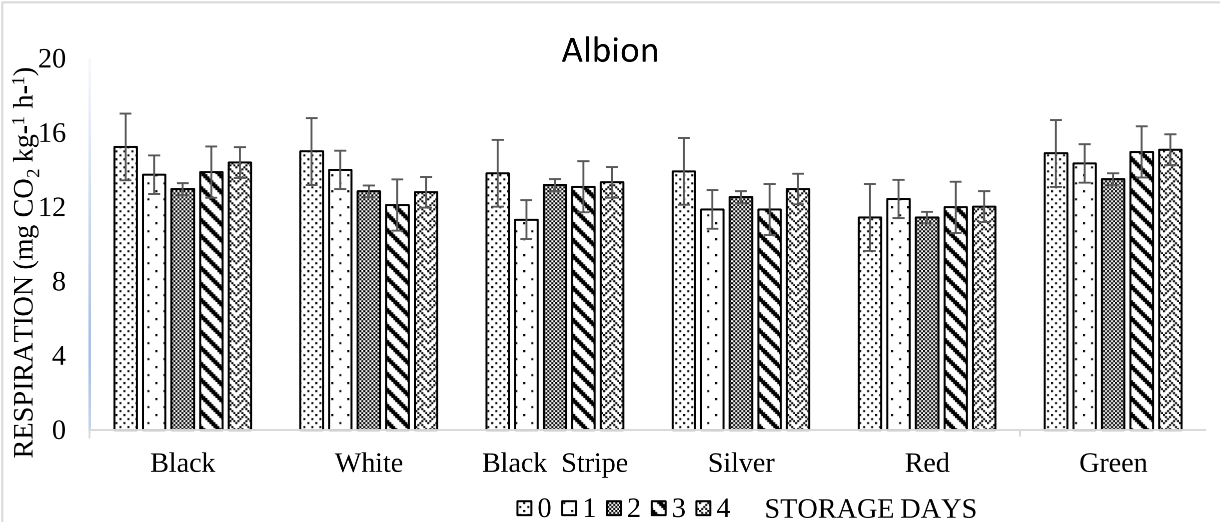

Figure 2.6. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Respiration of day-neutral strawberries ‘Albion’ four days of storage at 3˚C Average (‘Albion’) fruit respiration of fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

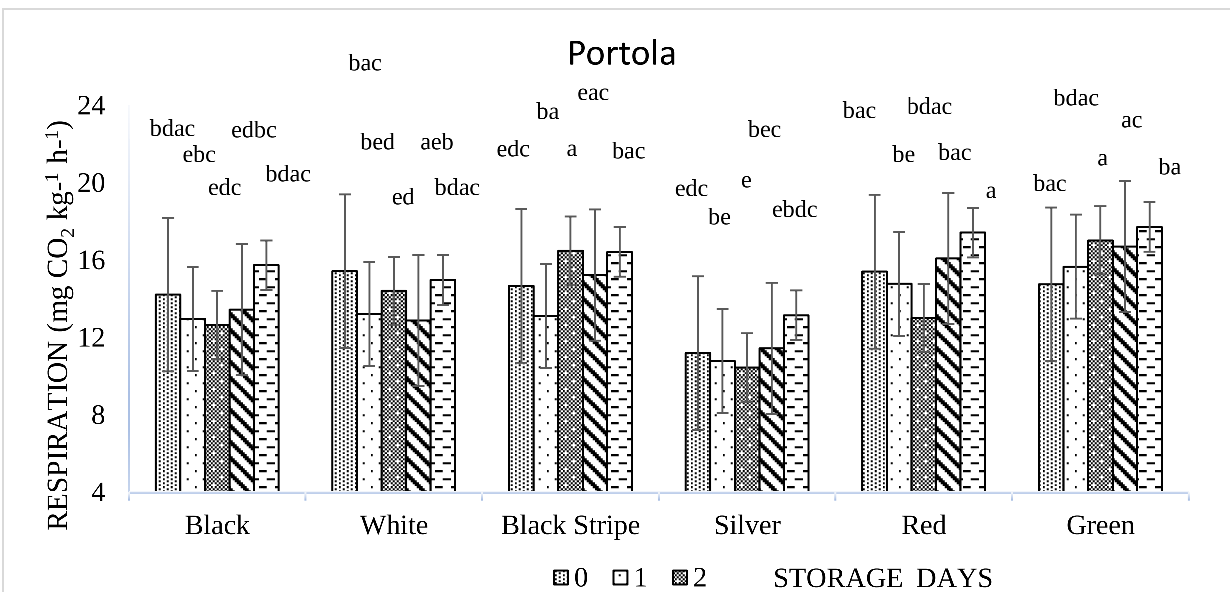

Figure 2.7. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Respiration of day-neutral strawberries ‘Portola’ during four days of storage at 3˚C. Average (‘Portola’) fruit respiration of fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean

Table 2.9. Effect of plastic mulches and two day-neutral strawberry cultivars on Firmness and Color of strawberry fruit on the day of harvest. Fruit was grown in a high tunnel system in 2020 in Olathe, KS.

Plastic mulch [z]	**Firmness (N)**	**Redness(a*)**	**Lightness(L*)**
Main Effect: Cultivar			
Portola	3.98a[z]	35.17a	35.43a
Albion	4.44b	33.84b	34.12b
P-value (cultivar)[x]	<0.001	<0.0001	<0.0001
Main Effect: Plastic mulch			
Black	4.44	34.20	35.60
White	3.88	35.12	35.12
Black Stripe	4.33	34.48	35.59
Silver	4.11	34.25	35.40
Red	4.34	35.12	35.70
Green	4.16	35.94	36.20
[x]*P*-vaule (Plastic mulch)[y]	ns	ns	ns

[z] Plastic mulch (black, white, black center stripe, silver, red and green) and two day-neutral strawberry cultivars (‘Albion’, ‘Portola’) were used

[z]Values represent the LSMEANS of fruit harvested at the 100% ripeness stage from three harvests in 2020. LSMEANS followed by the same letters are not significantly different (P>0.05) according to pairwise comparisons with a Tukey’s adjustment.

[x]Probability value for the ANOVA F-test using Type III hypothesis test for the fixed effect of cultivar where α=0.05.

[y]Probability value for the ANOVA F-test using Type III hypothesis test for the fixed effect of mulch treatment where α=0.05.

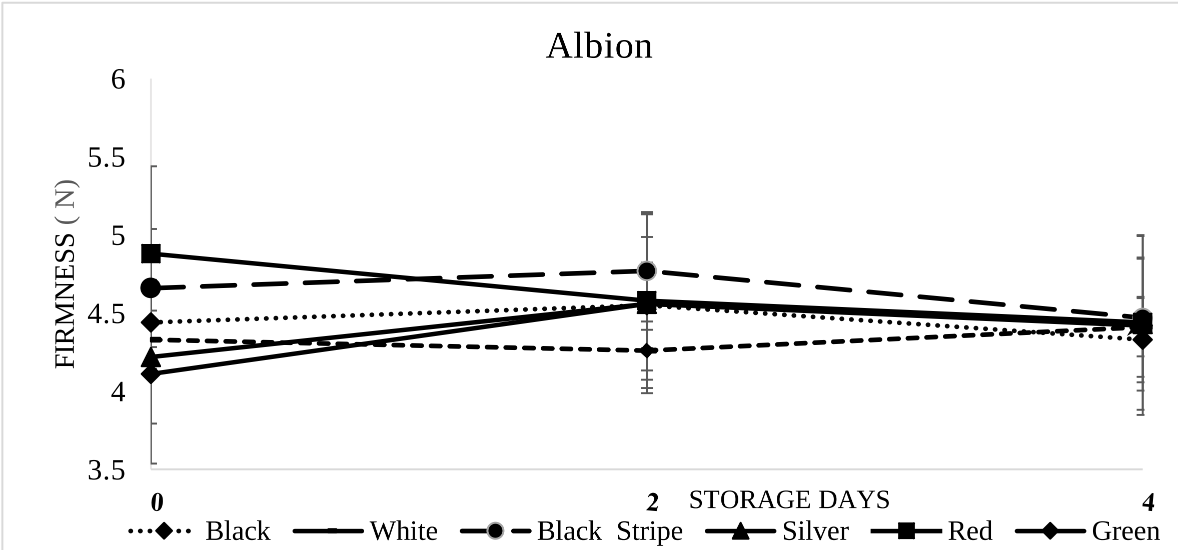

Figure 2.8. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Firmness of day-neutral strawberries 'Albion' over four days in storage at 3 ˚C. Average fruit ('Albion') firmness of fruit measured at 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean. Firmness was measured with a TA-58, TA.XT. plus texture analyzer a using a 2mm probe.

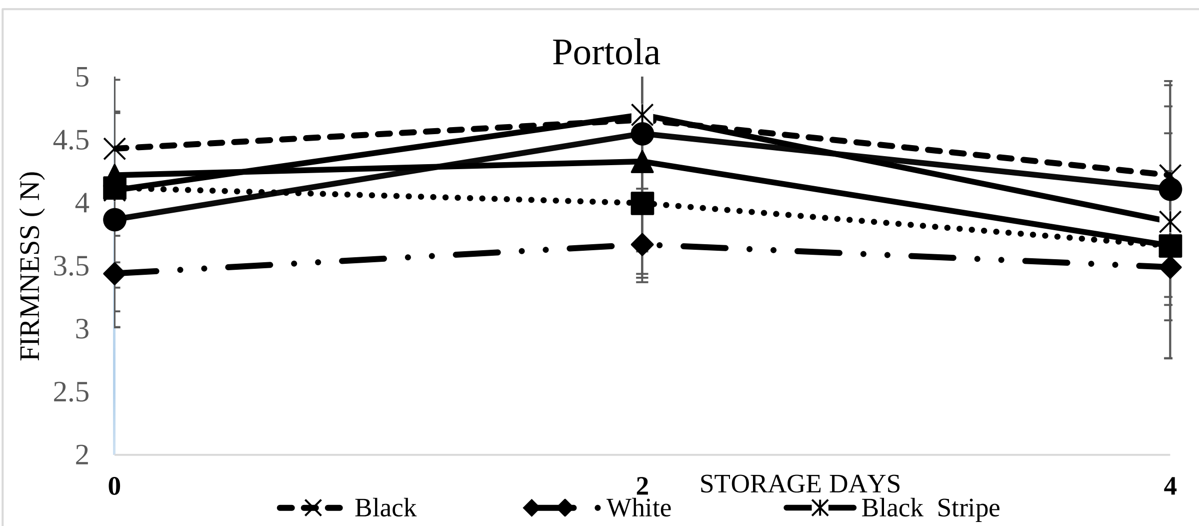

Figure 2.9. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Firmness of day-neutral strawberries 'Portola' four days in storage at 3˚C. Average fruit ('Portola') firmness of fruit measured at 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean. Firmness was measured with a TA-58, TA.XT. plus texture analyzer a using a 2mm probe.

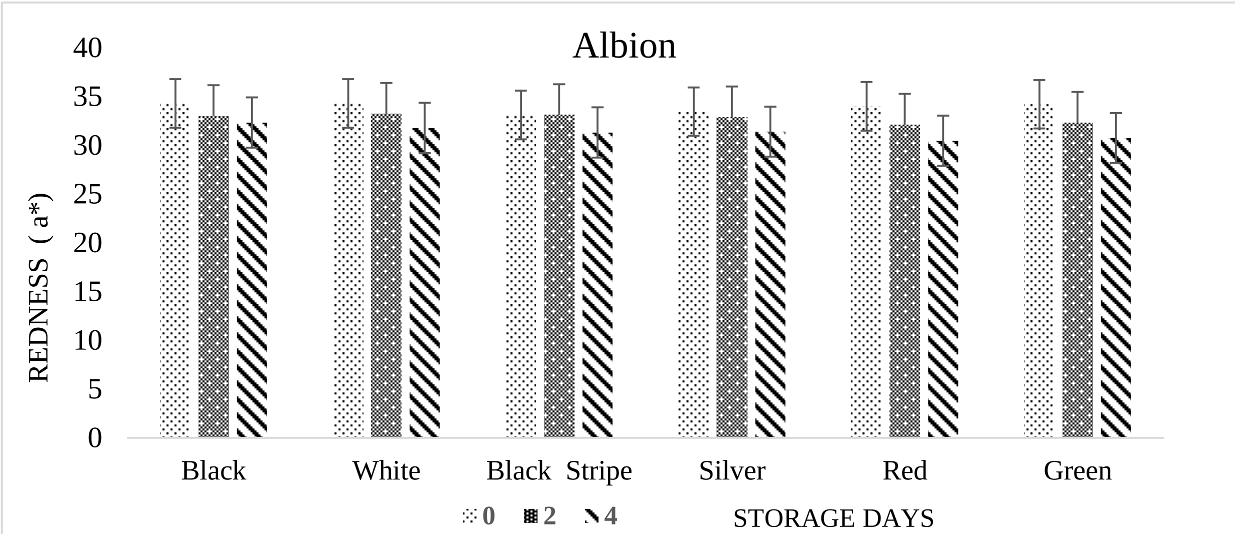

Figure 2.10. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Color - redness (a*) of day-neutral strawberries 'Albion' four days in storage at 3˚C.Average fruit ('Albion') color redness (a*) of fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

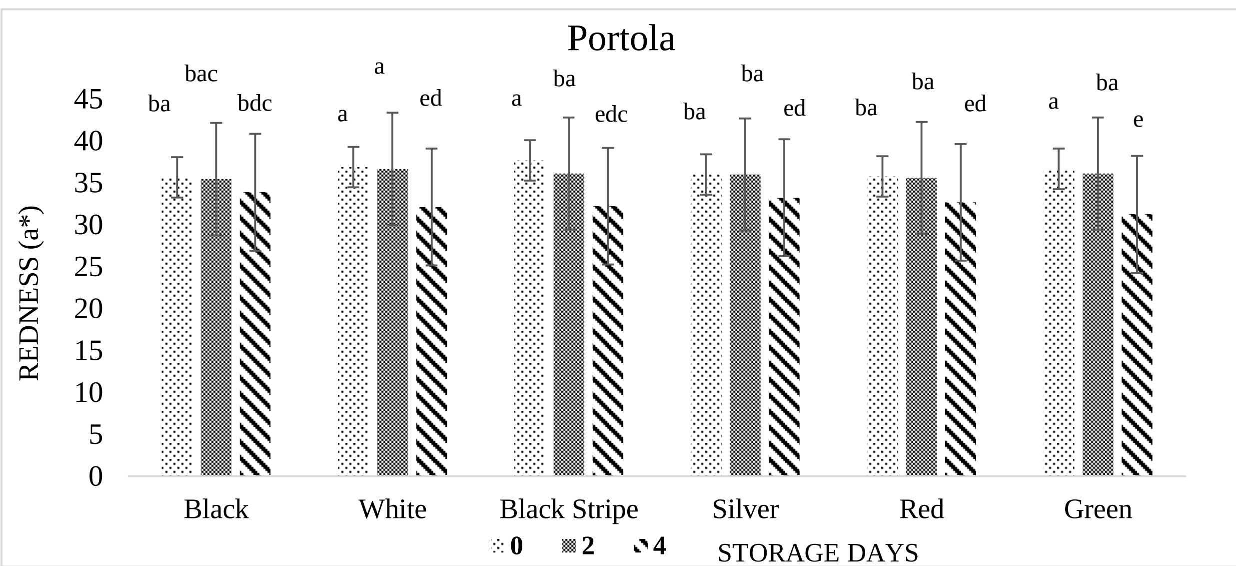

Figure 2.11. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Color - redness (a*) of day-neutral strawberries 'Portola' four days in storage at 3 ˚C. Average fruit ('Portola') color (a*) measured from harvested fruit at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

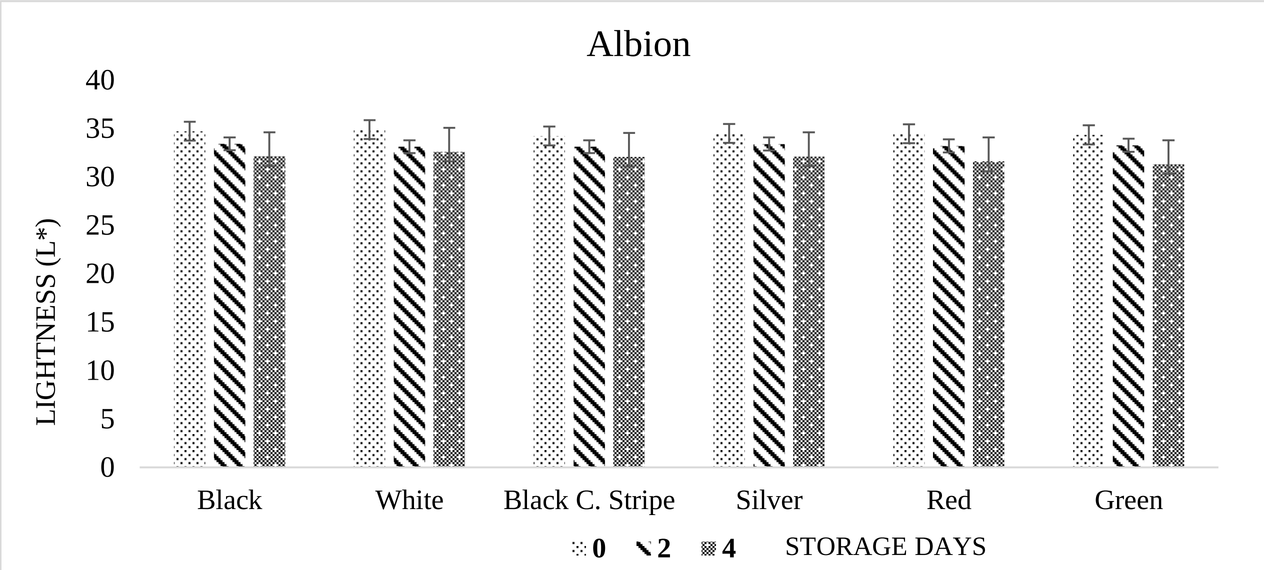

Figure 2.12. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Color - lightness (L*) of day-neutral strawberries 'Albion' four days in storage at 3˚C. Average fruit ('Albion') color lightness (L*) measured from harvested fruit at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

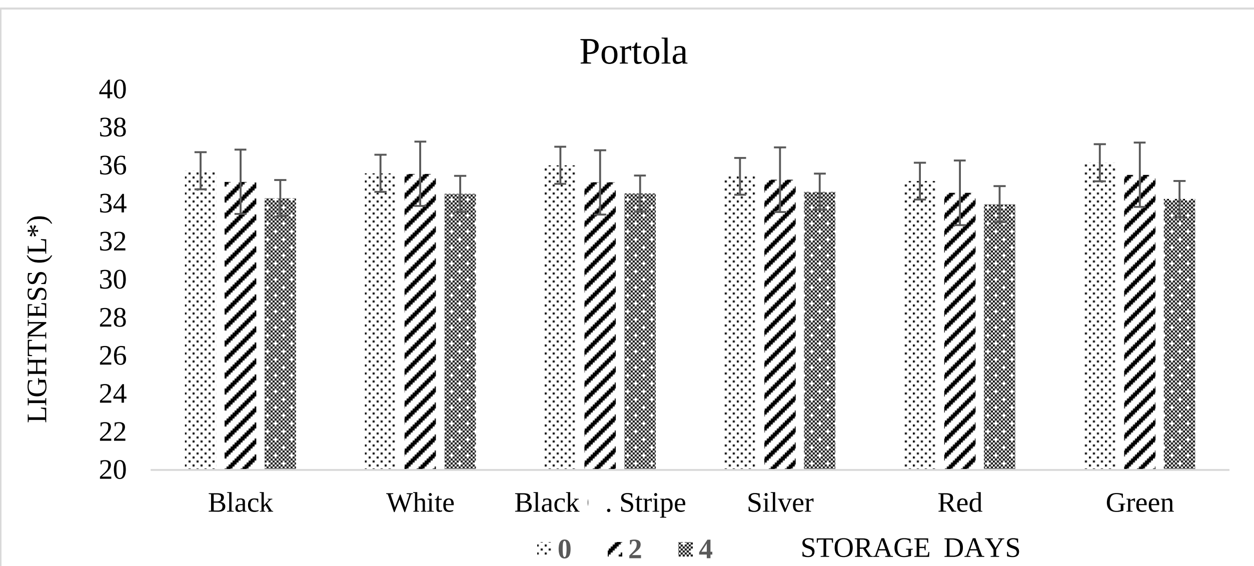

Figure 2.13. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Color - lightness (L*) of day-neutral strawberries 'Portola' four days in storage at 3˚C.Average fruit ('Portola') color lightness (L*) measured from harvested fruit at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

Table 2.10. Effect of plastic mulches on Soluble solids content (SSC), Titratable acidity (%) and the SSC/%TA ratio of two day-neutral strawberry cultivars grown in high tunnel, measured harvest day in 2020.

Cultivar[z]	Plastic Mulch[z]	Brix (%)	TA (%)	Ratio (SSC/TA)
Albion	Black	7.24[x]	0.871bac	9.29
	White	7.22	0.98a	8.87
	Black Stripe	6.91	0.76bdc	9.09
	Silver	7.30	0.79a	9.60
	Red	7.84	0.99a	8.34
	Green	7.60	0.96ba	8.63
Portola	Black	5.38	0.68dc	8.00
	White	5.81	0.69dc	8.44
	Black Stripe	5.42	0.70dc	8.37
	Silver	5.76	0.64dc	9.46
	Red	5.80	0.72bdc	8.63
	Green	5.64	0.66dc	8.92
P-value (Cultivar x Plastic mulch)		ns	0.025	ns
Main effect: Cultivar				
Portola		5.63a	0.69a	8.62a
Albion		7.35b	0.83b	8.93b
P-value (cultivar)		<0.0001	<0.0001	<0.0001
Main effect: Plastic mulch				
Black		6.31	0.78ba	9.29
White		6.51	0.85ba	7.87
Black Stripe		6.16	0.75b	8.02
Silver		6.58	0.81ba	8.57

Red	6.80	0.87a	8.34
Green	6.63	0.82ba	8.63
P-value (Plastic mulch)	ns	0.041	ns

[z]Plastic mulches (black, white, black stripe, silver, red and green) and two day-neutral strawberry cultivars ('Albion', 'Portola') were used
[y]Values represent the LSMEANS of fruit harvested at the 100% ripeness stage from three harvest in 2020. LSMEANS followed by the same letters are not significantly different (P>0.05) according to pairwise comparisons with a Tukey's adjustment.
[x]Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05.

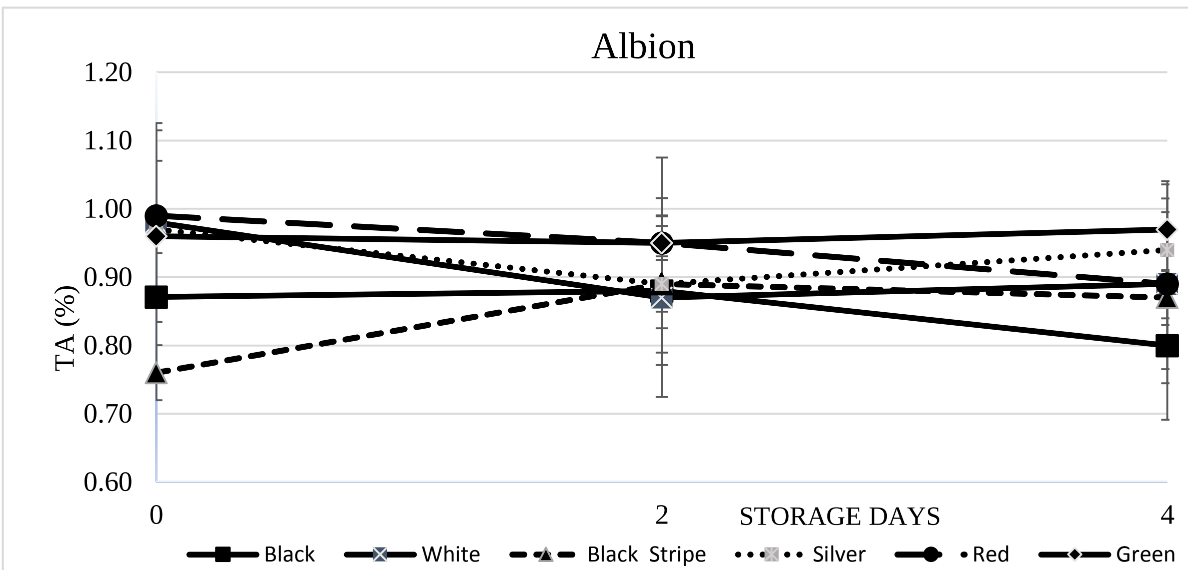

Figure 2.14. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the TA (%) of day-neutral strawberries 'Albion' four days of storage at 3˚C.Average TA (%) of ('Albion') fruit measured from fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

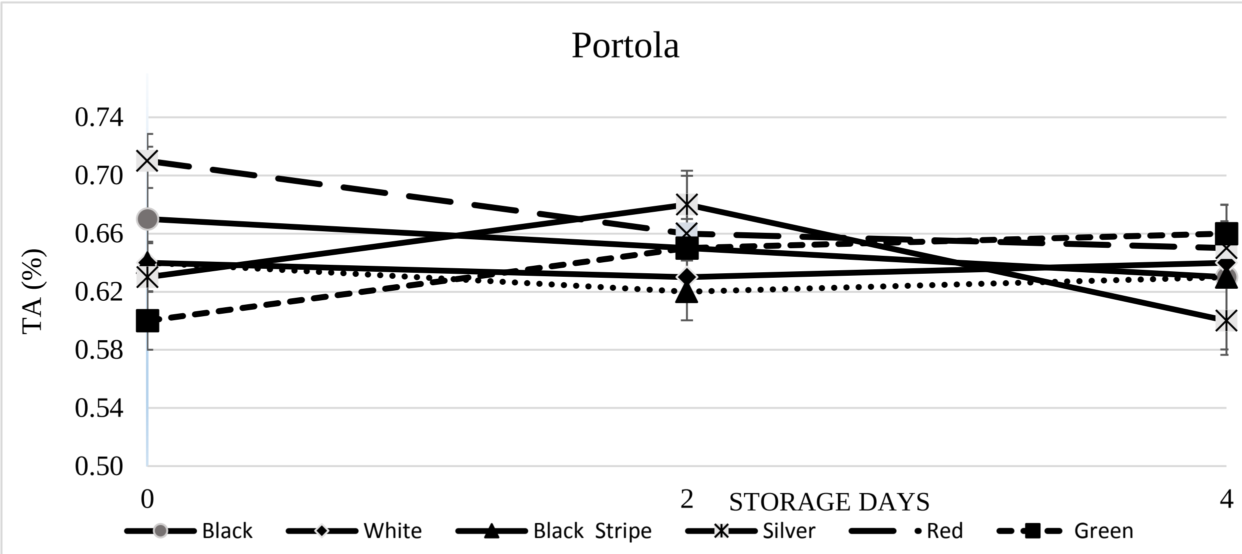

Figure 2.15. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the TA (%) of day-neutral strawberries 'Portola' four days of storage at 3˚C. Average TA (%) of ('Portola') fruit measured from fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

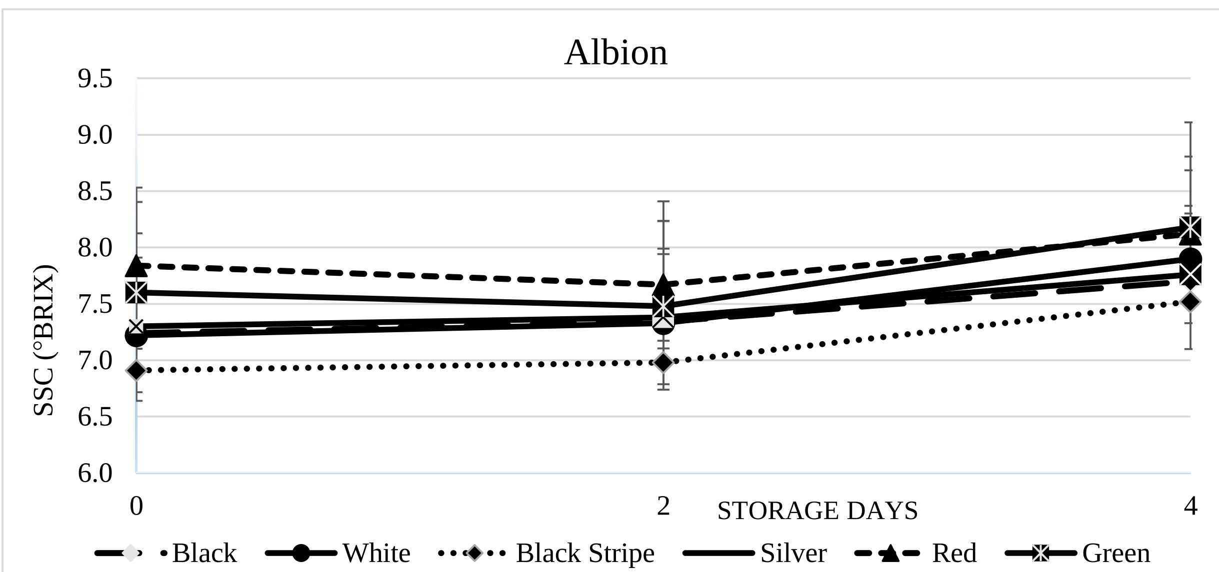

Figure 2.16. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the SSC (°Brix) of day- neutral strawberries 'Albion' four days in storage at 3 ˚C. Average SSC (°Brix) of ('Albion') fruit measured from fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

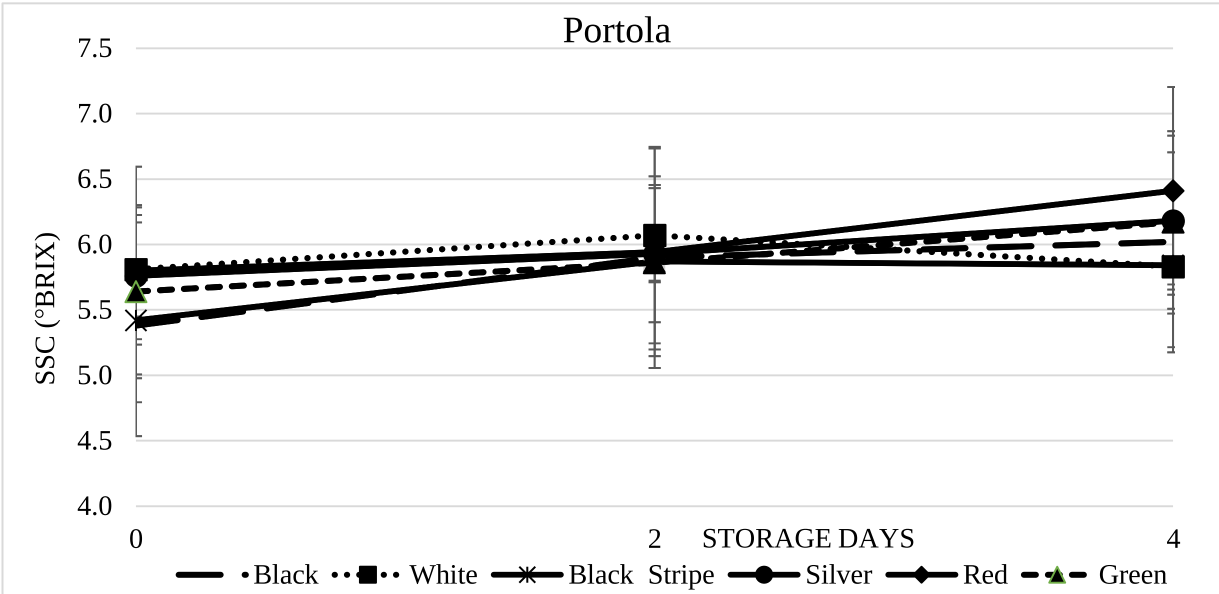

Figure 2.17. Effect of six different types of plastic mulch (black, white, black stripe, silver, red, and green) on the SSC (°Brix) of day-neutral strawberries ('Portola') four days in storage at 3°C. Average SSC (°Brix) of ('Portola') fruit measured from fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

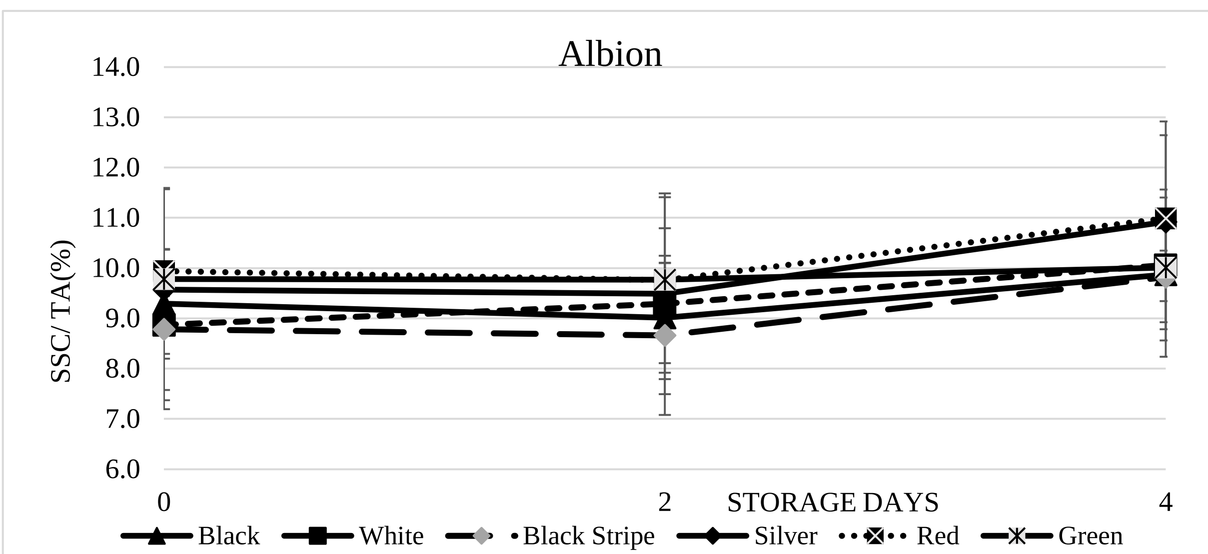

Figure 2.18. Effect of six different types of plastic mulch (black, white, black stripe, silver, red, and green) on the SSC/ TA (%) of day neutral strawberries 'Albion' four days in storage at 3°C. Average SSC/TA (%) of ('Albion') fruit measured from fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

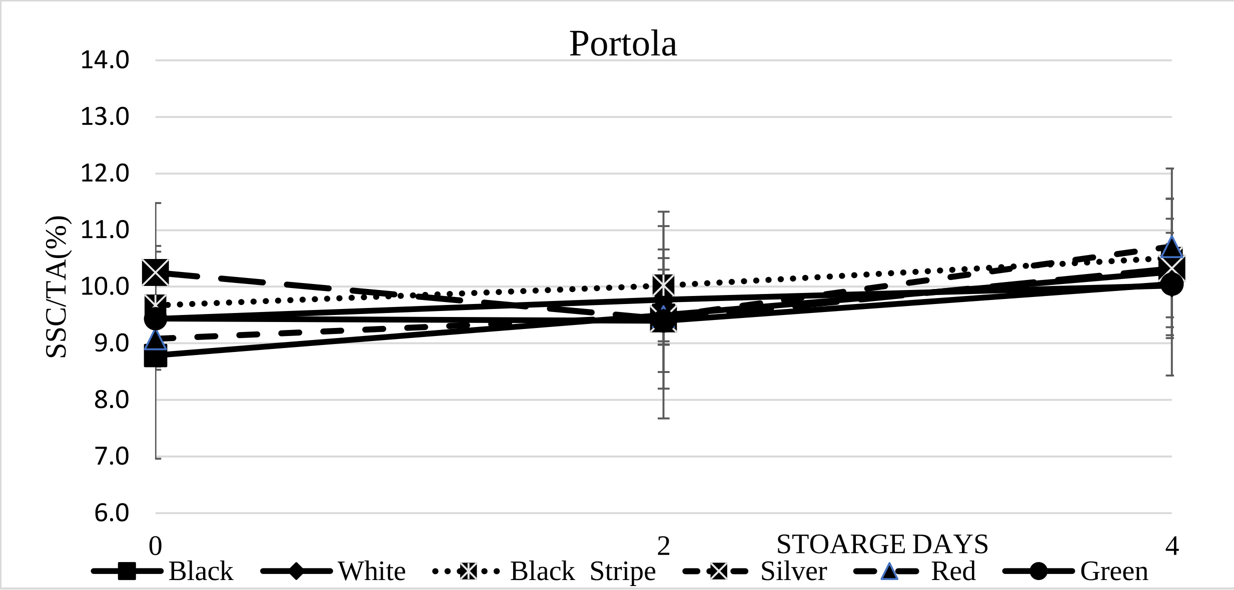

Figure 2.19. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the SSC/TA (%) of day-neutral strawberries 'Portola' during four days of storage at 3˚C. Average SSC/ TA (%) fruit ('Portola') measured from fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

Table 2.11. Effect of plastic mulches on Antioxidant activity (FRAP) and Total phenolic content (TP) of day-neutral strawberry cultivars grown in high tunnel, measured the day of harvest in 2020.

Cultivar	**Plastic Mulch** [z]	**FRAP (µmol 100 g-[1])**	**TP. (mg 100 g-[1])**
Albion	Black	1009.21 d	178.11
	White	1212.98 c	248.06
	Black Stripe	1559.62 a	197.63
	Silver	1497.16 ba	229.40
	Red	1330.73 bc	206.22
	Green	1527.88 a	214.98
[x]*P*-value		<0.0001	ns
Portola	Black	1020.21a	156.88 a
	White	642.64 b	123.17 ba

Black Stripe	576.12 b	115.94 ba
Silver	606.54 b	115.75 ba
Red	708.21 b	134.58 ba
Green	626.92 b	108.31 b
[x]*P*-value	<0.0001	0.0412

[z]Plastic mulch (black, white, black stripe, silver, red and green) and two day-neutral strawberry cultivars (‘Albion’, ‘Portola’) were used
[y]Values represent the LSMEANS of fruit harvested at the 100% ripeness stage from three harvest in 2020. Values are ls means of 9 fruits (3 fruits per rep) over 3 sampling times in growing season (2020 in Olathe, KS). LSMEANS followed by the same letters are not significantly different (P>0.05) according to pairwise comparisons with a Tukey’s adjustment
[x]Probability value for the overall ANOVA F-test using Type III hypothesis test where α=0.05.

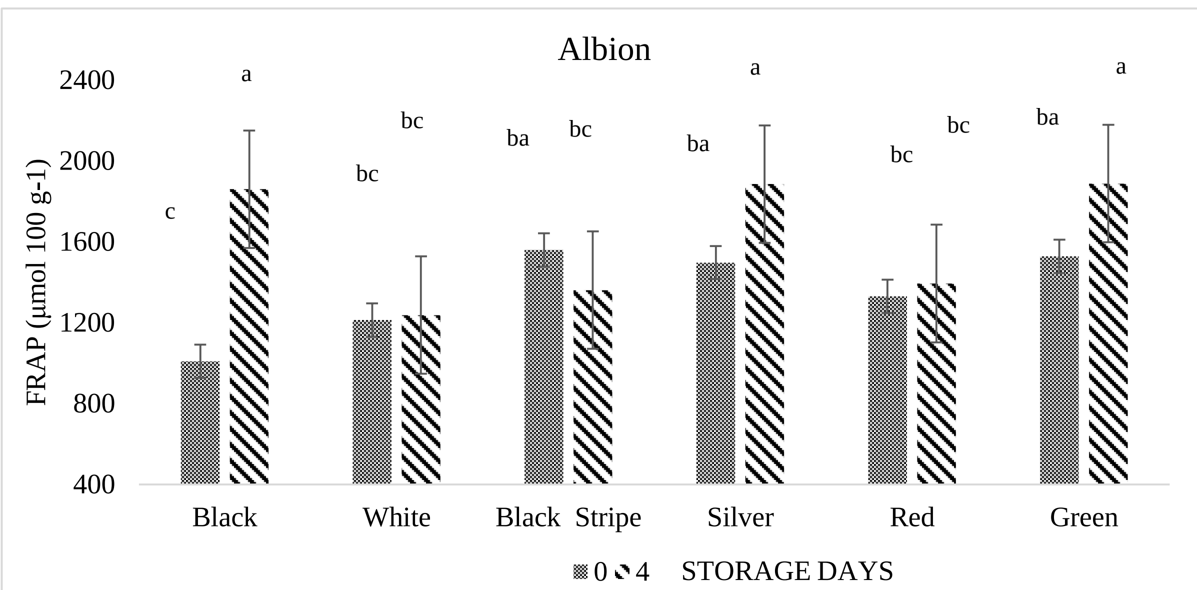

Figure 2.20. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Antioxidant (FRAP) of day-neutral strawberries ‘Albion’ four days of storage at 3˚C Average fruit (‘Albion’) antioxidant content measured (FRAP method) from fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

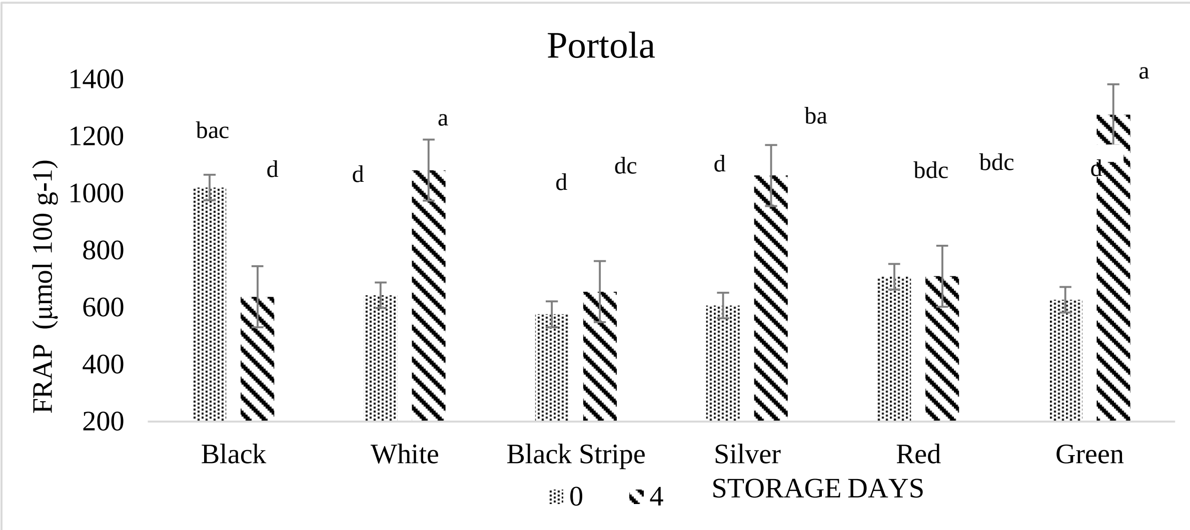

Figure 2.21. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Antioxidant (FRAP) of day-neutral strawberries ‘Portola’ four days of storage at 3 ˚C. Average fruit (‘Portola’) antioxidant content measured (FRAP method) from fruit harvested at the 100% red maturity stage in 2020. Bars represent LSMEANS for each treatment group and error bars are the standard error of the mean.

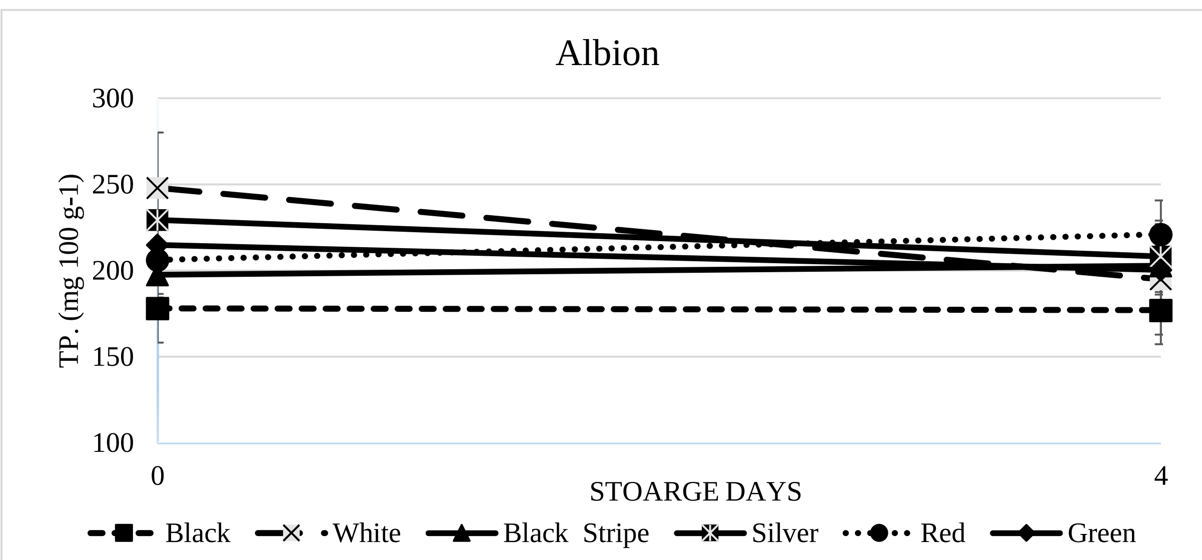

Figure 2.22. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Total Phenolic (TP) of day-neutral strawberries ‘Albion’ four days of storage at 3˚C Average fruit (‘Albion’) total phenolic of fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

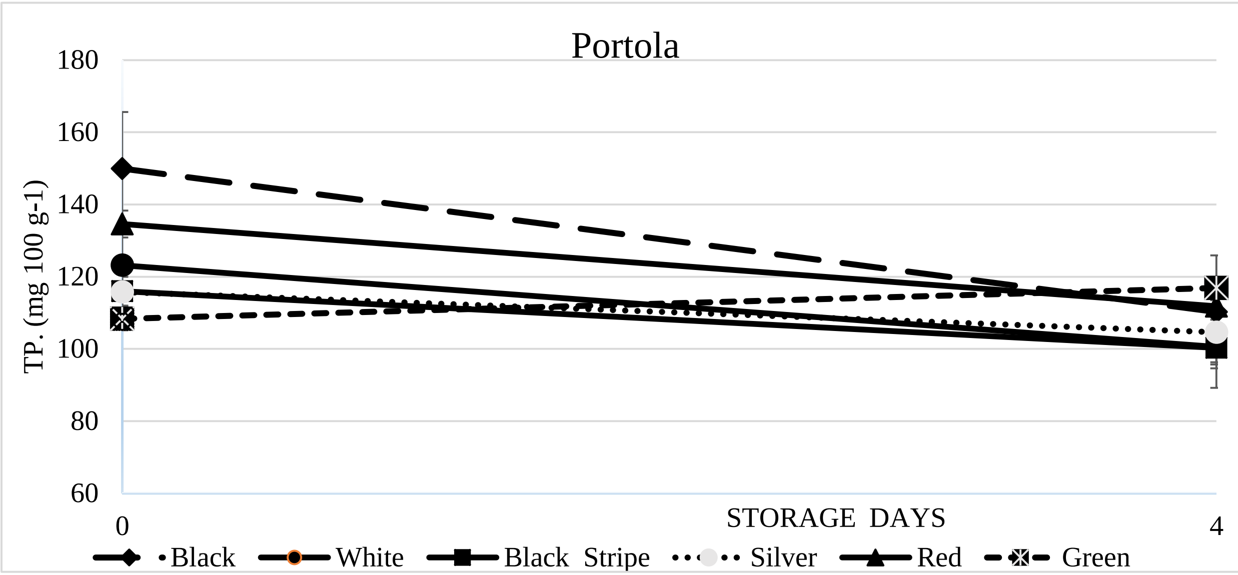

Figure 2.23. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the Total Phenolic (TP) of day-neutral strawberries ‘Portola’ four days of storage at 3 °C. Average fruit (‘Portola’) total phenolic of fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

Table 2.12. Effect of plastic mulches on Anthocyanin (Antho.) of two day-neutral strawberry cultivars grown in high tunnel, measured the day of harvest in 2020

Cultivar	**Plastic Mulch** [z]	**Antho. (µg 100 g^{-1} FW)**
Main Effects: Cultivar		
Portola		62.12
Albion		114.07
[x]*P*-value		<0.0001
Main Effects: Plastic mulch		
Black		90.77
White		90.90
Black Stripe		86.65
Silver		91.83
Red		95.45
Green		81.98
[x]*P*-value		ns

[z]Plastic mulch (black, white, black stripe, silver, red and green) and two day-neutral strawberry cultivars (‘Albion’, ‘Portola’) were used

[y]Values represent the LSMEANS of fruit harvested at the 100% ripeness stage from three harvest in 2020. LSMEANS followed by the same letters are not significantly different (P>0.05) according to pairwise comparisons with a Tukey's adjustment.
[x]Probability value for the F-test using Type III hypothesis test for the main effects of cultivar and mulch where α=0.05

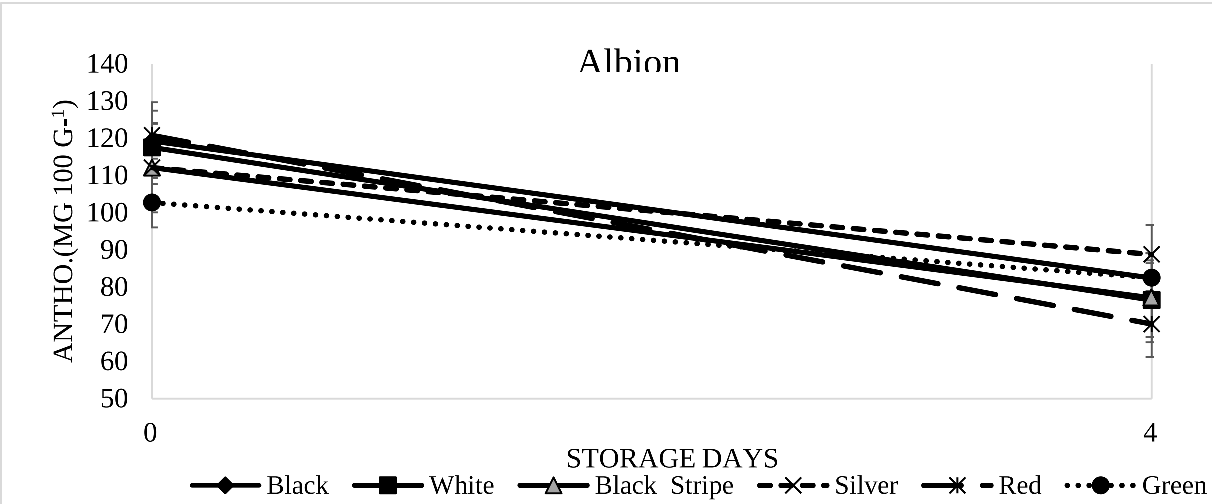

Figure 2.24. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the anthocyanin (Antho.) of day-neutral strawberries 'Albion' four days of storage at 3 ˚C. Average fruit ('Albion') anthocyanin of fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

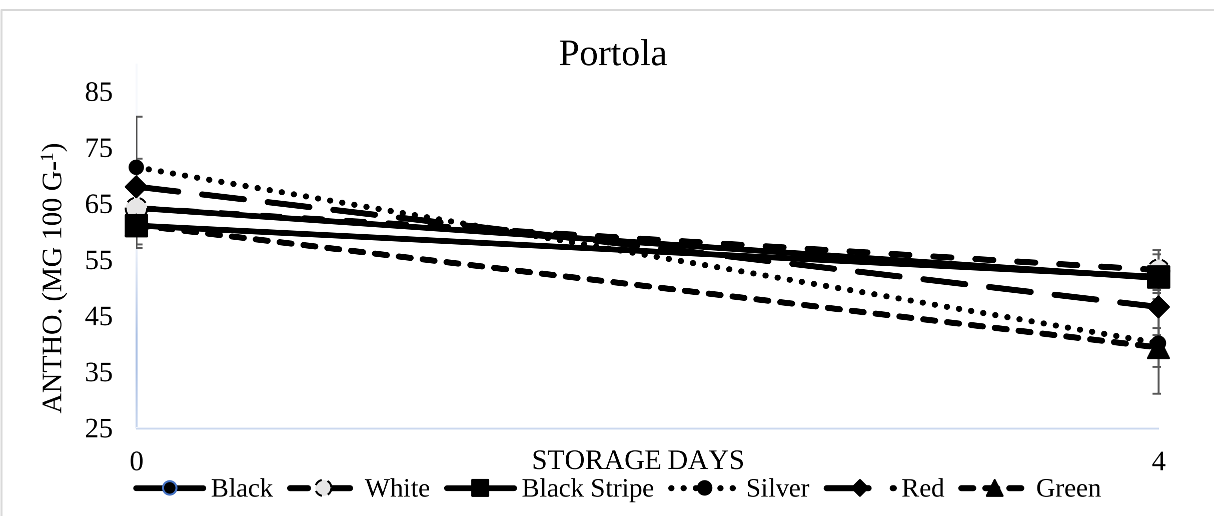

Figure 2.25. Effect of plastic mulch (black, white, black stripe, silver, red, and green) on the anthocyanin (Antho.) of day-neutral strawberries 'Portola' four days of storage at 3 ˚C. Average fruit ('Portola') Anthocyanin of fruit harvested at the 100% red maturity stage in 2020. Line represent LSMEANS for each treatment group and error bars are the standard error of the mean.

Discussion

Investigating the use of plastic mulch for day-neutral strawberries is vital to make high tunnel strawberries a more competitive alternative high-value crop with higher production yield and better fruit quality for the Kansas local market. One of the objectives of this research was to evaluate how the color of plastic mulch can impact the productivity of ‘Portola’ and ‘Albion’ strawberries, when grown in a HT production system. Based on our two-year trial, the total yield for strawberry cultivars ‘Albion’ and ‘Portola’ ranged between 0.93-1.68 lb./plant. Overall, this indicates a higher yield trend for both cultivars compared to previous research with the same cultivars grown in HTs, which ranged from 0.8 to 1.3 lb/ plant (Gude et al., 2018; Wallace and Webb, 2013). We also observed higher overall yields in 2020 than 2021. Many studies have found that strawberry productivity can fluctuate based on seasonal variation (Karhu et al., 2007; Soliman et al., 2015). Differences in UV light reflectance intensity rate of plastic mulches s might have variable effects on plant growth and production from year to year depending on weather conditions. In these trials, cultivar selection was a greater contributor to crop productivity than microclimate modification from plastic mulch. ‘Portola’ plants produced higher total and marketable yields compared to ‘Albion’, which is a similar finding from previous research conducted at Kansas State University (Gude et al., 2018).

In our study, we varied the planting method across the two years, which could also be a substantial contributor to the seasonal yield differences. In 2020, due to late winter weather, bare-root plants were grown as transplants in soilless media for three weeks before being placed in the high tunnel. However, in 2021, bare-root plants were planted directly into the soil two weeks earlier, which could have influenced the overall yield. Although the evidence provided was not replicated, Gude et al., (2018) also reported a similar trend with the same cultivars grown in HTs. The authors found that rooted transplants had higher yields in one year than the direct bare-root planting in the following season (Gude et al., 2018). Furthermore, several studies have shown that strawberry transplants (i.e., plugs) in open-field production systems have better root establishment, plant growth and require less irrigation and can achieve better fruit yield than direct bare-root plants (Jin et al., 2011; Li et al., 2015; Poling, 2006). Our assumption is the transplant plugs already have intact roots and can establish faster in the soil with minimum transplant shock compared to bare root plants. Clearly, more research is needed to determine the effect of bareroot planting vs. plug-planting for spring-planted, day-neutral strawberries. Our anecdotal observations were that planting bareroot plants into soilless media required a significant amount of labor, supplies, and (heated) greenhouse production space. Transplanting into the HT is also much more efficient with bareroot plants as compared to plugs.

Our study found that black stripe, silver, red and green plastic plot increased early season soil temperatures means by 1.4-2.7 °C compared to the black plastic plots (12.4 °C). However, white plastic mulch had 2.4 °C lower soil temperatures than the black control. Poling (2012) suggested that average early season soil temperature of 12.3 °C is critical for early plant establishment and root growth. Additionally, research in HT systems indicate that plastic mulch in HTs can help maintain minimum soil temperature above 8 °C. which can provide early season chilling protection (Ogden and van Iersel, 2009). Decoteau et al. (1989) reported that black or red mulches usually have 3- 5 °C higher soil surface temperature difference in the high tunnel than white mulch depending on the location and light intensity. Our results confirmed this trend and showed that red, and green plastic mulch could warm to soil temperatures up to 15 °C in the early- season. The differences in soil temperatures between the different colors of plastic mulch may be due to the variation in the light absorption capacity of plastic mulch. Dark-colored mulches absorb most of the light and convert it into energy that warms the soil in the early season compared to the highly reflective characteristics of white and silver mulch (Rowley et al., 2011). Our result found that red and green plastic mulch exceeded soil temperatures of (35/30 ˚C, day/night), in mid-season, whereas the black plastic maintained lower soil temperatures (28/20 ˚C, day/night). In contrast, the silver mulch had lower mid-season average temperatures (23/18 ˚C, day/night), compared to the black mulch. Phelps (2014) and Petran et al. (2017) reported that strawberry flower initiation can be delayed when temperatures are at least 20 ˚C-24 ˚C, which can negatively impact the overall yield of strawberries. Also, temperatures above 29 ˚C can inhibit plant growth and fruit quality. Although the dark-colored mulches tested here (black, red, green, black stripe) increased early soil temperature, and they resulted in above-optimal condition during the warm summer months.

Our results showed that silver mulch had the higher total and marketable yield, likely due to the reduced soil temperature fluctuation and a better maintenance of optional soil temperature ranges (24/18 ˚C, day/night) compared to the dark-colored plastic mulches (black, red, and green). Research indicates that soil temperature ranges between 18-22 ˚C is optimal for fruit initiation in day-neutral strawberries (Wang et al., 2009). Wang et al. (2000) also reported that for strawberry 18/12 ˚C (day/night) was ideal for roots and fruits and 25/12 ˚C (day/night) was also the best temperature for overall plant growth.

Our results showed that there was a cultivar x plastic mulch interaction on percent marketability. ‘Portola’, grown with green mulch had the highest percent marketability. It is likely that the green mulch influence over percent marketability was more cultivar-specific than microclimatic influence via plastic mulch color. In 2020 and 2021, ‘Portola' was high-yielding, and this cultivar has been confirmed to be high-yielding in many crop trials, and outperforming ‘Albion’, when studied together (Gude et al., 2018; Paparozzia et al., 2018; Richardson et al., 2022). However, Descamps and Agehara, (2019) indicate that microclimatic variations can affect strawberry fruit yield and quality via the thermal and radiation characteristics of colored plastic mulch, which vary depending on geographic location and genotype (Descamps and Agehara, 2019). The effect of green mulch on the percent marketability of ‘Portola’ fruit could be due to a reduction in insect or pest infestation from a specific mulch, or it could be due to the plant's chemical defenses being affected by high heat and UV light stress. According to Mayer et al., (2021), dark plastic mulch with more UV-B can stimulate chemical defenses against herbivorous arthropods in some plant genotype, which could be one of the explanations for the higher percentage of marketable fruit seen under green plastic mulch.

In our study, UV light intensity from different plastics varied with mulch color but also the month of the year. The highest UV-A and UV-B intensity was in August compared to September. According to Heidi et al. (2019) that this can be due to the change in light direction over time. Also, it can vary with material variances at different sample locations or chemical composition of plastic change over time due to high temperature, humidity, and light radiation (Dilara and Briassoulis, 2000). However, regardless of time of the year, our result showed that white and silver plastic had significantly higher reflectance of UV-A, but lower reflectance of UV-B compared to the black mulch. Our results indicate that the total and marketable yield in both ‘Albion’ and ‘Portola’ were significantly higher with silver mulch compared to black control. Research has shown that the higher UV- A but lower UV-B intensity in different plastic mulches might promote changes in strawberry fruit production. According to Karlsson et al. (2011), strawberry yields were higher in HTs when the covering film transmitted 5 % higher UV-A than films that block UV-A. Similarly, UV-A transmitting plastics improved more than 8 % marketable fruit yield compared with the open-field (Heidi et al., 2019).

In this study, the plants grown with silver mulch had increased total and marketable fruit yields compared to the black plastic mulch in one production year. The positive effects of silver plastic mulching on the fruit yield could be attributed to maintaining an optimum soil temperature below 24 °C during heat summer and reflecting higher UV-A light and lower UV-B light intensity than the black control plots. It has been reported that higher UV-A light irradiance capacity and low UV-B levels could increase the photosynthetic activity (Wang et al., 2009) by reducing the leaf area heat load to maintains optimum biomass accumulation via photosynthesis for the plant throughout the season (Palma et al., 2021; Pandey et al., 2015). Silver mulch has been shown to increase pepper and berry yields and minimize pest infestations in HTs when compared to black, black-on-white, and white mulch (Al Khatib et al., 2001; Mohamed, 2002). Our results are consistent with several previous studies that found silver mulch to maintain lower daytime root zone (20 °C) temperature than black mulch by reflecting more UV-A, which increases photosynthetic biomass accumulation and increases strawberry fruit yield (Díaz-Pérez, 2010; Lamont, 2005). Our results are also in agreement with a study from Pennsylvania State University that found silver mulch increased pepper yields by 20% (Ahmed et al., 2017; Andino and Motsenbocker, 2004).

In 2020, the black stripe plastic had higher total and marketable fruit yield weight than the black plastic mulch. This similarity might be due to the soil temperature difference in early and mid-season by black stripe and silver mulch. In our study, the black stripe plastic maintained an average early-season soil temperature of 13.4 ˚C and the mid-season temperature was above >28 ˚C. Also, black stripe plastic maintained lower UV-B light intensity than compare black control. In addition to the lower UV-B intensity, we assume the positive yield benefits of the black stripe plastic is due to its ability to warm the soils during plant establishment in early spring, while also reducing the heat load in the hot mid-season from the white shoulder. Other studies have indicated that striped mulches are effective at reducing soil temperatures by reflecting photosynthetically active radiation (Diez-Pérez, 2010) and lower UV-B reflectance allow plant to continue the optimum photosynthetic activity these processes enhance the overall fruit yield (Palma, 2021; Pandey et al., 2015).   In our study, white mulch had similar yield to the black plastic mulch, it probably was not able to maintain early growth and soil temperature was (<10°C). However, other research reported that white mulch can improve summer plant growth and strawberry yields by reducing extreme heat load in the open field (Deschamps and Agehara, 2019). In our investigation, the reduction in mid-season soil temperatures from the white mulch did not result in an increase in total or marketable weight harvested from the plants, but it did increase the total and marketable number of fruits harvested.

We found that the green mulch had the highest average maximum early, mid, and late season temperature compared with the black control mulch. In both year during mid-season green mulch reached extreme temperature up to >35 ˚C. However, the overall yield, fruit number and fruit size were similar with the black mulch. Strawberries can flower and produce fruit in a wide variety of temperatures. However, >29 ˚C is regarded the highest limit at which they will stop flowering as mentioned by Haifa (2014) and Hoover et al., (2017). Also, insufficient ventilation, higher air temperatures (>24 ˚C) and high light intensities could cause pollen sterility, and ripening abnormalities in berry resulting in a low marketable yield as reported by Elezabeth et al. (2019). In both 2020 and 2021, green plastic also had a higher UV-B irradiance capacity than black mulch. Higher UV-B reflection from the green plastic might increase the overall soil temperature to an extreme point, which might reduce the photosynthetic rate which is similar to the black control. Peng et al. (2019) also found that green mulch had high light intensity that generates excessive heat to the root zone temperature and hindered the optimal strawberry plant growth. Our study found that higher UV-B light irradiance from the plastics coincided with higher maximum soil temperatures, which likely means that the plastics expose more of the UV-B light. Heidi et al. (2019) also found that plastic film emitting higher UV-B light had the greatest maximum daily temperatures compared to an open field plot. Another study found that higher UV-B light radiation trigger temperature can create a drought stress on plants grown with green plastic, which result in lower strawberry yield (Escobar-bravo et al., 2017).

Our result showed that the use of red mulch also maintains higher soil temperature and resulted in similar yields to the control black plastic mulch. The soil temperature recorded under the red plastic was >31 °C and had similar UV-A intensity but lower UV-B. We assume that the heat stress and lower UV-A intensity led to poor photosynthetic ability of the plants, resulting in similar yields to the control black plots. In our experiment we found reduced productivity with red mulch in 2020, which have been caused by poor plastic quality that resulted in higher weed occurrence the first year. We observed weeds germinating and sprouting from underneath the plastic mulch, which pushed against the underside of the mulch, likely due to light transmittance within the mulch. This was corrected in 2021 by putting another layer of black plastic beneath the red plastic, but it is important to note that this practice would not be feasible in a commercial operation. Red plastic mulch has been used for increasing yield in tomato and eggplant (Ahmed et al., 2017), but it is clear that ensuring that the plastic mulch that does not transmit light is critical to commercial success.

We did not see any influence of plastic mulches on fruit size compared to black mulch which was similar the findings from Lalk et al. (2020). However, other studies have reported that strawberry fruit size significantly increased when grown with red plastic mulch (Shiukhy et al., 2015). Deschamps and Agehara, (2019) reported that fruit number increased over metallic stripe mulch.

Another component of this research was to evaluate the fruit quality at harvest and during storage for the strawberries that are grown with various colored mulches, to ensure customer preference and a better market price for local strawberry growers. Customers' initial readiness to pay higher prices for locally grown strawberries is mostly driven by the fruit's size, freshness (firmness and lack of damage) and eating quality, i.e., color and flavor (Retamales et al., 2012). Satisfactory eating quality increases repetitive purchases of berry fruits, which has a substantial impact on the profitability of strawberries in the local market (Colquhoun et al., 2012; Hinson et al., 2005; Retamales et al., 2012). Fruit firmness and color are the two major visual fruit quality parameters for consumer to determine overall appearance and freshness of fruit to buy.

Our study indicates that there was no significant effect of plastic mulch on visual quality and firmness. Result showed that 'Albion' fruit had better overall visual quality than 'Portola'. However, there were no significant changes in firmness over time between 'Albion' and 'Portola' grown with different plastic mulches.

Respiration and moisture loss are important indicators of shelf life and fruit quality. Our results showed that respiration rate and moisture loss were not influenced by any of the plastic mulch treatments compared to black on the day of harvest. However, after two days of storage, fruit from plants grown with the green and black stripe plastic mulch had the highest respiration rate compared to the black plastic in ‘Portola’. Cultivar-specific differences in respiration and moisture loss were more evident, where ‘Portola’ had higher respiration rates and moisture loss, which may more cultivar specific responses than microclimatic influence. Similarly, Dong et al. (2020) found that ‘Portola’ had higher respiration rates and moisture loss compared to five other day-neutral cultivar including ‘Albion.’.

It has been reported that ‘Portola’ is a soft fruit that is more susceptible to high humidity in the HT, which may increase fruit water turgidity and make the fruit more susceptible to increased respiration and moisture loss after harvest and during storage (Elizabeth et al., 2018). Lower antioxidant and phenolic content in strawberry can lead to higher water loss for ‘Portola’, which could be another reason for higher respiration and moisture loss mentioned by Kelly et al. (2018) and Nunes et al. (2010). However, the overall visual quality at harvest and after four days of storage was not significantly affected by plastic or cultivar at of harvest.

Dong et al. (2020) reports similar finding that ‘Albion’ and ‘Portola’ had no significant difference in firmness at harvest and storage grown with three different plastic film. Costa and Teodoro (2016) reported that fruit firmness was significantly higher when black and blue plastic was utilized compared to white plastic. Other studies have indicated that reflecting UV light intensity enhanced by the red and yellow color plastic mulch, can increase plant surrounding air temperature that influences fruit color (Todic et al., 2008). However, others have demonstrated that different color plastic mulch had no effect on strawberry firmness, visual quality, and color (redness, lightness) as measured by a* and L* value at day of harvest (Dong et al., 2020; Maria et al., 2019).

In our study significant cultivar differences were observed. ‘Albion’ was firmer, and had darker colored fruit compared to ‘Portola’ at harvest. Therefore, overall visual quality for score at of harvest for ‘Albion’ was higher than ‘Portola’. Gude et al. (2021) and Dong et al. (2020) also reported higher overall visual quality of ‘Albion’ fruit compared to ‘Portola. Genotypic differences in patterns of pectin and cellulose matrix breakdown can cause cultivar-specific differences in firmness of strawberry fruit at harvest and during cold storage (Serner and Fethiye 2017; Santiago- et al., 2008).

After four days of storage ‘Portola’ fruit showed more redness than on the day of harvest and day 2 for fruit grown with all the plastic mulch colors except for black. The different physiological response from differences in temperature and spectrum radiation could trigger phytochrome systems that sense the level, intensity, duration, and color of environmental light that regulate fruit physiology with a photoreceptor protein, leading to physiological changes that can be exposed not only harvest but also during storage (Li et al., 2011; Shiukhy et al., 2015). Strawberries, even when fully red, continue to change color and darken during storage (Kalt et al., 1993; Miszczak et al., 1995; Sacks and Shaw 1993). Sacks and Shaw (1993) suggested that strawberries darkened slowly during storage at 0 ˚C, although we stored our fruit at 3 ˚C.

Organoleptic features like soluble solid content and titratable acidity can help predict strawberry flavor. The intensity of sweetness is the most important factor influencing consumer preference (Gude et al., 2021; Schwieterman et al., 2014). In our study, plastic color did not affect organoleptic quality standards including SSC and SSC/TA, similar to several studies (DeVetter et al., 2015; Gu et al., 2017; Posada et al., 2011) which reported that SSC and SSC/TA of strawberries was not affected when grown with silver, red, black, blue, and yellow plastic. However, plastic mulch color differentially affected fruit TA for the two cultivars we tested on the day of harvest. For ‘Albion’, fruit from plants grown with the black center stripe plastic had significantly lower TA than those grown with the silver, red, and green mulch treatments. However, all mulch treatments produced fruit with similar TA for ‘Albion’.

Robbins et al., (2020) found that red, black, and silver plastic mulches were equivalent and yielded similar fruit quality (SSC, TA, SSC/TA). In another study, red plastic influenced higher TA in strawberries compared to black mulch (Fanors et al., 2010). However, there was no known information of black stripe plastic mulch on TA. Anttonen et al. (2006) and Minutti et al. (2019) indicated that 10-15 % higher UV-B light intensity can influence the weed suppression ability of red mulch and can improve higher SSC content (glucose and fructose) and lower acidity compared to black plastic. However, the red plastic mulch did not have an effect on fruit SSC in our study. Costa et al. (2014) had similar findings, where red mulch did not influence strawberry SSC content compared to three different mulch films tested. Lalk et al. (2020) also reported that day-neutral strawberries grown with black and red plastic did not affect the soluble solid content. Many other investigations have discovered that exposing growing fruit to high temperatures reduces the amount of SSC in ripe fruit (Wang et al., 2000). However, SSC in strawberry’s reliance on genotypes (cultivars) was supported by our finding as well as other studies demonstrate that SSC, TA, and SSC / TA was higher in ‘Albion’ compared to ‘Portola’ at harvest day (Gude et al., 2021; Sabatino et al., 2017; Samec et al., 2016).

Antioxidant and phenolic compounds in strawberries are well known health-promoting phytochemicals that have numerous health benefits (Giampieri et al., 2014). The total antioxidant, phenols, and anthocyanins in fruit are important nutritional quality parameters that also determine the berries' bright red color. In our study, at the day of harvest the strawberries antioxidant (FRAP) in content 'Albion' were higher in plants grown with silver, red, green, black center stripe mulch compared to the black plastic and white plastic mulches. However, total phenolic content was not significantly different among other colors of plastic mulches compared to black. 'Portola' did not show an influence of plastic mulch color compared to control black in regard to antioxidant and total phenolic improvement. However, other factors such as soil pH, crop genotype and temperature, humidity, rainfall, and CO_2 concentration in the atmosphere have also been reported to influence the quantity and quality of antioxidant chemicals in fruit at harvest (Kannaujia et al., 2021; Wang, 2009).

During storage, we found that the antioxidant content in the two different cultivars behaved differently. 'Albion' strawberries had higher antioxidant capacity after four-day storage but was not affected by plastic mulch color. In 'Portola', the antioxidant capacity increased during storage amongst the fruit grown with the white, silver, and green mulch treatments compared to the black plastic mulch. It's likely that flavanols have more genetic variability among cultivars, and that synthesis of individual polyphenols, especially flavanols, is stimulated during storage due to a time-temperature stress, which might affect a strawberry cultivar's overall phytochemical quality (Katherine et al., 2018). The reductions in total phenolic and anthocyanin during storage were not dependent on film type, which agrees with Lalk et al. (2021).

Total anthocyanins in strawberry fruit were influenced by cultivar, but not by mulch type in our trials, which is an agreement with Reham et al. (2019), who suggested that anthocyanin production was more cultivar and season-dependent, and not influenced by plastic mulch microclimate effects. However, Shiukhy et al. (2015) reported that 'Camarosa' plants grown over colored plastic mulch (black, white, or red) had higher anthocyanin content than un-mulched control plants (Shiukhy et al., 2015). Lalk et al. (2021) also reported that day-neutral strawberries grown with black and red mulch affected the total anthocyanin content. Anthocyanins are the only polyphenols to absorb light in the visible spectrum, therefore any changes in UV light intensity does not impact the overall anthocyanin content in fruit quality (Enaru et al., 2021). Even under regular physiological settings, phenolic concentrations in strawberries have been found to be insensitive to various UV screening films (Josuttis et al., 2010; Tsormpatsidis et al., 2011). Furthermore, our trial did not consider types of macro and micronutrients or ideal amounts to determine if this component may contribute to better nutritional quality under different plastic settings (Paydas et al., 1996).

Local high tunnel growers require a realistic solution that may minimize environmental stress (spring cold and hot summer) over early spring planted strawberries with higher production yield and quality to boost local production and marketability of spring planted day-neutral strawberries (Gude et al., 2018; Rowley et al., 2010). One objective of our study is to choose best performed plastic mulch in favor of yield and fruit quality improvement. In our study we evaluated six different plastic mulches and two day-neutral cultivars—one with higher production and one with better fruit quality. All six-plastic mulches in our trial behaved differently with varying UV-A and UV-B light intensity and soil temperature effects, but only the silver mulch resulted in a significant increase in total and marketable yield compared to the standard black plastic. Therefore, this finding indicates that silver mulch can be a potential management tool for improving early yields for spring-planted strawberry cultivars by maintaining optimal soil temperatures and ideal UV light reflectance throughout the season.

In our exploration of fruit quality, cultivar effects were more evident than plastic mulch influence. However, ‘Albion’ grown with silver had the highest TA and antioxidant capacity (FRAP) compared to the (standard) black plastic. In storage, fruit from plants grown with the silver mulch had higher FRAP content in ‘Portola’ at day four than day 0. Moreover, ‘Portola’ shelf life was better with lower respiration when grown in silver mulch compared to red, and green at day-2, day 4. The silver mulch had a strong treatment effect on the ‘Albion’ antioxidant capacity and total phenolic content compared to the black mulch. Muneer et al., (2018) showed that reflective silver plastic film increased fruit color, antioxidant, and total phenol levels in blueberry compared to black mulch.

Based on our findings, 'Portola' appears to be the ideal cultivar for production performance, while also having acceptable fruit quality. The similar finding on higher yield and quality also been reported by Gude et al. (2018), Paparozzia et al. (2018) and Richardson et al. (2022). Our results showed that none of the five plastic mulches tested in the HT substantially improved the physical and organoleptic fruit quality in ‘Portola’ at harvest. However, select mulch treatments caused marginal improvements of fruit quality during shelf life compared to fruit from plants grown with the black mulch. The silver mulch was the only plastic to improve FRAP content in ‘Portola’ during storage. ‘Albion’, on the other hand, has better fruit quality but a medium to low yield, which is consistent with earlier studies (Gude et al., 2021; Paparozzia et al., 2018; Richardson et al., 2022). Our study showed that silver mulch can improve TA percent, antioxidant (FRAP), and total phenolic content in ‘Albion’ fruit compared to fruit from plants grown with the standard black plastic mulch. But the yield improvements observed with silver mulch still did not make the ‘Albion’ yields competitive with the ‘Portola.’

Conclusion

Our results indicate that the silver and black stripe mulch increased overall strawberry yield (total and marketable) in both cultivars. Likewise, organoleptic, and nutritional quality was positively influenced when strawberries grown with silver mulch along with and black stripe mulch. This trend was seen with ‘Albion,’ but not so much with ‘Portola’. ‘Portola’ grown with silver mulch did not significantly improve fruit quality but maintained a standard fruit quality grown with black plastic. But red and green plastic mulch resulted in poorer shelf life compared to black with high respiration and moisture loss in ‘Portola’. Considering the overall performance of all six plastic mulches on yield and fruit quality measurement, silver has been identified as an important plastic mulch to improve yield and quality of strawberries grown in HT systems. To our knowledge, this is the first study to examine the impact of commercially available five plastic mulches on yield and postharvest fruit quality of day-neutral strawberry cultivars grown in a HT. Based on these results of this study, it apparent that using silver mulch to ensure a higher yield and improved nutritional quality should be an important consideration for high tunnels growers that are interested in producing day-neutral strawberries.

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Chapter 3 - An Economic Analysis of Plastic Mulch and Cultivar for High Tunnel Strawberry Production

Abstract

Day-neutral strawberry production in high tunnels (HT) has seen increased interest in the Central US, but little data has been reported to provide growers with the economic costs and benefits of utilizing this system. Strawberry HT trials were conducted in 2020 and 2021 to identify the yield and quality effects of using various plastic mulch colors for HT production with ‘Portola’ and ‘Albion’. In this study we provide an economic analysis utilizing the same: six different plastic mulches (black, white, black stripe, silver, red and green) and two-day neutral strawberry cultivars (‘Albion’ and ‘Portola’). Trials were conducted at the Kansas State University Olathe Horticulture Research and Extension Center (Olathe, Kansas). The goals of this study were to develop a production budget to determine plastic mulch-specific profitability using partial budget methodology. A sensitivity analysis was performed with market prices ranging from $2.80/lb. to $6.00/lb. and fruit marketability levels ranging from 60% to 90%. Total and marketable yields were affected by both cultivar and plastic mulch in 2020, but not in 2021. In 2020, silver mulch was identified as providing the highest yield for ‘Albion’ while the black stripe mulch was best for ‘Portola’ with lowest breakeven price $2.18/lb. and $1.92/lb., respectively. Both were profitable at the lowest potential selling price ($2.80/ lb.). Similarly, the average percent marketability in our trials was 69.4 %, which is estimated to provide $870/1000ft^2 in net revenue at $2.80/lb. The selling price of $3.20/lb for ‘Portola’ grown with black stripe mulch and $3.60/lb for ‘Albion’ with silver mulch was identified as having profit equal to the return-on-investment (100% ROI). The results of this study provide information that will enable growers to make decisions related to the economic potential of using silver and black

stripe plastic mulch in HT strawberry production systems. As growers adopt day-neutral strawberry production systems in HTs, careful consideration for market price and the ability to grow a crop with a high percent marketability will be important for maximizing profitability.

Introduction

High tunnels (HT) are typically described as unheated polyethylene film greenhouse structures that can provide a modest level of environmental protection using passive cooling and heating methods. For most crops, HTs provide season extension and enhance the productivity of the farm. (Lamont, 2009; Pool et al., 2014). The positive microclimate effects include warmer soil temperatures and altered light conditions that can result in significantly higher yields (Rowley et al., 2011; Werner, 2011), an extended growing season (Demchak and Hanson, 2013; Kadir et al., 2006), and better fruit quality with a longer shelf life (Nes et al., 2012). More recently, the implementation of HTs has shown to reduce food losses (Batziakas et al., 2019) and crops grown in HT system had higher quality (Batziakas et al., 2019) and/or consumer acceptability (Batziakas et al., 2019).

Although HTs have been shown to improve crop productivity and expand the availability of local produce throughout the US, there exists a critical need to develop profitable crop diversification methods for these system. During the summer, tomato is the predominant crop grown in HTs (Galinato and Walters, 2013; Janke et al., 2017; Sydorovych et al., 2013; Vescera and Brown, 2016) and many Extension publications have highlighted the need for developing effective crop rotation methods in HTs to prevent soilborne disease and maintain long-term soil health and sustainability (Charles et al., 2013; Elezabeth et al., 2019). To maintain profitability for HT systems, crops that have a high value per square foot are recommended (Bruce et al., 2021) and strawberries may be a viable alternative.

Plastic mulch is commonly used for high-value specialty crops like asparagus and strawberries (Heißner et al., 2005; Stevens et al., 2011). Many studies reported that the most significant economic impacts of plastic mulch are water savings (up to 25%) and reduced labor expenses for weed and pest management (Ingman et al., 2015; Jabran et al., 2015). Also, growers generally use 4 ft × 4,000-ft x 1.25 mil plastic mulch rolls, which can cost between$135 and $154 per roll (Velandia et al., 2018). Tyically black mulches are used in the Central US for strawberry production, Xie et al. (2005), reported that the increased expense of using infrared transmitting reflective mulches can reduce overall profits for small scale production systems. A comparative economic analysis on different color and types of plastic mulch suggested that using silver mulch in watermelon production could yield the highest net returns compared to black and red plastic mulch (Bajpai and Rao, 2017). Another study reported that using plastic mulch for melon production increased annual expenditures by about 6%, but also doubled revenue, resulting in a more than 5-fold profit increase (Nava, 2011).

End-of-season plastic mulch removal and disposal added extra labor and disposal costs, which can impact the overall profitability of the production system (Ghimire et al., 2018). Plastic disposal costs can vary between states and/or the location of the landfill but can range from $20 - $100 per ton (Velandia et al., 2018). These added labor costs can negatively impact the economic benefits of using plastic mulch in a larger production area (Velandia et al., 2018). Schonbeck (1999), also indicated that the added disposal and labor costs associated with plastic mulch systems can be offset by the long-term savings in weed or insect management in some cases.

However, comprehensive knowledge of the economic costs and benefits of plastic mulches is currently sparse and incomplete in the scientific literature (Steinmetz et al., 2016).

Numerous studies have demonstrated that plastic mulch increases fruit, yield and quality, helps prevent to soil erosion and weed growth and consequently reduces the use of n of herbicide and fertilizers (Chalker-Scott, 2007; Espí et al., 2006; Scarascia-Mugnozza et al., 2011). Black plastic mulch in the most commonly used mulch for strawberry production. In our study, we used different color plastic mulches, to determine if changes in the thermal and radiation characteristics of the plastics could improve HT strawberry yields and fruit quality compared to a black plastic mulch. The adoption of different color mulches could be a minimal cost investment difference.

In the Central US, the use of fall-planted, June bearing cultivars in open-field plasticulture systems are the most common for strawberry production. Numerous growers are also growing fall-planted cultivars for spring production in HTs similar to Kadir et al. (2006). However, the harvest period for this system in HTs is relatively short (May-June) and the crop takes up space in the HT during the winter months (Kadir et al., 2006). Using day-neutral cultivars in the high tunnel can extend production by four to five months (mid-May to mid-October) in the Midwest, whereas the production season with fall-planted cultivars can only be extended for 3-5 weeks in the HT (Gude et al., 2018; Kadir et al., 2006; Petran et al., 2016). Because day-neutral cultivars are planted in spring, they do not take up production space during the winter, which reduces the opportunity cost of not growing fall and winter crops. In Kansas, day-neutral cultivars flower and fruit through summer and fall, when grown in HTs with shade cloth (Gude et al., 2018). In 2018, Gude et al. reported that day-neutral cultivars could be grown successfully in HTs with shade cloth and could provide an alternative to tomatoes for crop rotation, pending economic data related to profitability Gude et al. (2018), evaluated feasibility of growing six day-neutral strawberry cultivars in HTs in Kansas, with the use of evaporative cooling. ‘Portola’ had the highest yield (1.33 lb. /plant), which was significantly higher than ‘Monterey’, ‘Albion’, and ‘San Andreas’. ‘Albion’ and ‘Evie-2’ had better fruit quality during storage than the other cultivars tested (Gude et al., 2021). Portola was identified as the best-suited cultivar, followed by ‘Evie-2’ (Gude et al., 2018). Other studies have also identified 'Portola’ as a high-yielding cultivar for HT plasticulture systems (Paparozzia et al., 2018; Richardson et al., 2022).

As urbanization encroaches on agricultural land, farms are increasingly located near densely populated areas, allowing for more direct-to-consumer sales. The increasing "Buy Local" trend has generated a market to sell high quality local items throughout the year (Curtis, 2014; Martinez et al., 2010). Prices for direct market fresh strawberries in the Central US average $4.95/lb. for in-season strawberries and $6.60/lb. for early-season strawberries (Maughan et al., 2015), which would suggest that this crop would be profitable, even in a HT. However, strawberries require significant labor (Conner and Demchak, 2018) and some day-neutral cultivar may not have adequate fruit yield in HT systems (Gude et al., 2018). An extension research report on cost return estimations from the University of Maryland suggested that growing day-neutral strawberry in HTs was profitable during the 15- to 20-week harvest period if the day-neutral fruit yielded 0.75 to 1.25 lb./plant and sold for $2.00 to $4.00 per pound or yielded 0.60 lb./plant and sold for $3.00 to $4.00 per pound (Lantz et al., 2010). However, this study did not compare different marketing methods or provide a detailed production cost estimation and profitability analysis with this price.

Other study also indicate that the profitability of HT crop production can vary by location, crop, and production method (Rowly et al., 2010). A study conducted at North Carolina State University showed that to maintain HT strawberry production as profitable enterprise, growers need to have a breakeven price of more than $1.28/lb (Ballington et al., 2008). A study conducted at Utah State University demonstrated that, the higher net returns of early strawberry production were reliant on cultivar-specific increases in early yield from ‘Seascape’, and direct marketing through local markets only. Therefore, the overall economic profitably of HT produced strawberries depend on the crop productivity, harvest timing, and the price premium (Maughan et al., 2015; Rowley et al., 2011).

Although HTs can provide numerous benefits, the initial investment and maintenance costs can be a barrier to growers. However, HT structures typically last more than 10 years (Olha et al., 2013; Wells and Loy, 1993). A year-round useable HT can cost $2 - $3/ft^2 per year (Blomgren and Frisch, 2007; Sydorovych et al., 2013). Studies have shown that the profitability of HT crop production can vary by location, crop, and production method. Cheng and Uva (2008) conducted a comparative profitability analysis for HT tomato, pepper, and lettuce in New York State. Considering fixed costs associated with tunnel construction, and varied economic returns from different crops, HT heirloom tomatoes were profitable and provided a positive net return within two years (Sydorovych et al., 2013). Rodriguez et al. (2012) conducted a sensitivity test to predict the value and numbers of years to recover the total cost for HT vs open field blackberry production. The overall gross return was high for existing HT blackberries compared to open field even with a greater investment than growing blackberries in the open field (Rodriguez et al., 2012).

The increased labor and time demand for HT strawberry production can challenge the overall profitability of this crop (Bruce et al., 2021). In Washington, one study reported that HT strawberry production costs were estimated to be $2.81/ft^2$, compared to $0.64/ft^2$ for strawberries grown in the open field. Just >15% higher yield in HTs strawberries had a net profit of $0.56/ft^2$ more compared to open field strawberries (Galinato and Walter, 2013). Grower survey studies report that a HT production system with diversified crops including tomato, blackberry, raspberry, and strawberry can make this production system profitable (Blomgren and Frisch, 2007; Everhart et al., 2010). Therefore, as HT growers integrate day-neutral strawberry production into their rotation, a better understanding of the economics of this crop will be important. The objectives of this study were to: (1) determine the economic viability of cultivating day-neutral strawberries in a HT plasticulture systems in Kansas, 2) estimate the profitability of utilizing different-colored plastic mulches, and (3) provide growers with information to examine different revenue scenarios based on price and percent marketability.

Material and Methods

The data used in this study were gathered from trials that were conducted in 2020 and 2021 at the Kansas State University Olathe Horticulture Research and Extension Center in Olathe, Kansas [Johnson County (lat. 38.884347°N, long. 94.993426°W; USDA Plant Hardiness Zone 6A)]. Six colors of plastic mulch as well as two cultivars were investigated. A production model consisting of material, equipment, and labor costs was developed based on these trials. The production model included (standard) black plastic mulch and any additional costs and returns of using the other five mulches tested were incorporated to determine a breakeven price for each of the treatments. Overhead (fixed) costs of the high tunnel structure were included in the estimation of annual costs but were based on previously- published findings (Sydorovych et al., 2013). The cultivar/mulch combination that showed the lowest breakeven price(s) were used to determine profitability and perform the sensitivity analysis.

Experimental Design

The trial was conducted within a three-season HT (200 x 24 ft^2) and the strawberries were grown on raised beds in an annual plasticulture system with drip irrigation. The experiment was arranged in a split-plot, randomized complete block design with four replications and conducted for two years. Six plastic mulch treatments (black, white, black stripe, silver, red, and green) served as the main plots and the two cultivars, 'Albion' and 'Portola', were the sub-plots. The two cultivars of day-neutral strawberries *(Fragaria x ananassa)* were selected based on yield and fruit quality potential identified by previous work (Gude et al., 2018) as well as plant availability. Bare-root strawberry plants (Nourse Farms, South Deerfield, MA) were used for the trials in both years. The black, red and green plastic mulch was provided by (Grower's Solution, Cookeville, TN) and silver, black stripe and white plastic was provided by (Film Organic, Laval, Canada). The trial was made up of three rows that ran parallel to the length of the tunnel (north and south). The rep/blocks divided the HT into four sections from north to south and consisted of 6 main plots each (across the three rows). The main plots were 25 ft sections of 3 ft wide rows. The six different color plastic treatment (main plots) as well as the cultivar (sub-plots) were randomized and re-randomized for the 2021 trial. Each sub-plot had 30 plants arranged in a staggered fashion with three rows of 10 plants each with 12 inches between each row and 12 inches in-row spacing. There were 3 ft buffer spacing maintained between the main and sub-plots to reduce inter plot interference by external factors like disease and insect pest infestation.

Crop Production and Yield Data Collection

The planting dates for the trials were 2 April 2020 and 19 March. 2021. A daily logbook was maintained throughout the season to record all the activities and cost related the trail. In 2020, due to late winter weather we planted the bare roots as transplants grown inside the green house for 2 weeks then transplanted them in the HT. In 2021, bare roots were directly planted to in the HT. The beds were prepared and shaped using a tractor powered bed-shaping machine (Rainflo 2550), and the mulch was laid manually by hand in the tunnel. We prepare three (24 ft x 3 ft) wide raised bed of three rows covered with six plastic mulches randomly. Black woven fabric was placed in between each row and across the ends of the tunnel to prevent weeds. Drip irrigation was used, and cultural management approaches were applied to maximize fruit yield. There were two drip tapes per bed (between each row of plants).

The harvest period started on 8 May in 2020 and 12 May in 2021 with an end date of 10 Oct in 2020 and 13 Oct in 2021. Mature fruit (100% red) were harvested twice weekly and sorted based on marketability. Non-marketable fruit were determined based upon the presence of decay, gray mold, and small size (smaller than 3cm diameter was included as non-marketable), and/or pest damage. The plot yield was measured for the number of marketable and unmarketable fruit as well as fruit weight.

Statistical Analysis

Fruit yield data was analyzed with SAS software using a [ProcMIXED (SAS version 9.2; SAS Institute,)]. Fruit yield measurements were subjected to a linear mixed model using PROC GLIMMIX. The fixed effects of the model included year, treatment, and cultivar and all two- and three-way interactions. The blocking factor was included in the RANDOM statement. The yield response variables with significant year main effects or significant interactions with year were analyzed separately by year. Means for significant effects and their interactions were compared using Tukey's HSD significant difference test when P <0.05 (Proc LSMEANS, SAS version 9.2) as described in chapter 2.

Production Cost Model

An enterprise budget based on data from the two years was developed to determine the annual variable costs of HT plasticulture strawberry production with standard (black) plastic mulch and utilizing direct-planted bareroot plants. The variable costs were developed for a production area of $3600ft^2$ (entire plot area) and then normalized into $1000ft^2$ for analysis and presentation of the data. Partial budget methodology was employed to determine the additional costs and potential returns of using the other five plastic mulches. Because estimated market prices for out-of-season strawberries being sold directly to the consumer are difficult to determine and/or highly variable, a breakeven price was determined for each plastic mulch type and cultivar.

Fixed (HT structure and construction) costs were based upon published literature. One of the main objectives of this paper was to build enterprise budgets for day- neutral strawberry production that could be used by existing HT growers. As a result, we did not analyze the actual HT structural costs, even though we included an estimated fixed HT costs in the production budgets. The tunnels in our case have been built for at least 5 years and were a common component of production equipment. As a result, based on the HT study by Sydorovych et al.,

(2013) a standard fixed cost for high tunnel materials and construction was utilized. The 30-by-96-foot HT from Sydorovych et al. (2013) is assumed to have a 10-year useful life, resulting in an annual fixed cost of $1,410.07 per 2,880 ft^2 HT ($0.49/$ft^2$) and a monthly fixed cost of $117.51 per 2,880 ft^2 HT ($0.041/$ft^2$). The HT fixed expenses are accumulated based on the amount of time necessary for bed preparation and crop cleanup and termination in mid-October both years. Mulch costs were estimated based on the manufacturer price., The black plastic was the lowest cost ($0.02/$ft^{2)}$ mulch according to the manufacturer cost recorded and is the most typical for strawberry production. The additional costs for the other mulches were determined by deducting the standard black plastic costs/ft^2 from the other color plastic costs/ft^2. The breakeven price was determined by combining the costs and dividing them against the yield that was the result of each mulch/cultivar/year combination (fixed cost + variable cost + harvest cost) = (yield x breakeven price). The treatments that provided the lowest breakeven price (ie most profitable) were utilized for the sensitivity analyses.

Net Revenue and Market Price Sensitivity Analysis

Two sensitivity analyses were conducted to determine the impact of price and the proportion of the fruit that were marketable (percent marketability). The best-performing treatment for each cultivar was examined in the market price sensitivity analysis. The range of the selling price ($2.80/lb. -$6.00/lb.) was determined based on reports in the literature (Gude et al., 2018; Kruse et al., 2021; Rowley, 2010) and anecdotal conversations with local strawberry growers. The net revenue was calculated for each year based marketable yield estimates and were multiplied by each sales price with total cost deduction [net revenue = (marketable yield x price) – total cost where total cost =fixed + variable + harvest costs].

The second sensitivity analysis was conducted to determine the combined impact of market price and percent marketability. The total fruit yield of the best-performing treatment and year was utilized as the basis for the sensitivity analysis. Marketable yield estimates were calculated and analyzed similarly to the market price analysis. Percent marketability levels (60-90%) were chosen based on previous research trials with day-neutral strawberry production (Gude et al., 2018).

Assumptions of the Economic Model

Commercial strawberry growers in the Central U.S generally grow strawberries in open-field plasticulture systems with June-bearing cultivars (Demchak et al., 2010; Kadir et al., 2006). Therefore, many of the best management practices that were developed were based upon recommendations for open-field day-neutral strawberry production from other states and general experience with HT systems with other crops. We utilized an assumed fixed cost (materials and construction cost) for HT according to a study by Sydorovych et al. (2013) as described above. The HT fixed costs are included in the budget based on the time required for the strawberry production cycle as well as the square footage occupied. The actual costs of materials and other inputs were used to develop this enterprise budget according to annual production cost data at the trial site. However, for certain items, we used the average of the input costs accorss the two-years.

This study assesses the variable costs and the profitability of annually grown raised bed plasticulture HT strawberry production system for existing HT growers that market directly to consumers. Although the fixed costs are included in our model, in many cases, we assume that the HT may already exist on the farm and growing strawberries would be considered as potential alternative to another crop to increase diversity. Therefore, the overhead HT structural costs will be considered as fixed costs and the high tunnel structure itself is not specific to strawberries. Strawberry production can be easily incorporated into most HTs as they are a short crop and do not require additional structures, or height, etc. Similarly, storage and marketing costs are not included here as we expect that most HT growers would be incorporating this crop into a diversified selection of products and selling to consumers shortly after harvest. To develop our variable cost budget, installation of standard black plastic mulches. Although the plastic mulch was installed manually for the purpose of the research study, we assume that a grower would utilize a tractor-mounted bed shaper.

In this study, we utilized a growing area that was 3,600 ft^2 with 1400 plants, which was centrally located (east-west) within a 4,800 ft^2 HT. In this case, half (1800 ft^2) of the production space was planted with strawberry plants, which is typical for open-field plasticulture production systems that use tractor-based equipment. Plant populations were based on theoretical plantings using the same plant spacing as the replicated trial to simulate a continuous planting without spaces (between the experimental treatments). We assume that machinery and equipment expenses in the production cost models reflected machinery components that might be employed for other farming operations besides strawberry cultivation. To estimate harvest cost, we assumed that the fruit was picked into 10-quart flats/paper trays by hired labor. Each flat took an average of 60 minutes. with each flat costing $1.10, in addition to the carrier cost $2.00/ flat. Labor rates have been assumed to be $12.50 per hour for hired labor and $16.47 per hour for operator labor across all budgets based on the 2021 adverse wage rate for the state of Kansas (US Department of Labor, 2021 plus an additional 26.75% for social security, workman's compensation, and Medicare). The variable costs for machinery (e.g., tractors, irrigation/water pump, etc.) is adapted from standard rates (Guidry et al., 2017) and includes fuel and maintenance.

Results

Strawberry Production Cost Model

Table 3.1 shows the annual variable (excluding harvesting costs) and fixed costs for HT production of day-neutral strawberries grown with black plastic mulch. The economic data was assessed for the 3600 ft^2 research trial, which was then normalized per 1000ft^2. To better communicate the variable production costs, the costs were divided by the months of the growing season. The annual production cost (excluding harvest and marketing) was $767.56/ 1000$ft^2$, with the variable costs accounting for 64% of the total and fixed costs accounting for the remaining 36% (Table 3.1).

Planting bare root plants took about 3 hrs. of labor, accounting for $37.50 in labor expenses.Standard black plastic was used to cover three beds which costed $72/1800 ft^2 total at $0.04/$ft^2$. The additional cost difference from using different color plastics was only $0.02 to $0.04/ ft^2 and had no impact on labor or machinary costs because the installation process was the same as the black plastic. Bed preparation, shaping and laying plastic mulch required 4.5 hrs. of labor. Approximately 800 linear feet of 4’ wide black woven fabric (priced at $65), was needed for weed suppression between rows is expected to last for 5 years.

A 200’ irrigation header pipe was installed at $0.25 per foot (0.5 hr. of labor for a day) along with an in line screen filter. The filter and header pipe connector will last for 5 years. Irrigation events consisted of turning on the water and inspecting each row for leaks, etc., which took 5 mins per row (3 rows = 15 mins/ labor) each time. The plants were irrigated to accommodate the climate in Kansas. Irrigation rates varied based on weather conditions and plant growth stage; from April to June, irrigation occurred 8-10 times per month, increasing up to 12-13 times/ month during the hot summer (July to August), and only 2-5 times/ month in mid fall (September -October). Irrigation took 30- 50 mins. labor/ week. A preplant fertilizer application took 0.5 hr. of labor. Weeding and cutting the strawberry plant runners was performed manually at the same time, usually 2-3 times/month. Weeding and cutting the runners also required 1.5-2.25 hrs/ month. Crop management and pesticide application were all completed as necessary and based on experience from Gude et al. (2018). Pest scouting usually took 2-4 hrs. of labor per month at a rate of $12.50/hr., rate especially in middle of the growing season (June-Aug.) Pesticide was applied 2-3 times/month depending on the pest infestation. Bacillus thuringiensis (BT) was sprayed most frequently between May and July to control for mosquitoes, black flies, caterpillars, and moths. In the month of June, when the temperature was consistently above 25 $^{\circ}$C, a shade cloth was placed over the high tunnel, and was removed in September. The shade cloth cost $167 in material cost when adjusted for a five year lifespan and required 1 hr. of labor with four people to install. Removing the of shade cloth took 45 min of labor. Hand removal of the plastic mulch and drip tape at the end of the season took 4 hours.

The strawberry plants were the highest expenditure, accounting for 23% of the total variable costs. The 3600 ft^2 tunnel model required 1400 plants, which totaled $402. Throughout the growing season, materials constituted the highest variable costs at $224 /1000$ft^2$ (approximately 29.19 % of total cost), labor was second at $210/ 1000 ft^2 (approximately 27.36 % of total cost), and machinery costs were lowest at $54/ 1000$ft^2$ (only 7 % of total cost) and fixed cost at $ 280/ 1000ft^2 (approximately 36.45 % of total cost).

Yield and Harvest Cost Estimate

Both total and marketable yield parameters (weight/plant, number/plant) had significant cultivar x year and treatment x year interactions. Therefore, the data for these parameters was presented separately for the two years. There were no significant treatment x cultivar interactions observed, except for percent marketability. 'Portola 'grown with green mulch had the highest percentage of marketable fruit (P<0.0001).

A more detailed interpretation of the yield data is published in Mukherjee et al. (Chapter 2). The overall strawberry fruit yield in 2020 was higher than in 2021 *(P*<0.0001). In 2020, plants grown with the silver mulch had 38 % higher strawberry total fruit yield and 49 % higher marketable fruit yield compared to black plastic (P<0.0001). 'Portola' was the highest yielding cultivar in both years (P<0.0001). In 2020 and 2021, the total yield weights for 'Portola' were 1.68lb/plant and 1.18lb/plant, respectively. In 2020 and 2021 the marketable yield weights of 'Albion' were 1.04lb/plant, and 0.82lb/plant respectively. Even though 'Portola' grown with green mulch had higher marketability (71.90 %) than the black plastic mulch (P< 0.001), the 'Albion' had the highest total fruit marketable percentage ranging between 72 % and 78 % across the treatments.

Experienced harvesters can pick 12 to 15 pounds (about 10 quarts) of strawberries per hour (Kaiser and Ernst, 2017). The fruit yield and marketability data used for the development of the budgets were collected from the HT strawberry research trials conducted at OHREC in 2020 and 2021.

Table 3.2 shows the normalized (per 1000 ft^2) mean yield data values from the 2020 and 2021 trials that were used to determine economic returns from both years. Harvest costs are proportional to the amount of fruit produced in each treatment. The additional cost of using colored mulches is combined with any observed benefits from the treatment to determine a breakeven price. Based on our production model, 1000 ft^2 equates to 167 linear feet of row. There was \$1.60/1000ft^2 difference between black control vs white and black stripe; the same price difference was observed for red and green vs silver mulch. The amount of variable expenses that were attributed to plastic mulch material cost was only 2-8% increase (compared to standard black plastic) of the total variable cost across all treatments. The breakeven price was estimated for each treatment and year based on marketable fruit weight and the summation of the total (variable + fixed + harvest) costs. In comparison to the black control, the silver and black stripe mulch had the highest marketable fruit yield and the lowest breakeven price. In both years, the lowest breakeven price among all the treatments was attained when 'Portola' was grown with black stripe mulch. However, the silver mulch performed similarly in 2020 and only slightly lower in 2021 for 'Portola'. For 'Albion', the lowest breakeven price was observed when the silver mulch was used in both years and the black stripe mulch and white mulch also performed well regarding net revenue. 'Albion' produced with silver mulch had a 30-45% lower breakeven price than the black plastic mulch, whereas 'Portola' grown with black stripe had a 13-17% lower breakeven price than the black plastic mulch.

Strawberry Profitability

Sensitivity analyses were conducted based on market price and percent marketability. Table 3.3 illustrates the annual net revenues when the best-performing plastic mulch was utilized for each of the two cultivars that were tested in the study. In all the growing conditions that were tested, the cropping system was profitable, assuming a selling price of \$2.80/lb. Interestingly, the profit is equivalent to the total production costs (variable and fixed) when the sales price is above $5/lb. across all the treatments. However, the profit equivalent to production cost (variable and fixed cost) can be achieved at the lowest price of $ 3.60/lb. when ‘Albion’ was grown with silver and at $.3.00/lb. when ‘Portola’ was produced with the black stripe plastic mulch.

‘Portola’ grown with the black stripe mulch and ‘Albion’ grown with the silver mulch were more profitable compared to black, and this trend can be seen as prices increase. In 2020, ‘Portola’ grown with black stripe resulted in 30 % more profit than ‘Albion’ grown with silver mulch when the market price was $6/lb. This is likely due to the higher fruit production in 2020 by ‘Portola’ compared to ‘Albion’. When the price goes up from $2.80/lb. to $ 3.00/lb., profitability increased by as much as 20% in ‘Portola’ and 29 % in ‘Albion’. In 2021, ‘Portola’ grown with black stripe produced a lower marketable fruit weight compared to ‘Albion’. Thus, the profitability of the ‘Albion’ plants grown with silver mulch was 1.8 times higher than ‘Portola’ grown with the black stripe mulch at $2.80/lb. Similarly, in 2020, proportional increases in selling price led to an even higher level of profitability. For example, doubling the sales price from $ 2.80/lb. to $5.60/lb. increased profitability by 3.5 times even with lower marketable yields of ‘Portola’ in 2021.

Impact of Percent Marketability on Profitability

In this study, the percent marketability across all the treatments and the two years ranged from 52% to 81%. Therefore, we included a sensitivity analysis with percent marketability ranging from 60% to 90%, which is shown in Table 3.4. This analysis is based on the 2020 total yield weight (lb. /plant) for ‘Portola’ grown with black stripe mulch, since ‘Portola’ had the highest yield and lowest breakeven price in 2020. Even at the lowest selling price ($2.80/lb.), the net revenue at 60% marketability was 2.4 times lower than the net revenue when the fruit were 90% marketable. At a marketability of 70% or higher, the cost of production equals the profit at the lowest price of $2.80/ lb. But at 60% marketability, the profit is equal to the cost of production only when the fruit sold at $3.40/lb. or higher.

With every 10% increase in fruit marketability the average net revenue of $288/1000ft^2$ is achievable with same total yield of 1030 lb. of 'Portola' with black stripe at selling price of $2.80/lb. If fruit marketability increases from 60% to70 %, the overall profitability increased by a maximum of 49%; whereas, increasing fruit marketability from 70% to 90% only increased the overall profitability by a maximum of 33%. As the selling price increases, the difference between the net revenue values across the various project percent marketability categories increases at a faster rate. For example, at a selling price of $2.80, net revenue is increased by $288 when percent marketability increases by 10%. Meanwhile, $618 of net revenue is attained with a 10% improvement in fruit marketability when the selling price was $6.00/lb. Similarly, when higher percent marketability is maintained, the net revenues increase at a faster rate as the selling price increases.

Table 3.1. Estimated annual variable and fixed costs per 1000 ft^2 for plasticulture day-neutral strawberries production in a high tunnel at Olathe, KS.

Months	Production operation [z] (Variable Cost Item)	Labor [y] ($/36000$ft^2$)	Machinery ($/36000$ft^2$) [x]	Materials ($/36000$ft^2$)	Total Cost ($/1000$ft^2$)
January	Plant material	0.00	0.00	344.00	95.56
	Shipping cost	0.00	0.00	58.00	16.11
	Total January costs	0.00	0.00	402.00	111.71
March	Soil bed preparation	37.50	55.00	0.00	25.70
	Pre-plant fertilizer	6 .25	0.00	8.25	4.03
	Laying black Plastic-(4" x100")	17.00	27.50	53.73	27.29
	Assemble drip irrigation	6.25	0.00	20.00	7.29
	Irrigation (x 2)	6.25	2.65	0.00	2.47
	Bare root planting & tools	37.50	15.00	0.56	14.74
	Total March Cost	110.75	100.15	82.54	81.51
April	Irrigation (x8)	25.00	3.65	0.00	7.96
	Weeding and cutting runners	18.75	0.00	00.00	5.21
	Fertigation (x2)	6.25	0.00	16.20	6.24
	Laying Aisle fabric & Staple	56.25			
	used		5.47	40.05	28.27
	Total April costs	106.25	9.12	56.25	47.67
May	Irrigation (x10)	31.25	3.65	0.00	9.69
	Weeding and cutting runners	18.75	0.00	0.00	5.21
	Fertigate	3.00	0.00	8.10	3.08
	Spray BT 0.5 oz. (x2)	6.25	0.00	2.12	2.33
	Diatomaceous earth	12.50	0.00	3.00	4.31
	Total May Costs	71.75	3.65	13.22	24.48
June	Irrigation (x10)	31.25	3.65	0.00	9.74
	Weeding and cutting runners	37.50		0.00	10.42
	(x3)		0.00		
	Pyrethrin 2 flz.	6.25	0.00	9.00	4.24
	Spray BT 0.5 oz.	6.25	0.00	3.00	2.57
	Shade cloth installation	50.00	0.00	170.00	61.11
	Spray BT	12.50	0.00	3.00	4.31
	Total June costs	143.75	3.80	182.45	92.33
July	Irrigation (x12)	37.50	5.20	0.00	11.84
	Weeding and cutting runners	25.00			
	(x2)		0.00	0.00	6.94
	Pyrethrin 2 flz.	6.25	0.00	8.50	4.10
	Spray BT 0.5 oz.(x2)	16.75	0.00	9.77	7.37
	Total July costs	85.50	5.20	18.27	30.27
August	Irrigation (x12times)	37.35	5.20	0.00	11.47
	Weeding and cutting runners	37.35			
	(x3)		0.00	0.00	10.42

	Pyrethrin 2 flz (x2)	12.5	0.00	18.00	8.47
	Spray BT 0.5 oz.	6.25	3.46	3.46	3.66
	Total August costs	94.45	8.26	21.46	34.02
September	Irrigation (x5)	15.60	3.65	0.00	5.35
	Weeding and cutting runners (x3)	37.50	0.00	0.00	10.42
	Pyrethrin 2 flz.	6.25	0.00	9.00	4.24
	Shade cloth removal	9.30	0.00	9.00	5.08
	Spray BT 0.5 oz. (x3)	18.75	0.00	10.00	7.99
	Total September costs	87.40	3.56	28.00	33.21
October	Irrigation (x2)	6.00	1.80	0.00	2.17
	Cleaning/Disposal	50.00	56.60	0.00	29.61
	Total October costs	56.00	58.40	0.00	31.78
Total variable cost (excluding harvest costs)					487.56
HT fixed cost – 1000 ft² x 7 months @0.04/ft² per month (Sydorovych et al., 2013)					280.00
Total cost					767.56

[z]Includes all activities between March-October, excluding harvest and packaging
[y]Labor cost $15.47/hr per adverse wage rate by U.S. Dept. of Labor, 2021
[x]The variable costs for machinery, e.g., tractors, irrigation/water pump and other self-propelled tools, includes the costs of fuel and repair. Six different plastic mulches (black, white, black stripe, silver, red and green) used for both 'Albion' and 'Portola' cultivar in the trial in 2020 and 2021 at Olathe, KS. The production trial was 1800 ft² inside of a 2400 ft² high tunnel that was normalized to per 1000 ft² later

Table 3.2. Yield, harvest cost estimates, and breakeven price for 'Albion' and 'Portola' strawberry cultivar grown with six different plastic mulch in a high tunnel in Olathe, KS.

Albion	**2020**						**2021**					
	Black	White	Black Stripe	Silver	Red	Green	Black	White	Black Stripe	Silver	Red	Green
Yield x												
Total (lb / $1000ft^2$)	425	620	615	745	410	415	450	475	500	565	420	375
Marketable (lb/$1000ft^2$)	305	435	445	525	285	302	360	370	390	455	315	305
Marketability (%)	70.10	69.70	72.40	70.20	69.30	72.80	79.20	77.50	78.00	80.00	74.80	81.10
Harvest costs												
Material ($/$1000ft^2$)	32	46	47	56	30	32	38	39	41	48	33	32
Labor ($/$1000ft^2$)	183	261	267	316	171	182	216	222	234	273	189	183
Total ($/$1000ft^2$)	216	307	315	371	201	214	254	261	276	322	223	216
Mulch ($/$1000ft^2$)	0.00	1.60	1.60	4.90	3.30	3.30	0.00	1.60	1.60	4.90	3.30	3.30
Total Cost ($/$1000ft^2$) ^{z}	983	1,077	1,083	1,143	972	984	1,021	1,031	1,045	1,094	993	986
Break Even Price ($/ lb)	3.13	2.41	**2.44**	**2.18**	3.32	3.17	2.76	2.71	**2.68**	**2.40**	3.07	3.14
Portola	**2020**						**2021**					
	Black	White	Black Stripe	Silver	Red	Green	Black	White	Black Stripe	Silver	Red	Green
Yield x												
Total (lb /$1000ft^2$) ^{Y}	745	735	1030	1140	710	685	480	605	610	675	580	590
Marketable (lb/$1000ft^2$)	465	480	635	630	370	470	335	395	440	430	348	425
Marketability (%)	62.10	61.80	61.60	58.40	52.10	68.70	71.70	67.40	73.30	67.70	58.20	73.20
Harvest costs												

Materials ($/1000ft²)	49	51	67	67	39	50	35	42	47	45	36	45
Labor ($/1000ft²)	279	288	382	379	222	282	201	237	264	258	209	255
Total ($/1000ft²)	329	339	449	445	262	332	237	279	311	304	246	300
Mulch ($/1000ft²)	0.00	$1.60	$1.60	$4.90	$3.30	$3.30	0.00	1.60	1.60	4.90	3.30	3.30
Total Cost ($/1000ft²)	1,135	1,108	1,217	1218	1,032	1,102	1,004	1,048	1,080	1,076	1,067	1,071
Break Even Price ($/lb)	2.33	2.22	**1.92**	**1.93**	2.79	2.27	2.94	2.60	**2.39**	**2.44**	2.84	2.54

[z] Total cost includes variable cost, harvest cost, mulch cost and HT fixed cost @ $0.04/ft² for 7 months
Six different plastic mulch (black, white, black stripe, silver, red and green) used for both 'Albion' and 'Portola' cultivar in the trail in 2020 and 2021 at Olathe, KS. The production trial was 3600 ft² inside of a 4800 ft² high tunnel that was normalized to per 1000 ft² later.
[x] Yields represent mean value of total and marketable yield of 500 plants for 1000 ft² plot in HTs

Table 3.3. Net revenue estimates based on sales price ($2.80 -$6.00) for 'Albion' grown with silver plastic and 'Portola' produced with black strip in a high tunnel in 2020 and 2021 at Olathe, KS.

	Net Revenue [y]			
	Albion- Silver Mulch ($/1000 ft^2) [z]		Portola- Black C. Stripe ($/1000 ft^2)	
Sales Price ($/lb) [z]	2020	2021	2020	2021
2.80	356	155	630	82
3.00	461	246	757	170
3.20	566	337	884	258
3.40	671	428	1,011	346
3.60	776	519	1,138	434
3.80	881	610	1,265	522
4.00[x]	986	701	1,392	610
4.20	1,091	792	1,519	698
4.40	1,196	883	1,646	786
4.60	1,301	974	1,773	874
4.80	1,406	1,065	1,900	962
5.00	1,511	1,156	2,027	1,050
5.20	1,616	1,247	2,154	1,138
5.40	1,721	1,338	2,281	1,226
5.60	1,826	1,429	2,408	1,314
5.80	1,931	1,520	2,535	1,402
6.00	2,036	1,611	2,662	1,490

[z] 'Albion' grown with silver mulch and Portola grown with black center stripe mulch in 24x200 ft^2 in HT normalized into 1000 ft^2 plot at various price range from $2.80-$6.00 for Albion grown with Silver and Portola grown with black stripe calculated based on 2020 marketable yield of in HT estimated at 525lb / 1000 ft^2 and 635 lb/ 1000 ft^2 tunnel, the average sale price of $4/lb taking into variable production costs and harvesting costs is average for both years and seven-month HT fixed cost.

[y] Net revenue estimates do not account for marketing costs, land rental rates, property taxes, or any other fixed costs except for HT cost @ $0.04/ft^2 for 7 months as these may vary depending on grower's preference. $4/lb. was indicated as an average seasonal sale price in the region by growers.

[x] 1 ft = 0.3048 m, $1.00/lb = $2.2046/kg

Table 3.4. Net revenue estimates based on percent marketability for 'Portola' grown with black stripe plastic in a high tunnel at Olathe, KS in 2020.

	Net Revenue Portola – Black Stripe [x y]			
	2020			
Sales Price($/lb) [z]	60% Marketable ($/1000 ft^2)	70%Marketable ($/1000 ft^2)	80%Marketable ($/1000 ft^2)	90% Marketable ($/1000 ft^2)
2.80	582	870	1,159	1,447
3.00	705	1,014	1,323	1,632
3.20	829	1,159	1,488	1,818
3.40	953	1,303	1,653	2,003
3.60	1,076	1,447	1,818	2,189
3.80	1,200	1,591	1,983	2,374
4.00	1,323	1,735	2,147	2,559
4.20	1,447	1,880	2,312	2,745
4.40	1,571	2,024	2,477	2,930
4.60	1,694	2,168	2,642	3,116
4.80	1,818	2,312	2,807	3,301
5.00	1,941	2,456	2,971	3,486
5.20	2,065	2,601	3,136	3,672
5.40	2,189	2,745	3,301	3,857
5.60	2,312	2,889	3,466	4,043
5.80	2,436	3,033	3,631	4,228
6.00	2,559	3,177	3,795	4,413

[z] Portola grown with black center stripe mulch in 24x200 ft in HT normalized into 1000 ft^2 plot at various percentages of marketable yield of Portola calculated based on 2020 average total yield in HT estimated at 618 lb/ 1000 ft^2 tunnel, the average sale price of $4/lb taking into variable production costs and harvesting costs is average for both years and seven-month HT fixed cost.
[y] Net revenue estimates do not account for marketing costs, land rental rates, property taxes, or any other fixed costs except for HT cost @ $0.04/ft^2 for 7 months construction costs as these may vary depending on grower's preference. Black Stripe plastic mulch cost $1.66/ 1000ft^2
[x] 1 ft = 0.3048 m, $1.00/lb = $2.2046/kg

Discussion

The overall objective of this study was to examine the economic feasibility of growing day-neutral strawberries in a HT plasticulture system in Kansas. We were also able to estimate the profitability of using different colored plastic mulches with a wide range of prices and fruit percent marketability. In 2020, the United States produced 1.6 million lb. of strawberries, valued at more than $3.2 billion (NASS, 2020). Locally grown strawberries can vary in profitability, which has been shown to range from $580 to $787 per 1000ft^2 with an average yield of 500-588lb/ 1000ft^2 (Wahl et al., 2014). There are several studies that report the economic benefits of growing crops in HTs as compared to the open field (Blomgren and Frisch, 2007; Eric et al., 2013; Sydorovych et al., 2013). However, it's important to note that this study is reporting the economic costs and benefits of a novel crop (day-neutral strawberries) for high tunnel growers in Kansas and that production of this crop in the open-field is not likely viable. The production budget of this study is critical information for local HT producers who need to estimate production costs in their unique situation based on market conditions, labor supply, age and equipment condition, managerial expertise, and a variety of other factors (Charles et al., 2013).

One of the key components for developing sustainable cropping systems in HTs is the integration of economically viable crops that can be utilized for rotation. (Janke et al., 2017) Adopting crop rotation in HTs can be challenging from an economic perspective, as the rotational crop must compete with tomatoes regarding per ft^2 gross revenue production and overall profitability. The economic value of crop rotation has been cited in various studies, although it is difficult to quantify numerically (Montri and Biernbaum, 2009; Rusch et al., 2013).

Tomatoes (*Solanum lycopersicum*) are one of the most popular and widely grown vegetables in HTs in the US (Carey et al., 2009; Knewtson et al., 2010). At an optimal fruit marketability percentage and premium price point, the profitability of HTs tomatoes reported up to \$3.66/ft^2 (Sydorovych et al., 2013), while our HT's strawberry profitability reached up to \$3.70/ ft^2. Tomatoes grown in high tunnels can generate \$2.30 -2.90/ ft^2 in gross revenue, (Sydorovych et al., 2013) while average strawberry net revenue ranges between \$1.30-2.00/ ft^2 based on a conservative and realistic price. Although tomato production is likely more profitable, it requires higher input costs and may require specialized and/or larger high tunnel structures as compared to strawberries. Jovicich et al. (2005) reported that tomatoes grown in high tunnels have a profitability of \$2.31/ ft^2 while bell peppers can generate gross revenues between \$0.83-\$2.30/ft^2. Cucumber (*Cucumis sativus*), on the other hand generates \$0.38/ ft^2 in profit (Chase and Naeve, 2012). According to our study, the overall profitability of HT strawberry profitability is \$3.70/ ft^2 whereas the HT's tomato profitability is reported up to \$3.66/ft$^{2.}$ These values for net revenue and profitability from different crops indicate that day-neutral strawberries grown with color plastic mulch is a viable candidate for diversifying crop rotations in HT production systems, comparable to solanaceous crops like tomato and bell pepper.

Our results suggest that the higher yield potential of 'Portola' made this cultivar more profitable than 'Albion'. There have been several reports that identify 'Portola' as a high-yielding cultivar compared to 'Albion' (Gude et al., 2018, Richerson et al., 2022). Selecting high-yielding cultivars is an important factor to boost overall profitability and revenue generation. Strawberries marketed predominantly through local direct marketplaces can boost net returns from strawberry production through early and greater yields, therefore the net profit can range from \$1,943.57 to \$15,548.56 per hectare (Maughan et al., 2015). It is difficult to understand how bringing strawberries to market during the "off-season" (summer and fall) will impact the market price. However, it's important to note that earlier harvests can increase the selling price by $1.50/lb, which could boost profits over the typical strawberry season (Maughan et al., 2015). Based on the results of our study and others (Gude et al., 2018; Kaiser and Ernst, 2019) it is evident that selecting higher-yielding cultivars and ensuring standard market price ($3.50 or $4.00) is an important consideration for this production system.

Our study indicated that different colored plastic mulches can cost marginally more than traditional black plastic ($0.04 to $0.07/ ft^2), which was only a 6-8% increase over black plastic in the overall variable cost. However, we observed increases in marketable fruit yield by 40-75%. Therefore, this small increase in the production budget plays an important role to increase the profitability of the system compared to black plastic. HT growers are typically concerned over the extensive labor that is required for HT production, which can contribute up to 50% of a HT production budget (Bruce et al., 2021; Paranjpe, et al., 2004). Therefore, identifying practical technology innovations that increase profitability and do not require more labor are likely advantageous to a grower. An interesting finding is that there were cultivar-specific economic benefits of producing strawberries with silver and black stripe plastic mulch in the HT. In 2020 'Albion' grown with silver mulch and 'Portola' with black stripe had higher profitability which is similar to the findings of Conner et al. (2010).

This study indicates that maintaining at least 70% fruit marketability is important for maintaining overall profitability of this production system. Our sensitivity analysis indicates that when at least 70% fruit marketability is maintained, there was a 100% ROI even at the lowest selling price, which was estimated to be $2.80/lb. When fruit marketability is lower than 70%, growers must maintain a higher selling price (at least $3.10/lb). The net revenue of HT tomatoes can be doubled even with a comparatively lower selling price at $2.40/lb with 65% marketability (Sydorovych et al., 2013), but strawberries can behave similarly in that net revenue doubles if the fruit marketability were able to increase up to 90%. Our results also indicate that a 20¢/ lb. price increase from $2.80 to $ 3.00 per lb can increase profitability 20% to 29%. The sensitivity analysis in this study is based on price and percent marketability interaction enables the growers to understand different revenue scenarios and the importance of improving marketability to achieve higher revenue for long term sustainability of this production system.

As growers integrate day-neutral strawberries into their HT production systems, it will be important to support research that addresses pest and disease management. Little information is currently available for HT strawberries in the summer/fall in the Central US. Over the course of our trials, it is likely that we observed *Phytophthora* root rot, *Verticillium wilt,* and various insect pests including cutworms, ants, aphids, and spider-mites. Despite the various advantages of crop integration and rotation in HTs, many studies demonstrate that shorter nonhost crop intervals result in greater verticillium wilt and poorer strawberry yields (Michuda et al., 2017; Subbarao et al., 2007). In addition, the increased secondary pest pressure may negatively impact the beneficial invertebrates in the HTs (Maughan et al., 2015). The incidence of specific pathogens or pest was outside the scope of this study but would be very useful to growers in the future.

Conclusion

In this study, economic data related to day-neutral strawberry production in HTs, and revenue estimates were presented. To the best of our knowledge, this is the first study to examine the economic viability of using day-neutral cultivars in HTs in the central US and as well as to document the impact of six different types of plastic mulch on net revenue. As growers in the US continue to adopt HT systems for local production, the ability to diversify and develop sustainable crop rotations will be critical. This study provides important input cost information as well as a sensitivity analyses that growers can use to determine their interest in day-neutral strawberry production for HT systems. When compared to other specialty crops like tomato and bell pepper, our data shows that day neutral strawberries are a profitable and high-value commodity with the potential to be used as a rotational crop to boost the diversity and profitability of existing HT systems. Due to higher crop productivity and a relatively small increase in cost, the decision to utilize silver and/or black stripe resulted in higher profitability compared to black plastic. The sensitivity analysis of this study suggests that maintaining high fruit marketability and increased price for out-of-season availability will be critical to maximizing profit. However, the actual costs and returns will vary from grower to grower based on many factors. Thus, growers should use this study as a guide to estimate their individual production, harvesting, and marketing costs based on their own situation. Day-neutral strawberry cultivation in HTs appears to be a profitable enterprise, but growers need to carefully assess the crop's marketability, cultivar selection, and plastic mulch selection, as well as the selling price.

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