Chapter

Winter Strawberries Production in Greenhouse Soilless Culture under an Arid Climate – Cultivars, Phenology, Physiology, and Consequent Practices

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Abstract

Fifteen years of research and development aimed at the production of high-quality early-winter strawberries in the Negev desert, are concluded. This goal required synchronization of seasonal yields with the peaks of the markets' demand, November–February. For this purpose, selected infra short-day (ISD) cultivars were used. Rooted plug plants with enhanced capacity of simultaneous fast vegetative growth and fruiting were produced. Production was carried out in greenhouses and various protocols aimed at yield enhancement were tested. Currently, drip-fertigated, eye-level hanging soilless system, with plant density at about 200,000 plants ha^{-1}, combined with biological pest management program, are employed. This system brought about a two-fold increase in yield compared to soil culture (80–100 t ha^{-1}), significantly reduced risks of soil- and air-borne diseases, reduced the use of fungicides, and eased extensive labor demands. However, beyond substantial refinements of practices, a significant proportion, 15–25% of the seasonal high-quality yield, was harvested during the earlier two months with no reduction in the total yield or fruit quality. In this chapter, the state of art in early-winter strawberry production is portrayed, including principles, approaches, and methods that have been used and improved during the project. Additionally, ideas for further possible enhancement are discussed.

Keywords: early winter strawberries, *Fragaria ananassa*, greenhouse, hung soilless systems, infra short day (ISD), Negev desert

1. Introduction

Strawberry (*Fragaria* x *ananassa*) is among the most appreciated fruit species due to its extraordinary appearance, shiny red color, sweet-sour balanced taste, and complex rich aroma. Most of the cultivars belong to the 'June-bearing' group, the floral induction of which is sensitive to short days (SD) and low temperature. In regions of a temperate climate, fruit production takes place during spring and early summer.

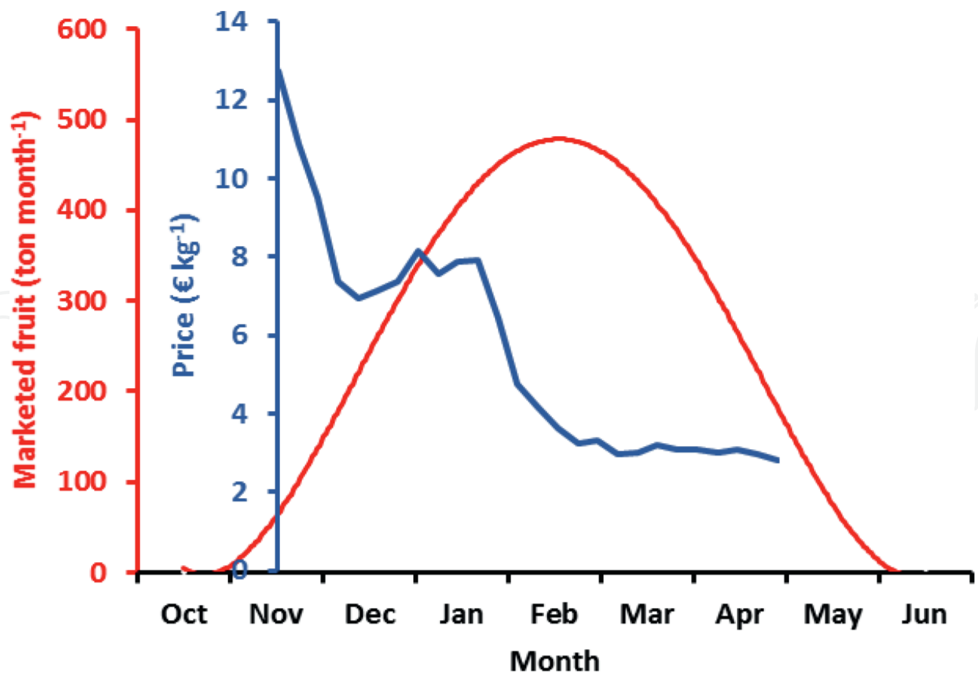

Figure 1.
A typical scenario of the dynamic strawberry marketing season in Israel, referring to produce quantities (red) vs. prices at the farm gate (blue) during mid-November to late April (values represent averages of 10 years of data, provided by the Plant Production & Marketing Board of Israel).

However, substantial demands for 'off-season' strawberries have triggered significant efforts to deliver the fruit as early as possible. Mediterranean climate regions harbor great potential for early season strawberry production; while the photoperiod noticeably changes with the seasons, the winter can be mild enough to allow plant growth. Californian breeding programs of short-day cultivars, and the development of plastic tunnels practices enabled the delivery of strawberry fruit to the markets already in early March.

Nevertheless, the exceptionally high produce prices at the very beginning of the marketing season, as clearly demonstrated in **Figure 1**, have promoted further research and development efforts aiming at strawberry marketing earlier than before. In Israel, during the recent 15 years, high-quality strawberries are available for export and local markets already in mid-November. The initial produce prices are extremely high, about 12 € kg^{-1}; they drop with the increasing production to a high level of 7–8 € kg^{-1} during December–January, and drop again to about 3 € kg^{-1} for the rest of the season, when the production peaks or the quality degrades (**Figure 1**). These achievements are primarily founded on continuous breeding programs that took place since 1980s at ARO (and later on, also by private breeders), and on consistent efforts carried out at regional R&D centers (Darom, Ramat Negev, and Central & Northern Arava) aiming to develop innovative technologies and practices that support, altogether, significantly higher yields, higher and safe fruit quality, and easier labor work. Most of the results have been published in Hebrew in annual reports of each R&D center. In this chapter, we gather the most up-to-date information, describe and discuss the principles and practices that have led to the successful early strawberry production in Israel, and illustrate lines for possible future progress of this culture.

2. Varieties

The modern strawberry, *Fragaria* x *ananassa*, was first found in the 1760s in Versailles gardens, France, via a cross of *Fragaria virginiana* from eastern North America and *Fragaria chiloensis*, which was brought from Chile [1]. Typically to species originated in temperate climate regions, temperature and photoperiod are the most important environmental factors that regulate the transition from vegetative to floral growth in strawberries [2]. Under temperate climate conditions, strawberry plants usually enter a vegetative phase and develop runners during the warmer and longer summer days. With the decreasing temperature and day length during autumn, flower initiation and dormancy are simultaneously induced in the young developing crowns [3, 4]. These young crowns, called daughter plants, are rooted and planted towards spring, develop a foliar canopy and realize their reproductive potential during early summer (June-yielding types). Nevertheless, the modern strawberry harbors substantially broad genetic diversity, including a wide sensitivity ranges to photoperiod or temperature [4–7]. Moreover, individual plants may possess significant plasticity in response to combinations of temperature and photoperiod.

To obtain significant early fruiting, two prerequisites must be fulfilled: early and extensive reproductive induction; and, avoided bud dormancy. The first has been met by breeding within the SD strawberry types. This way, young crowns that are detached from the mother plant on the end of August, when the declining photoperiod is still long (13 h), will continuously exhibit floral induction throughout the young plant establishment from August to October. Bud dormancy in many strawberry cultivars is facultative or considered a quantitative trait; hence, avoiding the conditional dormancy could be gained by breeding, by which genotypes that yield continuously for 7 months from November to May are selected.

Four decades ago, a few Californian varieties, mostly ‘Fresno’, ‘Tioga’, ‘Douglas’ and ‘Tuft’, the harvest of which began in late January, dominated the Israeli market. The breakthrough in obtaining earlier fruiting was accomplished through the establishment of a local (ARO, Israel) breeding program led by Izsak and Izhar [8], in which day neutral (DN) types were hybridized with SD strawberry types, resulted in the release of the first Israeli cultivars ‘Nurit’ and ‘Rachel’ in 1977, and during the 1990s—the commercial cultivars ‘Tamar’, ‘Hadas’, ‘Yael’ and ‘Malach’. All these are very early cropping cultivars patented as infra short-day (ISD) strawberry types [9]. Unlike the Californian short-day types, the Israeli varieties are less sensitive to temperature and can initiate their reproductive phase under the relatively warm and long-day conditions prevailing in Israel during August and September.

Over the last two decades, the ARO breeding program has been renewed in an attempt to enhance the already high commercial value of the previously developed local varieties [10]. The ARO’s in-house germplasm collection has been restored and its genetic base extended with new cultivars from different sources. As a part of this program, approximately 60 specific crosses have been carried out every year, resulting in 6000–10,000 seedlings that have been screened each year under various commercial conditions. While early fruiting is indeed compulsory for strawberry breeding programs in Israel, many other traits are carefully overlooked in order to develop cultivars bearing premium quality fruits suited for local and European markets. These traits include: plants with open canopies and long fruit pedicels for easier harvest; attractive fruit appearance with a bright red color, medium to large size, and a conical or heart shape; firm texture with extended shelf life; and, desired sweet/sour balance with excellent aromatic flavor. On top of these, tolerance to Powdery mildew (*Sphaerotheca macularis*) and anthracnose fruit rot (*Colletotrichum acutatum*), two major diseases affecting plant vigor and postharvest quality gains an increasing attention as a strategic means to overcome the challenge. Since there are no simple selectable markers for the resistance against these diseases, at least one resistant parent is always combined in the basic crosses, and clones with good field tolerance to those diseases are selected.

The attempts made by the ARO strawberry breeding programs, as well as simultaneous efforts made by the private sector, have yielded a growing number of qualified cultivars, all of which bearing early fruiting and desired quality trait (**Figure 2**). Among

Figure 2.
Representative cultivars released by the Israeli ARO strawberry breeding program for commercial use in the recent decade.

cultivars released at about 2005, 'Tamir' was selected as a vigorous, early-ripening, and highly productive cultivar, with orange-red, large, pretty, and very sweet fruit. 'Tamir' also does very well in hanging, soil-less growing systems. 'Barak' has a medium growth habit and long fruit stalks, which make it easier to harvest. It also exhibits good resistance to powdery mildew and mites. Its fruits are uniform in size, medium, and have an attractive appearance, with a strong red color, excellent flavor and aroma, and extended shelf-life. 'Yasmin' is one of the earliest Israeli cultivars, the harvest of which can begin by mid-November. It has a moderate-sized canopy and continuous waves of flowering and fruiting. The fruits are large to medium-sized, bright red, juicy and sweet. Yasmin's sibling-cultivar Shani has a large, erect growth habit. It produces relatively high annual yields of firm, large, juicy fruit. The cultivars Gili, Matan and Rocky were released in 2015; these three are characterized by a medium-size canopy bearing firm, large, red, and sweet fruits with an extended shelf-life. In addition, Rocky displays good tolerance to powdery mildew and high and stable yields along the season.

The most recently released (2020) cultivars of the ARO breeding program are Tammuz and Lavi (**Figure 2**); both cultivars exhibit vigorous growth habits, long fruit pedicels, early fruiting (late-November to early-December), high yield, continuous and stable production course, and above all, highly attractive fruit appearance, sweetness (Brix 8.5-10) and rich flavor, firm texture, and long shelf life. In addition, private breeders released competitive commercial strawberry cultivars based on the same genetic origin, among which 'Aya1', 'Daniel', 'Peles', 'Shaked', and 'Rotemi' (Yosef's Farm, Israel), and 'Yuval', 'Orly', 'Noa' and '6050' (Fertiseeds Ltd., Israel) have been evaluated and are available for growers.

Along with the continuing challenge to enhance early yielding cultivars, several points require special attention. Most of the breeding programs, including at ARO, are carried out under the traditional low-tunnels cultivation rather than on the advanced hanging soilless culture technology (which will be discussed below). Certain cultivar traits may significantly differ fitting to either set of conditions. For instance, while a vigorous plant canopy is undesired in the traditional cultivation, as it decreases the access for pollinating insects, promotes foliar diseases and makes harvest less efficient, this trait is considered an advantage in the hung soilless system, the fruits and vegetative canopy of which are separated, as it leads to higher yields and to better fruit quality. Concurrently, early strawberry plants grown under greenhouse conditions are more exposed to powdery mildew infection and red spider mites, and hence, more resistant cultivars are preferred [11]. In addition, considerable year-to-year variations in the weather conditions, particularly during the critical autumn season, and the impatient strawberry industry, both prevent the desired adequate long-term evaluation of new cultivars. On the one hand, the rapid rotation among the leading cultivars makes it difficult to point to uniquely promising and stable ones. On the other hand, simultaneously growing several sound cultivars in a season appears a good strategy to deduct failures in the performance of one cultivar or another and accomplish an acceptable operation over a whole season.

3. Propagation

An appropriate preparation of plug plants is essential to obtain significantly early yields. The leading principles include the establishment of a massive and functioning root system, adequate foliage, and an early reproductive readiness. The high investments in the growing system (as described later) and the consequent expectation for high outputs require high accuracy and uniformity levels in preparing the plug plants.

3.1 Mother plants

The mother plant material is derived from apical meristems that are first grown in tissue culture; the emerging seedlings are then tested for virus infection while grown in an insect-free core greenhouse. In a second stage, all the 'core plants' undergo a tight supervision by the breeders to guarantee its genetic identity and cleanliness, in a "true to type" process, before further propagated in a foundation greenhouse to produce clean mother plants. After 2–3 months of cold treatment, the bare-rooted mother plants are rooted in 7–7–8 cm pots and then distributed among farmers for the last propagation step. For propagation, plugged mother plants are transferred in late April to a hung coir channel system at a planting density of a single mother plant per 1 m row length, at height of 2 m above ground, and at 1.5 m distance between rows, thus providing maximum light interception and aeration throughout the propagation process. Coconut fibers packed in 1 m long growbags are the preferred growth medium. The mother plants are planted on top of the growbag and after a short rooting period, they start producing runners. Crowning joints of the runners are planted, while still attached to the mother plant, in empty holes between mother plants along the growbags. After rooting, these buds produce secondary runners that fall as curtains on both sides of the hung growbags. On early September, 100–150 daughter plants per meter-row, depending on the cultivar, are selected and retrieved from these secondary runners. During the propagation period, water is supplied at 4–6 mm day^{-1} using 1.6 l h^{-1} emitters, five emitters per 1 m dripline length. The irrigation water is of a high quality (desalinated water), fortified with a liquid composite NPK fertilizer Mor 4:2.5:6 (ICL, Israel) plus calcium and magnesium at 1 and 0.5%, respectively, and at a fertilizer concentration of 60–120 ppm N. Fertigation is operated four times a day, which can be raised up to 6 pulses a day under heat wave events.

3.2 Daughter plants

To provide stable temperature and moisture conditions for the root primordia, selected stolons carrying daughter plants are immersed in water and cleaned from auxiliary runners and sick leaves. Cuttings are then planted on moist Zohar-6 mixture (Tuff Agricultural Cooperative Society Ltd., Merom Golan, Israel) containing fertilizers. Rooting takes place in plastic trays of 77 conical cells, 2.5”-deep (50 ml). The trays are placed on tables under net tunnels that reduce ambient radiation by 50%. During the rooting process, which lasts about 21 days, both the irrigation frequency and the shading regime are reduced gradually. Low capacity (7.5 l h^{-1}) (CoolNet Foggers™ Netafim, Israel) provide the moisture required for a successful rooting process. The initial fogging intensity is gradually reduced from 48 pulses per day (2 min per pulse) during the first 3 days, to 6 pulses per day at the end of the rooting phase. This procedure is essential for adequate seedling hardening. Nutrient supply, for supporting a well-established root system and canopy, is carried out daily from the second week of the rooting phase applying a liquid composite NPK (6:6:6) Shefer fertilizer (ICL, Israel) at 60 ppm N.

3.3 Transplantation

After about 21 days, typically toward the end of September, the root system fully occupies the conical cells, the canopy comprises a few healthy leaves, and the plug plants are ready for transplantation into the final soilless growth system. However, in case of forecasted heat wave events, it is recommended to keep the seedlings under cool shaded nursery conditions for a longer time and delay the transplantation. The target growbags are carefully prepared: the condensed coir, which serves as the growth medium, is soaked in water to regain maximal volume, washed from excess salts, and recharged with fertilizer. Upon planting, plug plants with roots and growth medium are transferred from the trays and plugged into the new growbag sockets, positioned in a 45 degree angle to maximize canopy spread. This procedure of plug plants preparation is principal for successful transplantation as it minimizes stresses associated with former practices involved with plant uprooting and re-rooting, thus saving the precious time required for recuperation; using the plug plant method, the seedling continues growing with no interruption, with significantly better chances to enhance early production.

3.4 Floral induction

The concrete ability of well-established strawberry plants to produce considerably early fruit yield depends on the intensity of the floral induction of its crowns' primordia at the earliest stage of development possible. Most of the strawberry cultivars used in Israel for early fruiting are of an ISD origin, which potentially provides floral induction once leaves are exposed to shortening photoperiods of 13 h and below. Nevertheless, temperature is a dominant and not less important determinant of floral induction. High temperatures usually support vegetative vigor in the expense of initial reproductive processes, and *vice versa*. Low temperature, and particularly low night temperature, seem to have a crucial significance promoting the onset of flowering and, furthermore, on the subsequent floral induction of the auxiliary crowns, thus enabling a continuous bloom and fruit production during winter [12].

The response of strawberry cultivars to chilling conditions was extensively studied and significant progress has been made in elucidating the genetic factors and molecular mechanisms underlying its complex flowering responses (for a review see, [13]. However, most of the experiments in Israel that examined the effects of stable low temperature treatment were implemented in cold rooms and failed to produce consistent results. Presumably, the physiological impacts of the circadian rhythm of light and temperature, including seasonal effects on this regime, may be more important than the absolute temperatures alone [14–16]. Light must be adequately supplied during the chilling treatment to avoid carbon deficiency and etiolation. The circadian temperature rhythm is required to support sufficient carbon assimilation during the day under relatively high temperature, as well as its translocation and allocation during the lower night temperature. In Israel, where the autumn nights are cool while the days are still warm enough, both floral induction and carbon supply are favored. Consequently, arid locations at relatively high altitudes are advantageous for the production and establishment of daughter plants, since the cooler nights enhance floral induction and earlier fruit production.

Nevertheless, among the ISD cultivars, the relationships between floral induction and the temperature regime during the seedling establishment phase is yet obscure, due to two major reasons: (1) the substantially fluctuating temperature regime during September–October in Israel; and (2) the rapid rotation of commercial strawberry cultivars. Unequivocally, gaining a precise insight into a cultivar's response to temperature would require 2–3 years of investigation under phytotron conditions that provide various predetermined temperature and photoperiod combinations. In the absence of this kind of research, we conducted a meta-analysis of the early marketable

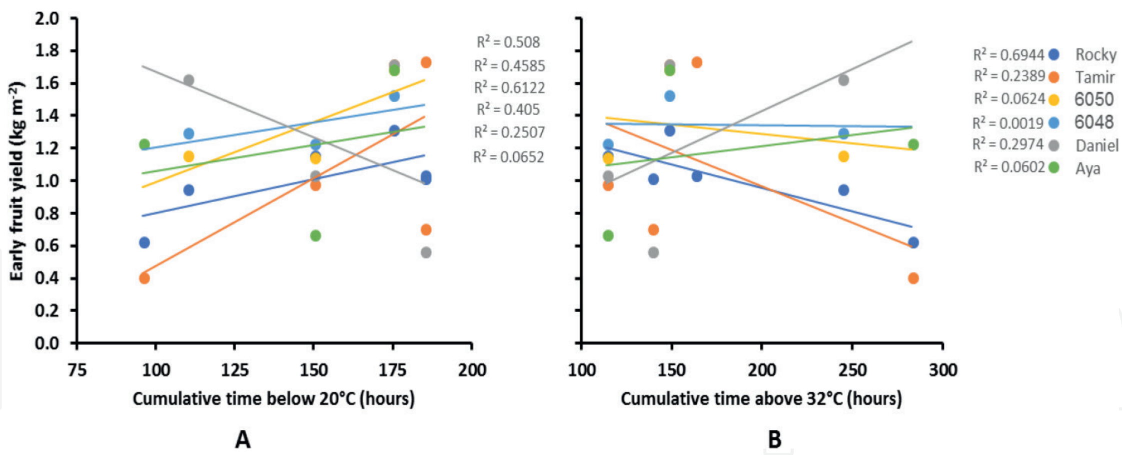

Figure 3.
Meta-analyses of the relationships between early yield (during November–December) and the ambient cumulative time under cool (hours below 20°C; A) or warm (hours above 32°C; B) during seedlings establishment in August–September of the corresponding years (2013–2021, Ramat Negev).

yield (November–December) of six commercial cultivars *vs*. the cumulative time under warm (hours above 32°C) or under cool (hours below 20°C) during plug plants establishment (August–September) in the corresponding years (**Figure 3**).

We assumed that greater cumulative cool hours would promote higher early yields, and that the accumulation of warm hours would delay fruit production. Although the expected response to cool temperature could be noticed, it substantially differed between cultivars (**Figure 3A**); only two cultivars (Tamir and 6050) exhibited a significant response, three cultivars responded positively but mildly, whereas one cultivar (Daniel) displayed a clear opposite response. The expected negative response of the early yields to cumulative high temperatures was visible only for Tamir and Rocky, but cultivars Aya1, 6048, and 6050 were unaffected, while 'Daniel', again, exhibited a clear positive response (**Figure 3B**). This rough analysis indicates an extensive variability in the sensitivity or responsiveness of the floral induction to temperature among the Israeli ISD cultivars. Further research is required in order to provide better matching of cultivars to specific climatic conditions.

4. Soilless culture technologies

4.1 Plant density

Out-of-season strawberry cultivation requires considerable investments in shelter from typical winter weather patterns and events, such as rain, hail and limiting low temperature. To compensate with these expenses, the crop productivity must be significantly boosted. A major means to achieve this goal is to substantially increase plant density.

In the traditional soil-cultured strawberry, plant density ranges from eight to nine plants m^{-2}. Within this range, plant density is determined by cultivar characteristics; however, the boundaries of this range are defined by aboveground inter-plant space considerations, such as light interception and mutual shading, and by the space necessary for technical operation (spray, harvest, etc.). In fact, in soil-grown strawberry, like in other cover crops, the canopy volume tends to be rather bi-dimensional, with the upper foliage layer receiving most of the light while shading the lower layers.

This canopy structure escalates the risks of plant diseases due to poor ventilation and proximity to the soil.

The transition of strawberry cultivation from soil to soilless cultures have significantly mitigated these constraints. Shifting strawberry cultivation to the three-dimensional space provides significantly higher plant density, enhanced light interception, and better aeration to larger canopy parts for longer time periods. As a result, crop productivity is expected to substantially rise, and the probability and severity of diseases - to decline.

Different approaches and technologies of soilless culture have been developed and examined in strawberries for decades, since the 1970s [17]. In this chapter, we describe the current perception and the recent design of strawberry soilless culture in southern Israel. It should be stated, however, that the technology is consistently 'under construction', as further enhancement is steadily sought.

4.2 Eye-level hung crop

The traditional cultivation of soil-grown strawberry is a labor-intensive crop, as fruit harvest requires daily-long hours of bending. Thus, lifting the strawberry culture from the ground closer to the workers' hand-reach brings significant ergonomic advantages easing harvest and other farming activities, which may appeal seasonal workers. One way to do so is placing the growth media containers on fixed shelves along the row, a method which requires an additional costly construction. An alternative solution, broadly accepted in Israel, is the eye-level hung system, in which the growth media containers are hung along the row using the existing greenhouse construction plus some accessory cables. This way, the system height is more versatile and can be adjusted once in a while to the average workers' height. Additionally, the ground below remains free or can be used for a secondary shade crop. Another advantage is the relatively flexible distance between rows; while a distance of 65 cm was found optimal for light interception, it can be temporarily and locally modified to facilitate ad-hoc workers' convenience. The hanging system should be designed to generate the uninterrupted slope (2.5%) required to guarantee a satiated water drainage. Therefore, the system height is about 1.9 m at the beginning of a 20 m long row, and ends at about 1.4 m aboveground.

4.3 System design

Designing the soilless culture system must obey several principal prerequisites, as follows: adequate rhizosphere space; minimal weight; rigid structure; efficient drainage; and, optimal plant positioning. In addition, the growth medium properties must be light (low self-weight when dry), chemically neutral and stable, well-aerated with adequate water retention and rapidly drained. These principles ensure optimum canopy and root development and function, provide crop uniformity, and prevent technical failures, all of which are essential for high and stable crop performance throughout the growing season.

The soilless system described here is comprised of two major elements: a rigid plastic support gutter (carrier), and a growbag—coir (compact coconut fibers) wrapped by a plastic sleeve. The gutter profile is designed in a wide U shape (11 × 5 cm), with a special mid-bottom drainage duct (**Figure 4A**). The upper edges of the vertical walls form a narrow wing; holes drilled every 1 m serve for hanging the gutter on cables attached to the greenhouse structure (**Figure 4B**). The gutters are supplied in 5 or 6 m long units that are attached (using special adaptors) in a slope

Figure 4.
Descriptive pictures of the hung soilless strawberry culture. A: Gutter system profile; B: growbags and drip line.

(~2.5%) to allow the continuous flow of the drainage water. The growbag packages, 1 m long each, are perforated in the bottom side to allow drainage, while two holes in the upper side, one at each longitude edge, allow the insertion of the drip irrigation pipeline through the package and above the coir throughout the row (**Figure 4A**). On delivery, the coir medium is dry, compressed, and a bit hydrophobic. For priming, the growbags are soaked in water until fully swelled, mount well above the gutter's walls, and the growth medium completely fills the growbag. As a result, the growbag profile gets a trapezoid shape. Eleven or 13 planting holes per meter are located in a zigzag manner on both sloping sides of the growbag (**Figure 4B**).

This plant positioning in the space generates a density of 170,000–200,000, compared to 60,000–80,000 plants ha^{-1} in field-grown strawberries. Furthermore, the fruit quality is enhanced due to the improved environmental conditions surrounding the plant canopy and fruit, including better light interception, reduced humidity, and a significant reduction in saprophytic diseases such as botrytis and aspergillus.

4.4 Growth media

The suitability of various growth media for hung soilless strawberry culture was thoroughly evaluated during the late 1990s [17–19]. Among these were peat from Germany, perlite, coir, and coir mixed with polystyrene foam flakes (30%). As no significant differences in crop performance, yield, and fruit quality were observed between the growth media, the coir medium was preferred due to its lower cost and convenient packaging. In addition, during the recent years, coir quality has been greatly improved, containing more homogeneous fine fibers and less salts. It should be noted that while other growth media can be more easily reused for several growing seasons, the careful disinfection procedure required is costly and labor demanding. Undoubtedly, the recycling of the growth media, including the growbags or not, remains an important challenge from both environmental and economic aspects.

5. Climate

5.1 Solar radiation

In Israel, only 500 km from north to south, the cumulative solar irradiation reaching the atmosphere during a given day do not vary among locations, but it significantly fluctuates during the annual cycle. However, due to differences in overcast, the ground-reaching solar radiation substantially increases from north to south, as well as with the distance from the Mediterranean Sea. These differences are demonstrated in **Figure 5** by means of monthly cumulative solar radiation records of 19 years (1999–2017) from three research centers, located at: 1. the northwestern coastal Negev (Besor); 2. Negev Highlands (Ramat Negev); and, 3. Rift Valley, Arava (Paran). During the critical winter months (November–February), the amounts of ground-reaching solar radiation are 7–19% greater at Ramat Negev, and 15–40% greater at Paran, compared to the northern coastal region of Besor center (**Figure 5**). Apparently, these differences provide some advantage to southern regions. Yet, the temperature regime might restrict this advantage.

5.2 Temperature regimes

The parameter of mean daily temperature might be misleading, as it hides a lot of important information about the actual temperature regimes. For example, during most of the season (from July to April), the mean daily temperature at Ramat Negev and Besor is quite similar, with slightly lower winter values at Ramat Negev. From November to late February, Paran values also merge with those of the other two regions (**Figure 6**). However, the extremum temperature means reveal significant differences between the three regions. Unequivocally, mean RN minimum temperatures are the lowest throughout the season, while Besor is the warmest during winter,

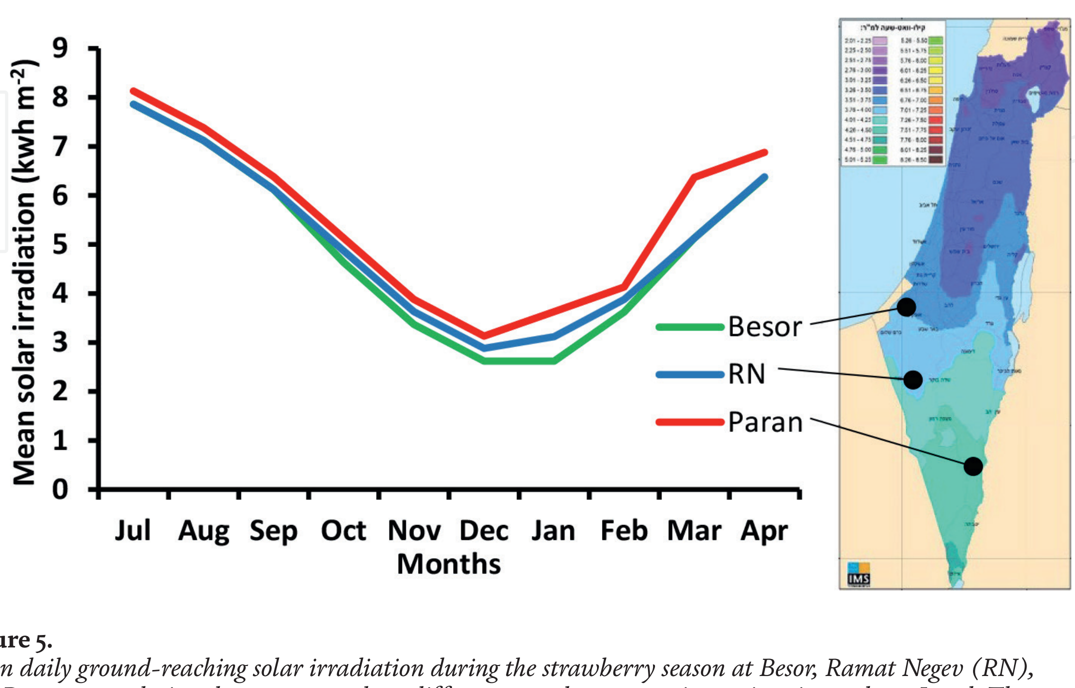

Figure 5.
Mean daily ground-reaching solar irradiation during the strawberry season at Besor, Ramat Negev (RN), and Paran research sites that represent three different strawberry-growing regions in southern Israel. The map indicates differences in ground-reaching irradiance in February. Data and map were extracted from solar radiation Atlas [20], expressing means of 19 years (1999–2017).

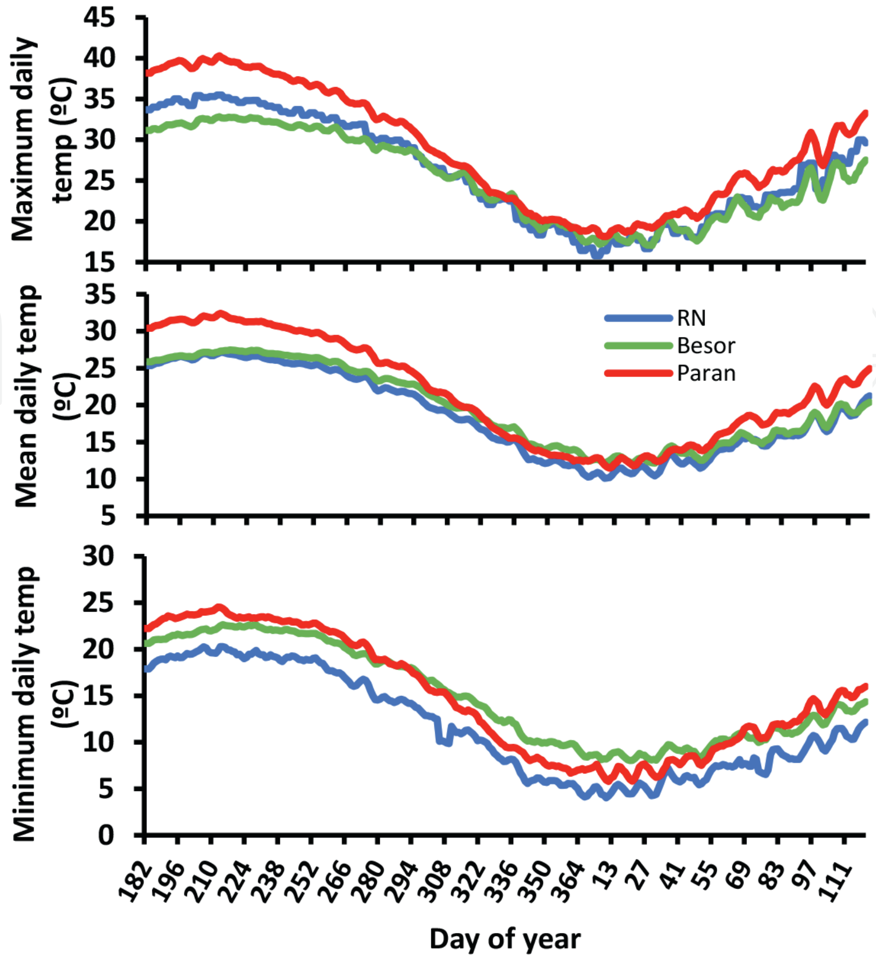

Figure 6.
Temperature regime during the strawberry season, from launching propagation on 1 July (DOY 182) until the end of the harvest period on 30 April (DOY 120) at the northwest Negev (Besor), Ramat Negev (RN), and the Arava Valley (Paran). Data present means of maximum, mean, and minimum daily temperature over years 2010–2021, using official meteorological stations.

and Paran is the warmest during fall and spring (**Figure 6**). Paran displays the highest mean maximum temperatures throughout the season, but from mid-November to late January, they are quite similar to those in the other two regions. During summer and early spring, Ramat Negev is warmer than Besor, but during December–January, daily maxima at Ramat Negev are the lowest (**Figure 6**).

The differences in solar radiation and temperature regimes introduce opportunities, as well as certain limitations for strawberry cultivation in each region. Relatively low temperature during summer and early fall enhance floral induction in most of the cultivars. Therefore, propagation and plug plants preparation are advantageous at the cooler Ramat Negev. Planting can take place first at Ramat Negev, as early as at early September, with the advantage of earlier harvest. However, low night temperatures often restrict plant development and fruiting during late December and January. The optimum planting time at the northern coastal Negev (Besor) would be late September, with the advantage of more stable mid-season (January–February) cropping due to the milder winter temperature. In the Arava Valley (Paran), the strawberry season is pretty much confined to late December to February; with optimal temperature and favorable solar radiation both plant and fruit development are enhanced, and fruit quality (Brix) is excellent. Nevertheless, the rapidly increasing temperature does not permit season extension there, whereas most of the yield of the two other regions is produced during March and April. The climate differences between the three regions may open opportunities for cooperation, exploiting the relative advantages of each region while covering possible gaps in production, altogether generating a complete and complementary strawberry marketing season from November until April. Thus, propagation and production of highly productive plug plants can take place at Ramat Negev for the three regions, whereas the production season can be allocated to Besor and Ramat Negev for the early- and late-season, and Besor and Arava Valley for the mid-season marketing.

6. Fertigation

Principally, soilless crop cultivation is highly susceptible to fluctuations in water availability due to the restricted rhizosphere volume and the risk of rapid salinization processes. In contrast, this technology easily permits collection and reuse of the drainage water. Irrigation water quantity varies from 3 to 6 mm day^{-1}, depending on the current daily weather and evapo-transpiration conditions. The electric conductivity (EC) of the drainage water is carefully monitored, as it is a good indicator for the maintenance of an optimum drainage coefficient of about 50%; a drainage EC increment above a certain predetermined threshold above the irrigation water EC indicates the occurrence of salinization and a need to raise the daily irrigation and the drainage rates, and *vice versa*. To avoid transient water shortage during the day, the daily amount is supplied through three to four pulses. Drip lines, with 1.6 l h^{-1} emitters every 20 cm allocate the irrigation water along the growbags, and the coir medium provides the hydraulic conductivity required for uniform water distribution among plants.

Strawberries are highly sensitive to salinity. Yield depletion occurs already at EC of 1 dS m^{-1}, with a yield decrease rate of 33% per every further unit of EC increase [21, 22]. Chloride ions are the major salinity component causing damage [23], suggesting not to exceed irrigation water EC of 1.2 dS m^{-1} and 1% Cl of the leaf dry matter. Therefore, when growing strawberries in warm arid climates, the highest water quality, as well as the lowest EC possible are recommended. Following a few failures with various mixtures of local brackish and fresh water, we exclusively use desalinated water at 0.5 dS m^{-1}. However, in recycling hydroponic systems using greater water rates, where the risk of salinization is reduced higher EC levels may be considered [24, 25].

The alkalinity of the desalinated water used for irrigation is relatively high (pH 7–8), above the optimum pH for strawberry. Alkaline growth media restrict the absorption of essential micronutrients (e.g., Fe, Mn, Zn, and Cu), resulting in vegetative and reproductive growth retardance and poor yield and quality [26]. Earlier attempts to resolve this problem included the use of high-NH_4^+ fertilizers; however, the combination of those with occasional high temperature was followed by gradual plant deterioration, which was related to a cascade of rapid sugar depletion and anoxia during NH_4^+ metabolism in the roots [27]. This was overcome using a micronutrient-fortified composite liquid fertilizer with sulfuric acid to adjust for the desired pH. In the recent years, we apply commercial liquid composite fertilizer comprised of 4:2.5:6+6 (N:P:K) with a N–NO_3^-:N–NH_4^+ ratio of 9:1, fortified with 600, 300, 150, 22, and 16 mg kg^{-1} of Fe, Mn, Zn, Cu, and Mo, respectively, plus Ca and Mg at 2% and 1%, respectively. Fertilizer concentration varies from 60 to 150 ppm of N, adjusted to plant size and crop stage. The fertilizer is applied through the irrigation system (fertigation) constantly in every irrigation pulse and provides a stable pH at the desired range of 6–7.

In order to save water and fertilizer and reduce environmental consequences of the drainage water, considerable attempts have been made to recycle the irrigation water. Nevertheless, obtaining this goal requires a careful Nano-filtration of the water to avoid the spread of diseases, as well as continuous monitoring and adjustment of water quality and nutrient concentration and composition. The technological challenge and the subsequent costs did not justify the benefits, so far. Therefore, the drainage water are monitored, collected, and utilized to irrigate other crops, nearby, thus increasing greater use efficiency.

7. Pollination

Flowers of commercial strawberry cultivars are hermaphrodite and self-fertile. However, self-pollination through gravity and wind is often partial since the pollen might drop on many, but not necessarily all of the pistils [28, 29]. The fertilized ovules, through auxin release, promote receptacle development and formation of fleshy tissue [30]. However, non-fertilized ovules fail to develop, resulting in fruit deformations that raise the proportion of non-marketable produce [31]. In addition, there is a relationship between the number of fertilized ovules (achenes) and berry weight [30, 32]. Insects, mostly honeybees (*Apis mellifera* L.) serve as complementary pollinators of strawberry [33–35]. Nonetheless, beehives in the recent years have been facing the severe worldwide problem of the colony collapse disorder [36], which has significantly decreased the beehives availability for pollination, and consequently brought about a dramatic rise of the rental prices [37]. Additionally, honey bees foraging is temperature-limited [38, 39] and hence, pollination performance sharply declines under high day temperature during fall, as well as under low winter temperatures. Indeed, greenhouse strawberry crops often suffer from inadequate flower fertilization, so alternative insect pollinators that replace or act together with honeybees seemed reasonable.

Bumble bees (*Bombus terrestris* L.) have several attributes that are beneficial for pollination [40, 41]. Therefore, bumble bees have been introduced and have successfully replaced honey bees as pollinators of greenhouse vegetable [41] and orchard crops [38, 42–44]. Today, *B. terrestris*' colonies are a "ready-made shelf product", easily

Figure 7.
A bumble foraging on a strawberry flower. (Photograph by O. Guy.)

suitable for marketing and transport to any given greenhouse or habitat [41]. The efficiency of bumble bees as a greenhouse-strawberry pollinator was found comparable to that of honey bees [45, 46]. In greenhouse-strawberries in Israel, *B. terrestris* displays considerable advantages compared to honeybees, particularly in respect of foraging under harsh weather conditions (**Figure** 7).

8. Plant protection

Alongside the expanding export to Europe during late 1990s, the approach to plant protection issues has drastically shifted from massive use in pesticides to biologically based integrated pest management. For this purpose, specific beneficial insects such as wasps and predator mites against strawberry pests make chemical use against pests almost unnecessary.

The mostly common pest in greenhouses-grown strawberry is the red spider mite (*Tetranychus urticae*) that feeds from chloroplasts in the leaves, leaving typical yellowish signs. At high infestation levels, leaves and whole plants are severely damaged and fruit production declines. Although red spider mite is the main pest throughout the growing season, its population substantially declines during cold periods. Therefore, the risk of red spider mite infestation of winter strawberries occurs mainly during crop establishment in October-November or during March-April, and is subject to weather fluctuations. To date, red spider mites are effectively treated using the predator mite *Phytoseiulus persimilis* (Bio-Bee, Israel). These predatory mites are applied at the beginning of the season, when it is still warm, and a balance is reached between the pest and the predator populations. As long as this balance is preserved, no pesticides are needed. However, once disrupted (e.g., in incidents of hot and dry weather), the balance must be re-established using a pesticide spray.

More recently, infestation by Castor thrips (*Scirtothrips dorsalis*) has been increasingly observed. This pest causes blackening of main leaf veins and petioles and to growth retardation. Such infestation may be acute mainly during autumn, when high temperatures and humidity stimulate pest population and, if not treated timely and appropriately using Abamectin or Spinosad, the damage to the young seedlings might be quite severe.

Strawberries are susceptible to a wide range of plant diseases. The hung growbags culture, which provides enhanced aeration and light interception for the canopy, reduces risks of canopy diseases related to high air humidity or long-lasting dew. Strawberry gray mold (*Botrytis*), a well-known disease under cold and moist conditions, hardly occurs on fruit hanging in the air. In a similar way, anthracnose (mainly *C. acutatum*), which often spread under warm and humid conditions when grown on plastic-covered soils, rarely strikes the hung strawberry culture. In contrast, powdery mildew (*S. macularis*), which harms greenhouse crops primarily in the fall, requires careful attention. Practically, susceptible cultivars, such as 'Tamir', are gradually withdrawn from the lists of cultivars recommended to farmers. Avoiding contaminated young plug plants is of primary importance. Under conditions of warm and dry days followed by cool and humid nights, powdery mildew can be efficiently prevented using sulfur vaporizers during the night. In case of disease outbreak, mild chemical sprays that are even permissible for use according to the organic standard are quite effective.

Soil-borne diseases are extremely rare in the hung growbag technology, particularly when propagation is carried out according the methods described above. Among soil diseases, *Macrophomina phaseolina* has recently become a threat endangering increasing areas of various crop species, including soil-grown strawberries [47, 48]. This pathogen might be introduced to a hung strawberry greenhouse only through contaminated plug plants, which must be carefully avoided. So far, no chemicals were found adequately effective against *Macrophomina* and hence, in case it does occur, an early removal of the infected growbags should easily solve the problem.

Nevertheless, the main and long-term strategy is breeding for disease-resistant cultivars. Alongside the approach of minimum use of chemicals and no plant growth regulators, this crop protection strategy supports high yields of high quality off-season strawberries.

9. Source-sink relations

The term source-sink relations points to the balance between supplying plant organs and receiving ones in respect to any kind of an essential resource, such as water, nutrients, carbohydrates, or other secondary metabolites. Strawberry plants are simple and small, lacking organs or tissues specialized in reserve accumulation, such as tuber, trunk or others. Therefore, source-sink relations in the strawberry plant are fragile; when demands exceed supply, a competition between sink organs would immediately occur, with crucial consequences on further plant development, including fruit yield and quality [49–51].

The case of out-of-season, early yielding strawberries, is particularly interesting in respect of the carbohydrate balance. Naturally, under their original temperate climate, young strawberry plants develop a considerable vegetative biomass during the early spring, which would adequately support the carbohydrate requirements of the emerging reproductive phase. Nevertheless, when strawberry seedlings are manipulated to early fruit bearing, the carbohydrate balance might be extremely brittle. While possibly adequate to successfully support initial reproductive development (flower bud differentiation, initiation, and even fruit growth and development), the foliar biomass existing at that stage might be too small to reinforce further plant development. The typically declining temperature and the descending light availability during autumn both limit carbon assimilation, and hence, further restrict plant growth. In extreme cases, crop development and production might be restrained for a long period. Under less extreme situations, the fruit yield might considerably fluctuate over time with the alternating vegetative and reproductive flushes, with negative consequences on the marketing.

The strawberry growing season of 2020–2021 at Ramat Negev provides an example of the interactions between the temperature regime and the current fruit yield, fruit size, and TSS during the season (**Figure 8**). Compared to the temperature means of the recent decade (**Figure 6**), November 2020 was considerably cold, particularly at night (**Figure 8A**). However, the rest of the winter (December–January) was consistently warmer than the average of the former decade, with average maximum and minimum temperatures above 20°C and 7°C, respectively (**Figures 6** and **8A**). In contrast, February and March 2021 were quite normal. The relatively cold November repressed fruit growth and ripening, giving rise to lower early yielding in the five cultivars examined. Significant differences between cultivars occurred during December, with 'Aya' and 'Daniel' displaying two peaks while the other three cultivars exhibited moderate to low yields. In January, 'Rocky' and '415' emerged to yield, while 'Aya', 'Daniel' and '6050' produced low fruit yield. From February and later on, all five cultivars showed increasing yield levels that followed the rising but fluctuating temperature (**Figure 8A** and **B**).

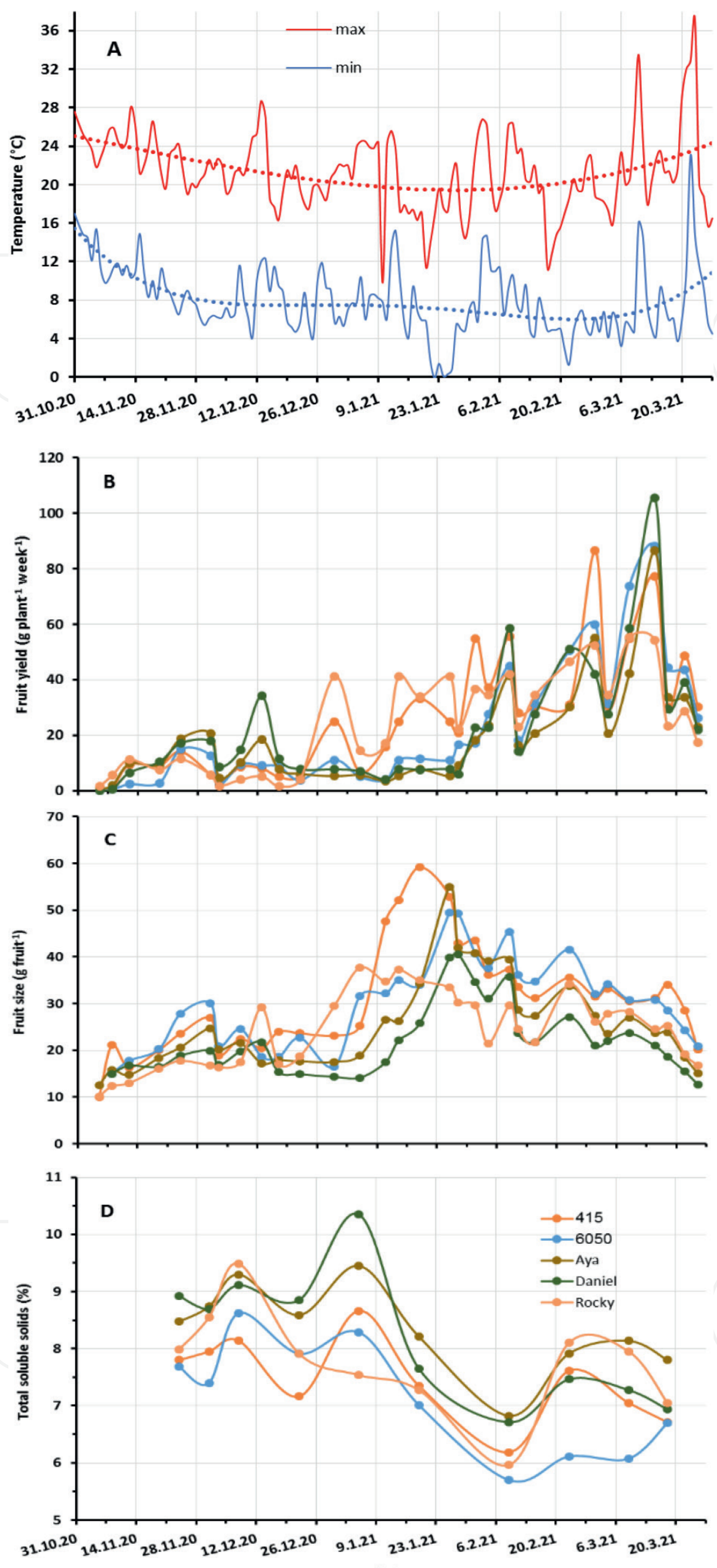

Figure 8.
Yield parameters of five early-yielding strawberry cultivars during the 2020–2021 season at Ramat Negev, Israel. Daily maximum and minimum temperatures from 31 October 2020 until 27 March 2021 (A); weekly fruit yield (B); mean fruit size (C); the average concentration of total soluble solids in the fruit (D).

Fruit size (**Figure 8C**) was relatively small until late December, ranging from 15 to 30 g per fruit. It steadily increased during January, and then gradually declined until the end of the season. Beyond being a varietal trait, fruit size negatively corresponds with the number of fruit per plant. Thus, fruit size is suppressed at the beginning of the fruiting season by the large number of fruit relative to the current plant canopy size. During January, fruit size peaked with the depletion in the number of fruit, however, it decreased again when plants' productivity was restored from February and later on.

Fruit TSS (**Figure 8d**) negatively reflected the changes in fruit yield (**Figure 8b**) during the season, but also expressed the current plant capacity. Thus, TSS was quite high until late December, as long as the fruit yield was low; it surged at the beginning of January as a result of a relatively long period of low yield *vs*. increased plant canopy and capacity, but then sharply declined in response to the rising fruit size and, later on, fruit yield. At the end of the season, TSS was partially restored with the warming weather and increasing plant capacity. Unfortunately, the frequency of TSS measurements did not allow a direct analysis of its relationships with other yield parameters (**Figure 8**).

There are several possible practices that might assist avoiding imbalanced source-sink relations. The most critical one is planting well-established seedlings that already have significantly developed root system, and a considerable number of healthy leaves. Suitable cultivars should display a good balance between extensive vigor and adequate tendency to reproductive development; excessive vigor or ample reproductive potential should be avoided. Heating [52] and additional artificial light [53] can be considered when necessary and economically feasible. In addition, a temporary application of fortified nitrogen nutrition, especially in the beginning of the season before night temperatures drop, was found to support the vegetative growth, thus increasing the leaves/fruit ratio (data not shown).

Recent research efforts have opened deep insight into mechanisms governing sink-source relations and carbohydrate translocation in strawberry [54, 55]. Nonetheless, the effects of leaf canopy manipulations may vary considerably between cultivars, production systems, and with varying time and duration of application [51]. Consequently, recurrent efforts will be needed to fit an appropriate solution to each combination of cultivar, climate, and growing system.

10. Concluding remarks

Substantial research and development efforts have been made in southern Israel during the recent two decades aiming at early winter production of strawberries. An inter-disciplinary augmentation of cultivar selection, refined propagation methods, highly-intensified cultivation technologies, enhanced pollination, and sheltered growing conditions has brought about to a consistently high proportion (15–25%) of very early production (November–December) of high-quality produce, followed by a considerable yield proportion during January and February, without any yield reduction during the main production season of March and April (**Figure 9**). However, in order to further increase the proportion of the early winter yield, and to mitigate undesired yield fluctuations during the winter, more research is required, focusing on the following challenges:

1. Thorough examination of candidate cultivars for early winter fruiting, including particular study of their floral induction response to temperature.

2. Enhancement of floral induction during plug plants establishment using controlled temperature at the growth medium and in the vicinity of the crowning zone, according to cultivars' chilling requirements.

Figure 9.
Heavy yields in the mid of the fruiting season Hung strawberry culture. Photograph by Nir Dai.

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