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CROP PRODUCTION

Strawberry growth and dry matter partitioning due to fertigation systems

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ABSTRACT. Strawberry cultivation possesses unique features, including the need for high-quality seedlings adapted to the cultivation environment and proper fertigation management. These elements influence plant growth and production. This study evaluated the growth and dry matter partitioning of strawberry plants of the cultivar "Albion" at different seedling ages (0, 14, 28... 196 DAT) using two fertigation methods: open-loop and closed-loop systems. Fifteen evaluations occurred throughout the cultivation cycle, spanning from planting to 196 days after transplanting (DAT), with the study replicated over two consecutive years. We evaluated dry matter partitioning among roots, stems, leaves, senescent leaves, flowers, commercial fruits, and non-commercial fruits. We also measured root volume and length, besides counts of leaves, flowers, and both commercial and non-commercial fruits. Despite no significant differences between fertigation systems for most variables, the closed-loop system shows promise, contingent on proper nutrient solution management. The partitioning analysis revealed that fruits, followed by leaves, were the primary consumers of photoassimilates.

Keywords: *Fragaria* x *ananassa* Duch; fertigation; water; photoassimilates; production.

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Introduction

Strawberry cultivation plays a pivotal role in job creation and revenue for rural producers. Particularly beneficial for small-scale farmers, strawberries provide a favorable return on investment. Global strawberry production has surged in recent decades (FAOSTAT, 2023). In Brazil, the states of Minas Gerais and Rio Grande do Sul are at the forefront, followed closely by São Paulo, Paraná, and Santa Catarina (Intituto Brasileiro de Geográfia e Estatística [IBGE], 2018). Brazilian production is approximately 120,000 tons from 5,278 hectares, involving 6,030 producers, with an average of 0.9 hectares each (Kist, Santos, Beling, Carvalho, & Rudolfo, 2019). Optimal strawberry yields require specific temperature, humidity, and solar radiation conditions combined with water and nutrition (Gonçalves, Vignolo, Antunes, & Reisser Junior, 2016b). Favorable environments maintain nighttime temperatures below 15°C and daytime temperatures not surpassing 30°C (Almeida, 2016; Gonçalves, Picolotto, Cocco, Vignolo, & Antunes, 2016a)

Seedling selection is crucial for strawberry cultivation. Ideal nursery conditions, like cold hours and rainfall, contribute to seedling physiological quality, leading to many nurseries situated in high-altitude regions (Cocco, Gonçalves, Reisser Junior, Marafon, & Antunes, 2016). Although strawberries are perennial, they are often cultivated annually due to fluctuating phytosanitary conditions and yield potentials (Antunes, Cuquel, Zawadneak, Mogor, & Resende, 2014; Cerutti, Santos, Gemeli, Adams, & Pereira, 2018; Thiesen et al., 2018). In substrate cultivation, some farmers have begun using plants for two or three consecutive years, as seedling acquisition can constitute up to 25% of total production costs. Producing healthy and productive domestic seedlings could cut costs compared to imported ones and ensure timely availability (Diel et al., 2018; Dal Picio, Andriolo, Jänisch, Schmitt, & Lerner, 2013; Diel et al., 2017).

Strawberry cultivation in substrates is gaining traction in Brazil. In the country, nutrition occurs through fertigation, predominantly in open-loop systems where excess application drains into greenhouse soil, leading to nutrient loss and potential soil salinity over time (Gonçalves et al., 2016a; Godoi et al., 2009). In contrast, closed-loop systems recirculate the nutrient solution using gutters, enhancing cost-effectiveness and sustainability (Andriolo et al., 2009).

When introducing new cultivation systems, understanding their performance is essential. Evaluating plant growth, especially dry matter accumulation and distribution, helps monitor plant adaptation and identify system-induced variations (Strassburger et al., 2010; Strassburger, Peil, Schwengber, Martins, & Medeiros, 2011). Given the economic significance of strawberries and their increasing cultivation under diverse systems, this research probes the effects of open and closed fertigation systems on their growth and dry matter partitioning.

Material and methods

Location and characterization of the experimental area

The experiments were conducted in the experimental area of the Federal University of Santa Maria, Frederico Westphalen, Rio Grande do Sul State, Brazil, situated at 27°23' S, 53°25' W, and an altitude of 493 m. The mean annual temperature is 19.1°C, ranging from 0 to 38°C, with a cumulative annual rainfall of 2,040 mm. The regional climate is classified as Cfa (humid subtropical) according to the Köppen classification, with precipitation well-distributed throughout the year (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). The study was conducted using a substrate inside a galvanized steel structure measuring 10 m in width by 20 m in length and 3.5 m in ceiling height, covered with a 150 µ polyethylene plastic film. Strawberry seedlings were transplanted into white tubular plastic bags, 150 µ thick, and placed on wooden benches about 0.8 meters above the ground.

Plant material and growing conditions

Strawberry plants (*Fragaria* x *ananassa* Duch.), of the cultivar Albion, originating from bare root seedlings were used. The seedlings were transplanted after pruning their leaves and roots to 5 cm in length. The substrate consisted of a mixture of carbonized rice husks and a commercial substrate, H-Decker®, based on pine bark and vermiculite, in a 2:1 ratio.

Drip irrigation was employed for both irrigation and fertigation, with emitters spaced 0.15 m apart for each evaluated fertigation system. The nutrient solution was based on a formulation recommended by Bortolozzo and Bernardi (2006) and prepared directly in the water tanks. Its electrical conductivity and pH were maintained around 1.5 dS m^{-1} and 6.0, respectively. Every two months, the solution in the closed-cycle fertigation tanks was fully replaced.

The minimum and maximum air temperatures inside the protected environment were recorded during the growing cycle in both years using a thermo-hygrograph, installed 0.8 m above ground level. The average air temperature was calculated as: $Tave = (Tmax + Tmin)/2$, where T*ave* = average temperature, Tmax = maximum temperature, and Tmin = minimum temperature. The plants underwent phytosanitary treatment as per the recommendations for the crop by Bortolozzo and Bernardi (2006). Flowers were removed up to six weeks post-transplanting and stolons were throughout the cycle to ensure optimal photoassimilate distribution in plants.

Experimental design

The study utilized a randomized block design (RBD) in a 2 × 15 factorial scheme, encompassing two fertigation systems (open-loop and closed-loop) and 15 plant ages at 14-day intervals post-transplanting (from 0 to 196 DAT). This amounted to 30 treatments, with four blocks per treatment. The experimental unit comprised two slabs with eight plants each, totaling 16 plants per block. In the first year, the study commenced on June 13, 2017, and concluded on December 27, 2017; in the second year, it spanned from June 18, 2018, to December 31, 2018.

Variables analyzed

The parameters assessed comprised: root length (RL, cm), root volume (RV, mL), root dry matter (RDM, g), stem dry matter (crown + peduncles) (SDM, g), number of leaves (NL), dry matter of leaves (DML, g), leaf area (LA, cm^2), dry matter of senescent leaves (DMSL, g), number of senescent leaves (NSL), number of flowers

(NF), dry matter of flowers (DMF, g), number of commercial fruits (NCF), dry matter of commercial fruits (DMCF, g), number of non-commercial fruits (NNCF), and dry matter of non-commercial fruits (DMNNF, g).

For each evaluation, a plant from every experimental unit was selected, its roots cleaned, and then separated into its constituent parts. At the start of the experiment, specific plants were earmarked for analysis. Any parts harvested during the study, like mature fruits or senescent leaves, were included in the values noted during each plant's collection. The dry matter of the plant parts was determined by drying them in a forced-circulation oven at 45°C until they reached a consistent weight, and then they were weighed on a precision scale. Non-commercial fruits were categorized as fruits with fresh weight below 6 g, deformed fruits, or immature fruits present in the plants at the time of analysis. Leaf area measurements were derived from scanned leaf images processed individually via ImageJ software.

Statistical analysis

Initially, data were checked for homogeneity of variance before undergoing an analysis of variance (ANOVA) to determine treatment impacts and potential interactions. The normality of residuals was assessed using the Shapiro–Wilk test. When ANOVA results were significant, Tukey's test evaluated qualitative factors, and linear regression was applied to quantitative factors. All statistical analyses, conducted with a 5% significance level, employed the ExpDes (Ferreira, Cavalcanti, & Nogueira, 2014), ggplot2 (Wickham, 2016), and metan (Olivoto & Lúcio, 2020) package R software (R Core Team, 2021).

Results

During the first cultivation year, greenhouse average daily air temperatures ranged from 11.6°C to 35.2°C (Figure 1A) and from 11.6°C to 33.4°C in the second year (Figure 1B). Extreme minimum and maximum temperatures for the two years were -2.0°C and 47.2°C, and -0.4°C and 47°C, respectively (Figure 1A and B).

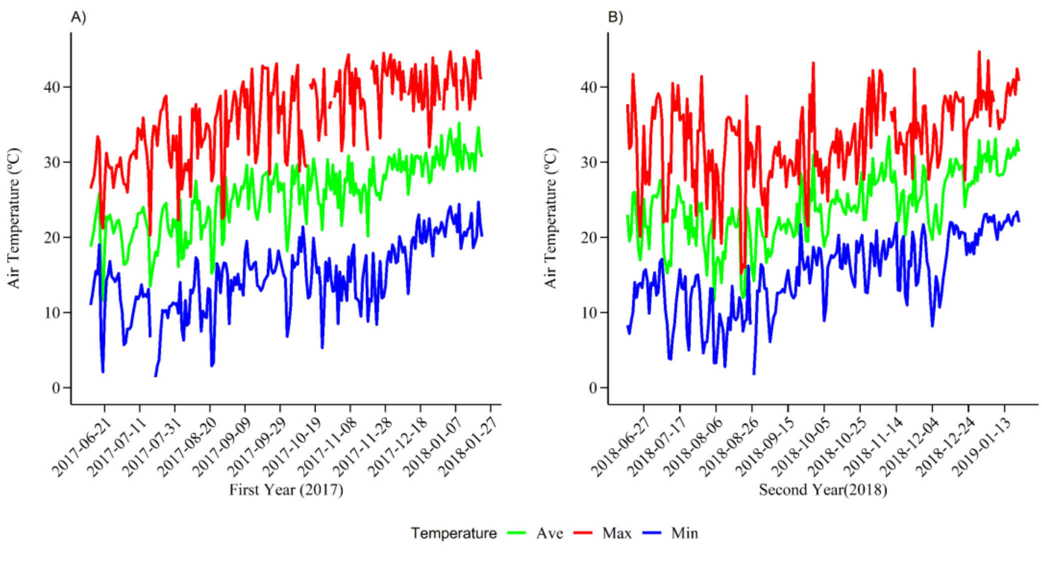

Figure 1. Minimum (Min), average (Ave), and maximum (Max) air temperatures inside the protected environment during the first (2017) (A) and second (2018) (B) year of cultivation of strawberries (cultivar Albion).

In the first cultivation year, the analysis of variance identified a significant interaction between the fertigation system and plant age (DAT) concerning the DMF variable. However, plant age was the only other factor that significantly impacted the other variables. In the second cultivation year, there was a notable interaction between the fertigation system and plant age, specifically affecting the RDM and DMSL variables. Additionally, the fertigation system alone had a significant impact on the DML and LA variables. All variables studied showed a substantial correlation with plant age. At transplanting, the RL variable measured 7 cm and reached a growth peak of approximately 32 cm around 150 DAT (Figure 2A). The RL, RDM, and NL variables demonstrated a cubic growth pattern, initiating rapidly, plateauing briefly, and then growing again to peak at 196 DAT (Figure 2B, C, and E). The SDM and DML variables followed a quadratic growth trajectory; after a slower growth post-transplant, they achieved larger sizes by 196 DAT (Figure 2D and F).

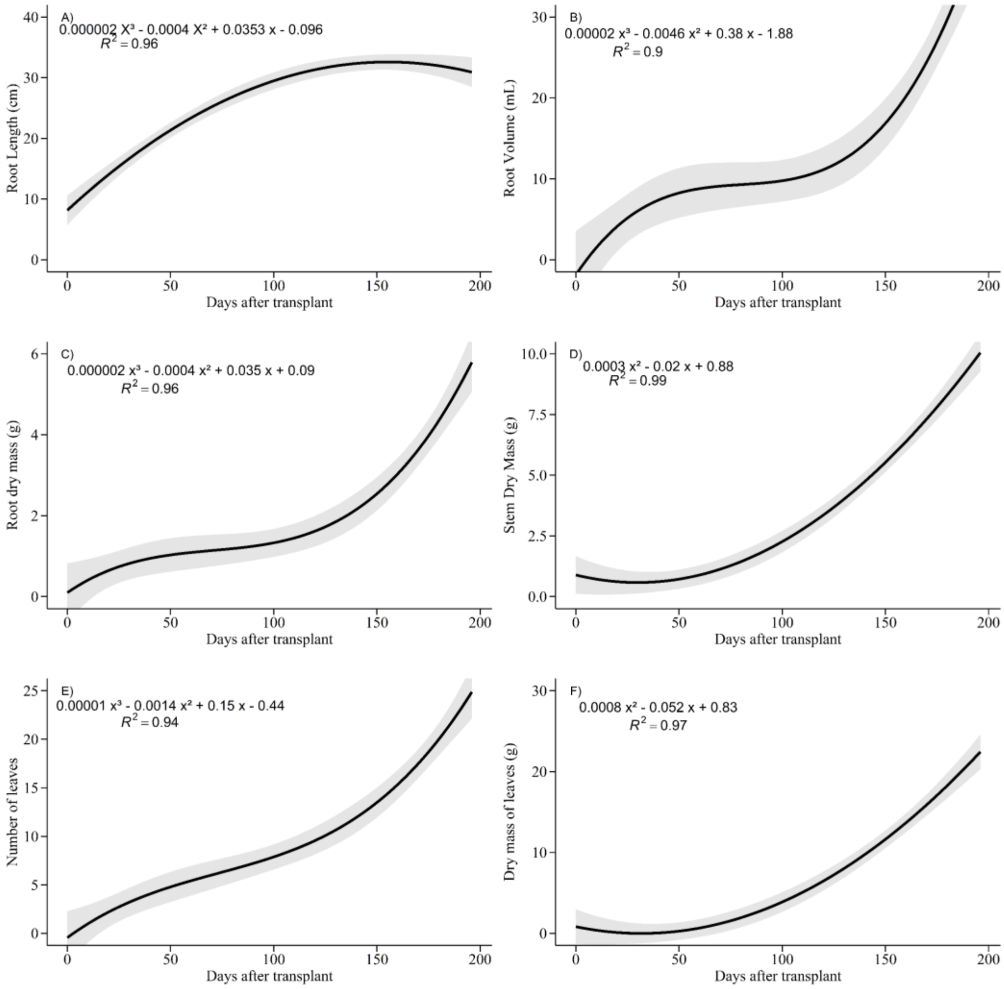

Figure 2. Growth of strawberry plants of the cv. Albion under two irrigation systems (open-loop and closed-loop) at different plant ages (DAT), in the first cultivation year (2017). A) root length, B) root volume, C) root dry matter, D) stem dry matter, E) number of leaves, and F) dry matter of leaves.

The variables LA, DMSL, NSL, NCF, and DMCF exhibited a quadratic growth pattern, starting slowly and accelerating in later evaluations (Figure 3). The NF variable demonstrated a negative quadratic trend, with flower emission dropping significantly by the end of the cycle due to rising temperatures (Figure 3D).

The NNCF and DMNNF variables displayed a quadratic growth curve. As the plants aged, these metrics escalated, peaking towards the end of the cycle (Figure 4A and B). For DMF, the open fertigation system showed a more significant increase than the closed-loop system until around 112 DAT. At that point, the two systems equaled in terms of this variable. Beyond 112 DAT, the DMF in the open-loop system plateaued until its decline at the end of the cycle. In contrast, the closed system saw a reduction in DMF starting from 112 DAT (Figure 4C).

During the subsequent cultivation period, many variables reflected the patterns observed in the first year, but there were notable distinctions. RV and NL variables exhibited linear growth, peaking at 196 DAT (Figure 5A and C). SDM displayed a quadratic response, reaching its peak at 196 DAT. Initially, this variable declined due to stem water loss until the plant stabilized (Figure 5B). The DML, LA, and NSL variables followed a cubic growth pattern. While DML and NSL had a minor dip early on, they peaked at 196 DAT (Figure 5D and F). In contrast, the LA variable peaked around 178 DAT, declining until the end of the cycle (Figure 5E).

The NF peaked near 168 DAT and subsequently decreased towards the end of the cycle, mirroring the trend of DMF (Figure 6A and B). For NCF and DMCF, the production apex occurred at 196 DAT, yielding approximately 30 fruits per plant and a fruit dry matter of 40g per plant, respectively. The first fruits appeared after 50 DAT (Figure 6C and D). NNCF and DMNNF exhibited a quadratic response, culminating at 196 DAT, with an average harvest of around ten non-commercial fruits per plant (Figure 6E and F).

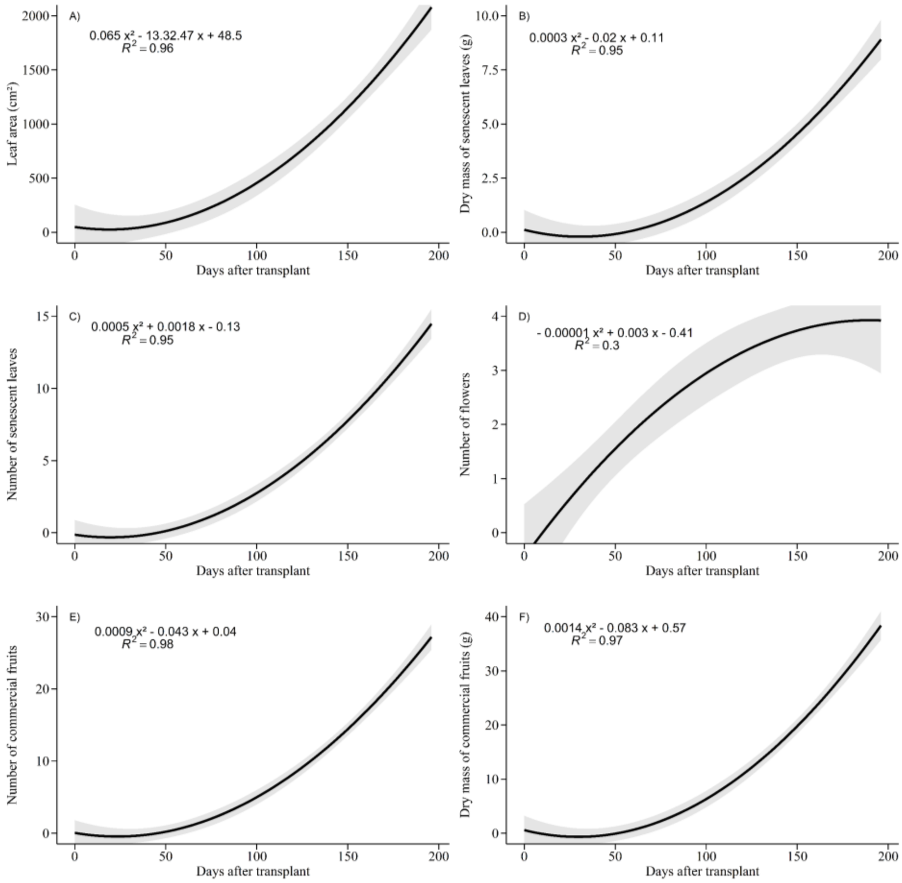

Figure 3. Growth of strawberry plants of the cv. Albion under two irrigation systems (open-loop and closed-loop) at different plant ages (DAT), in the first cultivation year (2017). A) leaf area, B) dry matter of senescent leaves, C) number of leaves, D) number of flowers, E) number of commercial fruits, and F) dry matter of commercial fruits.

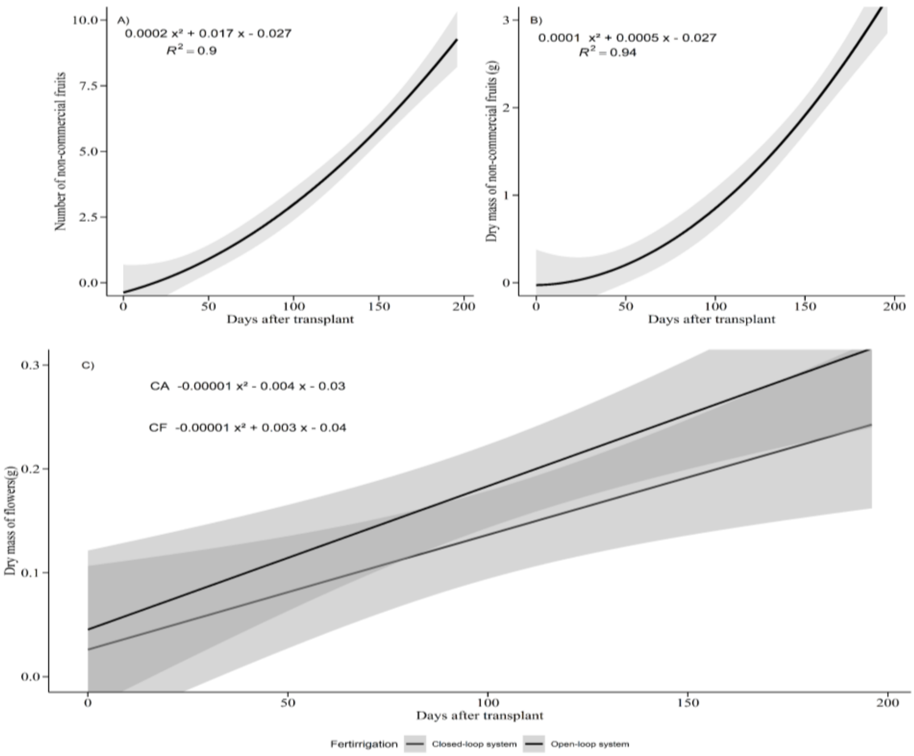

Figure 4. Growth of strawberry plants of the cv. Albion under two irrigation systems (open-loop and closed-loop) at different plant ages (DAT), in the first cultivation year (2017). A) number of non-commercial fruits, B) dry matter of non-commercial fruits, and C) dry matter of flowers.

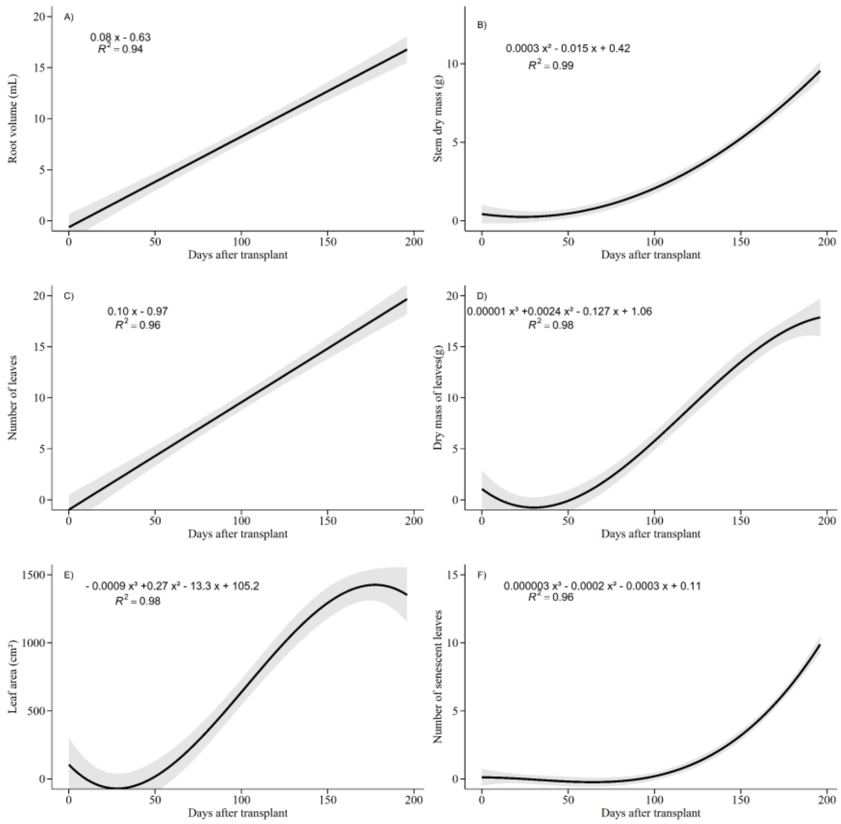

Figure 5. Growth of strawberry plants of the cv. Albion under two irrigation systems (open-loop and closed-loop) at different plant ages (DAT) in the second cultivation year (2018). A) root volume, B) stem dry matter, C) number of leaves, D) dry matter of leaves, E) leaf area, and F) number of senescent leaves.

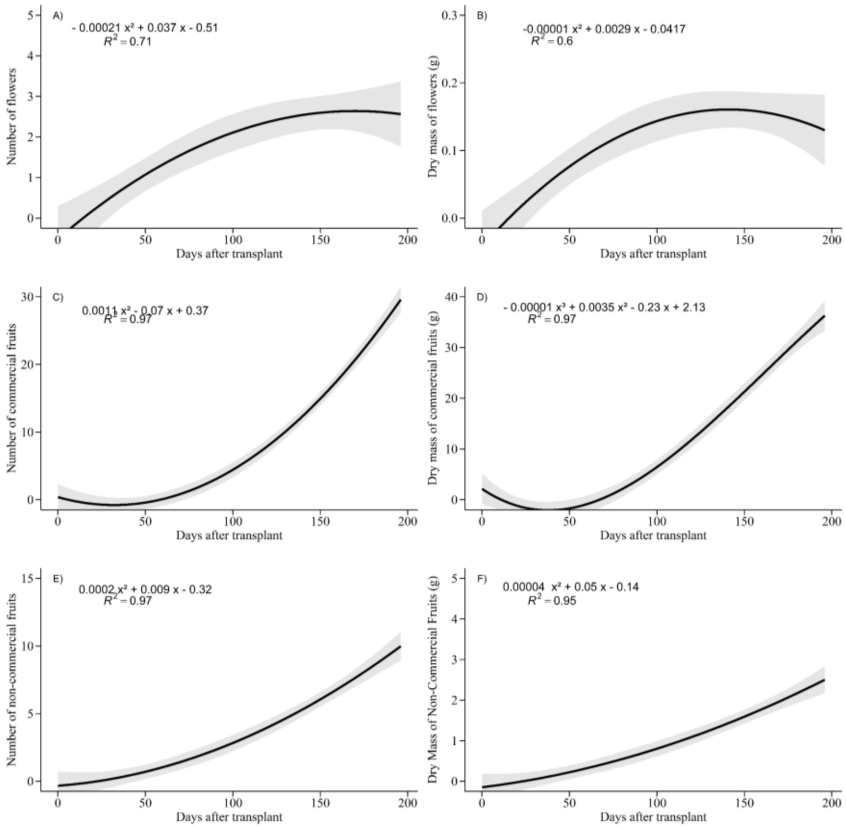

Figure 6. Growth of strawberry plants of the cv. Albion under two irrigation systems (open-loop and closed-loop) at different plant ages (DAT) in the second cultivation year (2018). A) number of flowers, B) dry matter of flowers, C) number of commercial fruits, D) dry matter of commercial fruits, and E) number of non-commercial fruits and dry matter of non-commercial fruits.

For RDM, the closed-cycle fertigation system exhibited faster initial growth than the open-loop system. However, after 98 DAT, the open-loop surpassed it. Both systems reached peak RDM at the end of the cycle, 196 DAT (Figure 7A). Senescent leaves (DMSL) only emerged after 112 DAT in both systems. Subsequently, the open-loop system outperformed the closed-loop, with both reaching their peak at 196 DAT (Figure 7B).

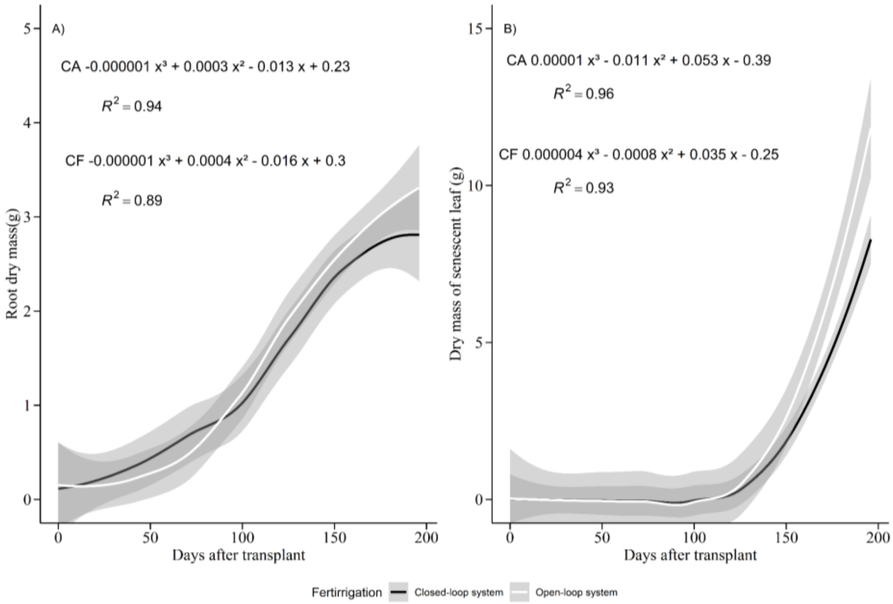

Figure 7. Growth of strawberry plants of the cv. Albion under two irrigation systems (open-loop and closed-loop) at different plant ages (DAT), in the second cultivation year (2018). A) root dry matter, and B) dry matter of senescent leaves.

The only variables significantly influenced by the fertigation system were LA and DML, with the open-loop system outperforming the closed-loop (Table 1). This outcome is likely due to the continuous renewal of fertilizers in the open-loop system, ensuring consistent nutrient composition. In contrast, the closed-loop system's nutrient recirculation may cause some nutrients to concentrate, even though both systems use the same formulation.

Table 1. Leaf area (LA) and dry matter of leaves (DML) of strawberry plants of the cultivar Albion under two irrigation systems and on different days after transplanting in the second cultivation year (2018).

Fertigation system	LA (cm^2)	DML (g)
Open-loop	0.07 a	7.72 a
Closed-loop	0.06 b	6.24 b

*Means followed by the same letter do not differ statistically from each other by Tukey's test at a 5% error probability.

In the first cultivation year, the seedlings, which were transplanted leafless, consisted of roots and stems making up 46.9 and 53.1% of the plant mass, respectively, at the time of transplanting. By 14 DAT, the first leaves emerged. Flowers appeared from 42 DAT, marking the onset of the reproductive phase. By 70 DAT, leaves predominated, making up about 36.3% of the dry matter. Non-commercial fruits were evident by 70 DAT, with commercial fruits following at 80 DAT. The flower count reduced after 168 DAT. By the end of the cycle (196 DAT), the plant composition was 11.8% stem, 6.9% root, 24.8% leaves, 11.1% senescent leaves, 0.3% flowers, 4.1% non-commercial fruits, and 41.1% commercial fruits. Most photoassimilates were allocated to fruits, followed by leaves (Figure 8A).

In the second year, at transplanting, the stem constituted approximately two-thirds of the dry matter (67.2%), with roots making up the remaining third (32.8%). Despite this disparity from the first year, the growth pattern seemed consistent. Leaves emerged at 14 DAT in both years, although more abundantly in the second year. The reproductive phase, marked by flower emission, started at 56 DAT, 14 days later than the previous year. At this point, leaves constituted the bulk of the plant, representing 41.5% of the dry matter. Flower counts began decreasing from 154 DAT. By the end of this cycle (196 DAT), the plant composition was: 12.8% stem, 4% root, 22.5% leaves, 14.1% senescent leaves, 0.1% flowers, 2.1% non-commercial fruits, and 44.5% commercial fruits (Figure 8B).

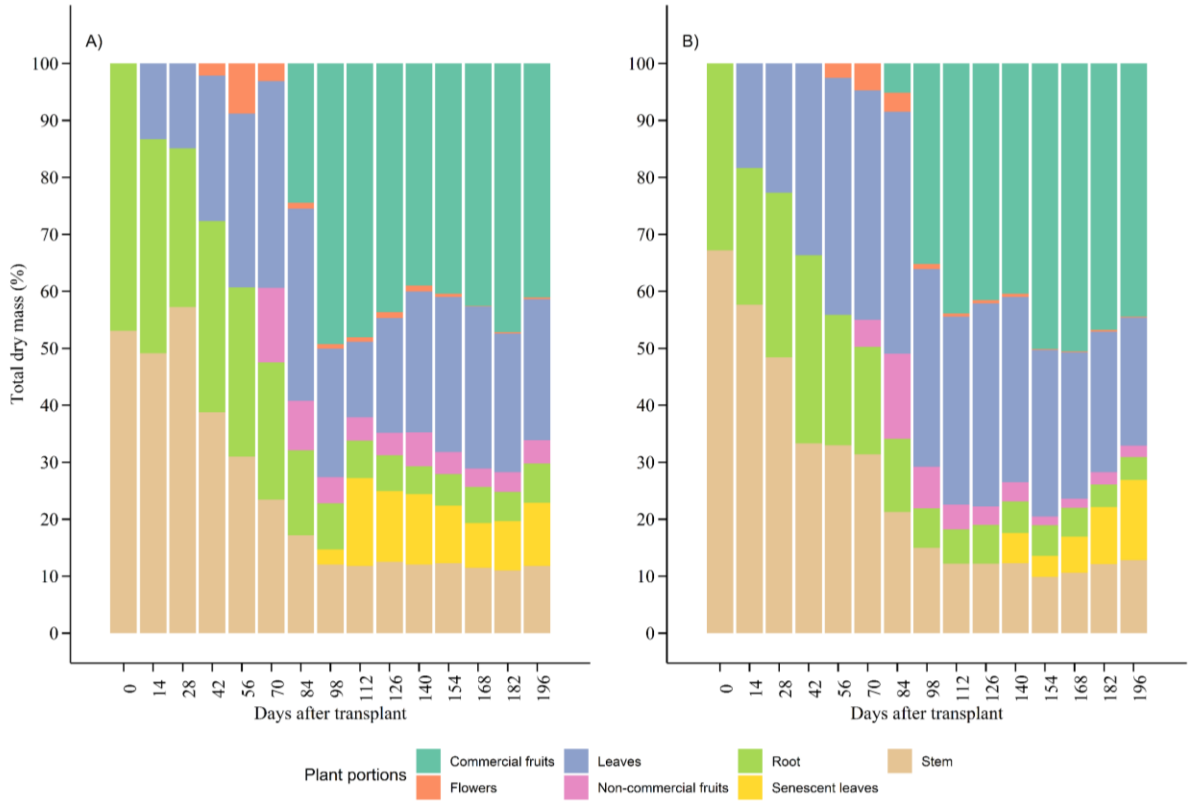

Figure 8. Partitioning of total dry matter into organs of strawberry plants (cv. Albion) under two irrigation systems and on different days after transplanting. A) first year of cultivation (2017) and B) second year of cultivation (2018).

Discussion

Temperatures throughout the experiments varied significantly (Figure 1). Daily temperature range is vital for strawberry cultivation since it stimulates flowering and enhances crop production. However, temperatures should not exceed 35°C. Exceeding this threshold can hinder flowering, halt growth, and diminish fruit production (Cerutti et al., 2018; Gonçalves et al., 2016a; Sønsteby, Solhaug, & Heide, 2016).

Strawberry vegetative growth is dependent on favorable climatic conditions, such as optimal temperature and high radiation levels, which are prevalent in spring and summer. These conditions prompt an increase in leaf number (Franquez, Andriolo, Janisch, & Godoi, 2008). Thiesen et al. (2018) noted that plants originating from high-altitude national seedlings require fewer degree days for leaf emission. Differences in leaf count between cultivation years can be attributed to yearly air temperature variations.

Strawberries thrive across a broad temperature from under 10°C to about 35°C. Ideal conditions for floral induction feature daily minimums around 15°C, while temperatures near 30°C are optimal for vegetative growth and fruit maturation (Gonçalves et al., 2016a). Given the high temperatures observed during this experiment and the plant's developmental stage, we noticed significant dry matter accumulation in leaves and stems starting from 126 DAT.

In both experimental years, root lengths averaged between 30 and 35 cm. Strawberry roots typically concentrate within the upper 30 cm depth due to constant renewal for nutrient absorption (Gonçalves et al., 2016a). Such range may be related to the space available in cultivation slabs, with lengths reaching 60 cm under favorable conditions (Martins, 2009). Secondary roots begin to develop soon after transplanting, a critical phase for effective nutrient absorption. The most significant root growth occurs post-fruiting (Martins, 2009). Cocco et al. (2015b) proposed that a plant's root dry matter correlates with the accumulation in shoot and leaf counts, which can subsequently enhance production.

Senescent leaves began appearing at 98 DAT in the first year and 140 DAT in the second year. This event indicates that leaves can sustain their photosynthetic capacity for extended periods, accumulating photoassimilates in various plant organs. Andriolo (2017) reported that strawberry leaves typically last one to three months, which is shorter than our observed duration. This difference may be attributed to the evolving nature of both the cultivar and cultivation systems.

The results obtained by Andriolo, Bonini, and Boemo (2002) differ from our findings. They recorded a higher stem dry matter with corresponding lower leaf and fruit dry matter within the same post-transplantation window. These results showcase the crop's evolutionary trajectory and the selection of cultivars emphasizing production. The Albion cultivar stands out, adapting well to hotter summers and being non-photoperiodic, allowing year-round production given proper nutrition and sanitation.

Although strawberries require cold periods during seedling formation, excessive cold can be detrimental. Chilling temperatures spur leaf and stolon growth (Cocco, Gonçalves, Picolotto, & Antunes, 2015a), which can reduce fruit yields. Some cultivars have evolved with a lower chilling requirement and can produce well in temperate regions (Franquez et al., 2008). Therefore, the increased dry matter accumulation of fruits in plants from national seedlings suggests that the Albion cultivar has adapted to the climate of southern Brazil during cultivation.

The chosen fertigation systems (open-loop cycle versus closed-loop cycle) had minimal impact on the variables measured because the fertigation strategy ensured adequate nutrient supply. However, the open-loop system might be costlier due to salt wastage, posing environmental concerns like soil salinization (Haj-Amor et al., 2022).

Evaluating the dry matter accumulation of commercial and non-commercial fruits revealed an inverse relationship with root mass, volume, and length. This finding contrasts with that of Cocco et al. (2015a), who observed a direct correlation between seedling root dry matter and early fruit production.

As observed in some of the analyzed variables, plant growth and development variations are typically ascribed to fluctuations in climatic conditions, particularly temperature and radiation. These factors significantly affect strawberry growth (Antunes & Peres, 2013). This experiment aligns with other studies where researchers found disparities between strawberry crops due to seasonal climatic variations, even under protected cultivation (Barros Mainardi & García De Souza, 2015; Martínez, Oliveira, Calvete, & Palencia, 2017).

Plant development and growth are distinct yet complementary processes. For strawberries, development begins with bud bursting into leaves, crowns, and stolons during the vegetative phase or inflorescences for the reproductive stage (Palha, 2005). In commercial farming, the vegetative development commences post-transplantation of the seedling to its permanent site, guided by the apical meristem. This stage is succeeded by cell elongation and differentiation. During the reproductive phase, there is a shift from vegetative to floral meristem (Cocco et al., 2015a). An emphasis on vegetative growth has also been linked to enhanced flowering and fruiting. The data from this study, showcased in Figure 8, indicates that the emergence of vegetative organs was evident from 14 DAT. The growth of organs, such as leaves (Figure 5C and D), remained consistent throughout the cultivation.

Reproductive organ development began from 42 and 56 DAT in the first and second cultivation years (2017 and 2018), respectively. Commercial fruits started emerging from 84 DAT and showed an increasing trend for the rest of the cycle, as corroborated by dry matter accumulation data (Figure 6D). Reproductive development strongly depends on temperature and photoperiod conditions. These conditions are sensed by leaves, setting off a three-stage response. First, floral organs are formed, marked by physical and chemical changes in the buds. This phase is followed by flower differentiation, involving the formation of floral organs and inflorescences. Ultimately, plants reach anthesis, which is when floral organs become externally visible, facilitating pollination and subsequent fruit development (Gonçalves et al., 2016b)

Later evaluations revealed an increased fraction of dry matter partitioning in fruits, underlining that they primarily assimilate the plant's photosynthates. While examining four strawberry cultivars, Strassburger et al. (2011) discerned a comparable pattern in the Albion cultivar. In our study, fruits constituted over 50% of the plant's total dry matter, with leaves being the subsequent significant photoassimilate drain. This study echoes these findings, underscoring the prevailing trend in commercial strawberry farming aimed at maximizing fruit yield.

Conclusion

Both open- and closed-loop fertigation systems yielded comparable results in our evaluations. However, the closed-loop system offers potential advantages due to its effective monitoring and management of the nutrient solution. This benefit ensures optimal nutrient levels for production and facilitates consistent plant growth and development. Dry matter partitioning data revealed that strawberry fruits are the primary drains of photoassimilates, followed by leaves.

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