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Review

Table-Grape Cultivation in Soil-Less Systems: A Review

Antonino Pisciotta *, Ettore Barone * and Rosario Di Lorenzo

Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, 11, 90128 Palermo, Italy; rosario.dilorenzo@unipa.it

* Correspondence: antonino.pisciotta@unipa.it (A.P.); ettore.barone@unipa.it (E.B.); Tel.: +39-091-23861217 (A.P.); +39-091-23861212 (E.B.)

Abstract: Table grape (*Vitis vinifera* L.) is considered to be one of the most popular fruit crops in the world. Italy is the leading table-grape producer in the EU and is the main European exporting country. However, to stay competitive, new solutions and perspectives, including varietal renovation, are now needed in addition to the already well-established Italian table-grape production lines consisting of conventional open-field cultivation and greenhouse cultivation. One of these new perspectives is represented by the development of table-grape soil-less cultivation systems (TGSC) under greenhouse. In fact, TGSC systems are alleged to offer many advantages in terms of the advancement of berry maturity, extreme varietal flexibility, easier manipulation of the vegetative–reproductive cycle, higher yields of high quality extra-seasonal production, higher sustainability for reduced pesticides application, and higher use efficiency of water and fertilizers than conventional (soil-grown) cultivation. They can be also useful for overcoming soil- and rootstock-related problems. In this review, the opportunities offered by the recently developed table-grape soil-less cultivation systems are thoroughly examined and updated to the latest experimental and application findings of the sector's research activity. A special emphasis is given to the evolution of the applied technical solutions, varietal choice, and environmental conditions for the aims of table-grape soil-less cultivation.

Keywords: table grape; soil-less cultivation; double-cropping viticulture system; Sicily; growth-cycle manipulation

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1. Introduction

Table grape is one of the major temperate fruits worldwide with an annual production of about 27 MT. In the last 20 years, this sector has shown positive trends in terms of production (+70%), consumption (+73%), and international trade (+50%) [1,2]. In the ranking of producing countries, India (7%), Turkey (7%), Iran (6.3%), Egypt (5.6%), Uzbekistan (4.4%), and Italy (4.1%) rank well below China (35.2%) but above the USA (3.7%), Brazil (3%), and Chile (2.6%) [3].

Italy, with more than 1.1 MT/year of table grape, is the leading table-grape producer in the EU and the main European exporting country, both in terms of volume and value, primarily to Germany, France, Poland, and other EU countries that intercept about 90% of the Italian table-grape export. In 2017, the value of the Italian table-grape exports, just after apple exports, amounted to EUR 752 million and a volume of 494,000 t (i.e., about 40% of the total production), with a variation of +5.2% and +2.9%, respectively, compared with 2016. Table grapes are produced commercially in about 46,000 ha distributed throughout several Italian regions, with an absolute major concentration (≈90%) mainly south of the 42° parallel in Apulia and Sicily, which represent about 65 and 25% of the total domestic production, respectively [4,5].

The Italian commercial production calendar covers a very long period of more than 7 months (last ten days of May–December), with a restricted number of cultivars: 'Italia' (~40%) and 'Victoria' (15%), followed by 'Red Globe' and 'Black Magic', and a limited but increasing number of seedless cultivars ('Sugraone', 'Crimson Seedless', 'Regal Seedless', and even more new released cultivars such as 'Allison', or 'Arra® group', etc.). In the rest of the world, only Peru and Chile have a similar extension of the production calendar (October–November to March–April).

Despite its prominent commercial position, the Italian table-grape industry is now entering into a phase of stagnation. Old and new issues are emerging, such as excessive costs of hand labor, low prices of productions, and high competition exerted by both new emerging producing countries and traditional ones. Indeed, currently, the table-grape sector is a perfect example of what globalization represents and implies [6]. Together, traditional and new producing countries of both hemispheres, thanks to the improved transportation technology and post-harvest storage, cover the global demand and consumption of this product throughout the year, a growing partial overlap of supply at the end and the beginning of each hemisphere's harvest season. The world table-grape marketing period is opened in January by the South African production, closely followed by India, Chile, and Egypt and later by Italy, Spain, and Greece. It is closed by Brazil and Peru, and then again by Italy and South Africa, which is increasing its exports exponentially in the December market window, with many overlaps along the year. Nowadays, off-season table-grape production coming into the European market from the southern hemisphere during the first semester of the year has exceeded that of the traditional producing countries [7]. Additionally, new producing northern African countries, such as Algeria and Tunisia, with high potential for the precociousness of their products, are rapidly emerging [8]. In any case, there is no production at all from the Mediterranean producing countries in the period January–April, which in turn represents an interesting transfer window and an extraordinary market opportunity.

As a whole, this situation is determining increasingly evident conditions of commercial competition and is potentially leading to ever more restricted profit margins for those areas with higher production costs, such as the Italian ones. Together, technical and varietal innovation is unanimously considered the key factor to allow Italy to maintain its leading position on the European and global markets [9]. With respect to the varietal aspects, the scarce incidence of the seedless-type cultivars on the Italian entire table-grape varietal asset, until recently about 20% [10], even if with a growing trend [11], has long been recognized as one of the main weak points of the sector, together with the insufficient degree of renovation of the existing plantations [1]. On the other hand, technical innovations are needed to meet the increasing demand for sustainable, organic, or biodynamic productions and, in any case, to extend the product availability along the harvest season [12]. To stay competitive, new solutions and perspectives are therefore needed with reference, and in addition, to the already well-established Italian table-grape production lines consisting of conventional open-field cultivation and greenhouse cultivation to anticipate or to delay the harvest [13]. The incorporation in recent decades of berries and fruit tree crops, including table grape, among the species grown in protected cultivation has been recognized as one of the most notable aspects of an innovation trend in protected cultivation in the Mediterranean environments [14].

In this context, guaranteeing the necessary varietal renovation and flexibility according to market requests and allowing a significant extension of the harvest period are the most effective tools for increasing the sector's competitiveness in the global market while ensuring a reasonable profit margin for the producers.

In this review, the opportunities offered by the recently developed table-grape soil-less cultivation system (TGSC) to meet some of the problems raised so far is extensively examined and updated to the latest experimental and application findings of the sector's research activity.

The Rationale for the Soil-Less Table-Grape System Cultivation (TGSC)

The possibility of growing vines in containers has long attracted the attention of horticulturists. At the beginning of the last century an Italian agronomist reported that: '*the cultivation of vines in pots, as well as provide pleasure and satisfaction, may be advantageous* *because it often gives amazing results for quantity, quality, and beauty of the product'* [15]. On the other hand, there is some historical evidence of ancient usage of container grown plants from the Egyptian age to the Renaissance age [16,17].

However, it is only recently that soil-less cultivation has been developed as an innovative commercial system for table-grape viticulture for suitable precocious mild-winter areas of southern Italy [18]. This substrate-based system differs from hydroponic culture, which in turn excludes any solid media [19] and consists essentially of own-rooted *Vitis vinifera* L. scion cuttings grown either on inert or organic substrates in pots (4–10 L) under unheated greenhouses that are located in warm areas well suited for early production. A table-grape soil-less cultivation system has been proposed for taking advantage of the further advancement of berry maturity than conventional (soil-grown) greenhouse cultivation, induced by the combined effect of the greenhouse and of the growing system. Additionally, this system should allow for overcoming any inconvenience coming from soil- and rootstock-related problems such as those inter alia related to root diseases and soil compaction [20,21], while offering at the same time supplemental advantages with respect to traditional vineyard plantations. These advantages mainly consist of a lower cost of plant material, extreme varietal flexibility (rapid cultivar turnover), easier manipulation of the vegetative–reproductive cycle, better use of available space with higher yields per hectare of high quality extra-seasonal table-grape production, higher sustainability for reduced pesticide application, and higher use efficiency of water and fertilizers. A schematic overview of some of the main advantages of soil-less table-grape cultivation (TGSC) in comparison to traditional growing systems is given in Table 1.

Table 1. The main advantages of soil-less table-grape cultivation (TGSC) in comparison to traditional growing systems [Z].

Related Area or Terms of Comparison in Conventional Soil-Grown Cultivation	Alternatives Used in TGSC	Advantages
Soil	Mixtures of substrates	Overcoming soil replant problems, quality, and soil-borne diseases
Growing environment	Containers	Make the most of the available space Yield increase per unit area Maximum control of water and nutrients Reuse of nutrient solution
Plant material	Own-rooted cuttings	No graft requirement Low cost Quick varietal turnover Rapid adaptation to consumers' preferences
Cultural techniques	Greenhouse	Manipulation of vegetative and reproductive cycle Anticipate and/or delay ripening and harvesting Multiple cropping cycles in a year High productivity Reduce pesticide and labor requirements Improve product quality High water and fertilizer use efficiency

[Z] Source: modified from [18,22–24].

On the other hand, the TGSC system implies high investment costs (greenhouse and auxiliary equipment) and requires adequate professional skills [25]. Moreover, since not all the table-grape cultivars show the same suitability to the soil-less system, a fine tuning of this technology is required from site to site and on a case-to-case basis. In particular, newly released cultivars, which may significantly differ from each other in terms of vigor, fertility, water and nutrient requirements, phenology, fruit development period length, and response to temperature [26], etc., have to be carefully tested for their adaptation to the soil-less system before making big investments.

In the discussion to follow, the results of the research carried out so far are reviewed under the aspects of the evolution of the applied technical solutions and procedures, varietal selection, and environmental conditions, with respect mainly to the Italian experience on table-grape soil-less cultivation but also to some new plantations very recently established in other parts of the world.

2. The Italian Research Activity on TGSC

Building on previous research reports [27–29], the first Italian experimental soil-less table-grape cultivation was carried out in the southernmost part of eastern Sicily (Ragusa province, 37°01′ N 14°29′ E) in 1998, with the scientific support of the University of Palermo and with the technical and financial support of the Regional Agriculture and Forestry Department [30]. This area has a consolidated tradition for growing table grapes under cover [31,32] for the advancement or delay of berry maturity. In the former case, a film covering is applied after winter pruning to very early season table-grape varieties [33]. The term 'soil-less' was since then adopted with reference to the use either of inert or organic substrates (peat, perlite, vermiculite, rock wool, pumice, coconut fiber, and mixtures) as soil substitutes for pot growing own-rooted *Vitis vinifera* L. scion cuttings. By this system, entailing growing conditions under greenhouse, the plants are supplied of water and nutrients through a nutrient solution containing macro- and micro-elements and may or may not involve the reuse of the drainage water ('closed-' or 'open-' cycle system, respectively) [34].

The greenhouses where this system was first established were of the traditional type commonly used for horticultural crops, i.e., 'low technology' cold greenhouses [35] with a gutter height of 2.15 m and a ridge of 2.65 m, covered with polyethylene added with EVA and mineral fillers plastic film. The open-cycle system adopted initially did not foresee the reuse of the nutrient solution distributed through a micro-irrigation system with self-compensating drippers (5 L per hour); in this case, the 3.5 L polyethylene containers where the vines were grown were raised above the ground to facilitate the irrigation water drainage (Figure 1).

Figure 1. Table-grape soil-less cultivation in polyethylene containers under low-technology greenhouse.

The number of potted plants (planting density) was 11,482 or 17,142 plants per hectare. These first trials were carried out with 'Victoria' and 'Matilde' seeded cultivars and with the seedless cvs. 'Centennial' and 'Perlon' and have shown better yields (total range = 1.5–3 kg per plant) with the former than with the latter two varieties, due to the less-pronounced shoot fertility of the seedless ones.

Furthermore, also shown was the possibility to obtain a further advancement of the berry maturity date of about 15–25 days with respect to conventional soil-grown greenhouse cultivation, depending upon the advancement of budbreak, as related to: (i) the application of a period of plant winter chilling exposure in cold rooms (20 days at 4–5 °C) and to (ii) the application of bud-breaking agents such as hydrogen cyanamide (H_2CN_2-Dormex®) at 4–6%. However, a lower cluster weight (−50%) and smaller berries (−25%) were obtained in these first TGSC trials compared with soil-grown greenhouse cultivation. This research also observed, for all the tested varieties, a significant yield decrease in the year after the first fructification due to a very significant reduction in the number of clusters per node. Therefore, this last result suggested, on the one hand, the need to replace these 'old' plants with new ones, or, on the other hand, the opportunity to use containers of greater volume with presumably a lower aging effect on the plants [30,36]. As a whole, this simplified approach had the benefit of requiring low initial investment costs, but implied low efficiency in water and fertilizer use and large polluting risks for the environment [34]. In these trials, a total amount of 580 L of water per plant was supplied along the entire vegetative–productive cycle.

Successive refinement of the TGSC technique was carried out under greenhouse tunnels designed for recovery of drainage irrigation water (semi-closed cycle system) which allowed to save about 30% of the total amount of irrigation water (Figure 2).

Figure 2. Table-grape soil-less cultivation in pots under greenhouse tunnels designed for recovery of drainage irrigation water (semi-closed cycle system).

Trials were then extended also to 'Black Magic', a very early seeded table-grape cultivar, with high fertility and yield. Yields ranged from 2.2, 2.7, and to 4 kg per plant for 'Matilde', 'Victoria', and 'Black Magic', respectively, at a plant density of about 6000 plants ha^{-1}. During the entire productive cycle, each plant received 26.3 g N, 7.28 g P, 41.5 g K, 27 g Ca, and 7.2 g Mg. These trials led to ascertain the uselessness of the preventive cold room winter chilling exposure of the plants, but at the same time confirmed the utility of the application of hydrogen cyanamide (4%) 40 days before the programmed date of budbreak, to obtain a final 15–30 days of ripening advancement, depending upon the cultivar. Concerning the training system to be adopted, it emerged that a vertical trellis with an inclination of the cane (4–6 buds) at 70 cm of height gave the best results [13,37].

Further research carried out in Sicily [38] with 'Victoria', 'Matilde', and 'Black Magic' under TGSC 'open cycle' conditions, highlighted several greenhouse effects in conditioning the main indoor environmental characteristics such as air temperature and humidity, substrate temperature, vapor pressure deficit (VPD), and photosynthetic photon flux density (PPFD). While the former values were all compatible with a good vegetative and productive response of the plant, the latter (PPFD) was particularly influenced by the plastic material used for covering (polyethylene added with EVA and mineral filler plastic film). In fact, PPFD measured in correspondence of the fruit zone of the canopy reached values close to 300 μmol m^{-2} s^1 only at midday, whereas at the same time values of about 600 μmol m^{-2} s^1 were recorded at the top of the canopy. Furthermore, the PPFD measured inside the greenhouse, compared to the PPFD measured outside the greenhouse, varied within the range of −49% to −72% depending upon the hour of the day. Inside the greenhouse, fully exposed leaf temperature never fell below 25 °C, attaining 30 °C or more at midday. The leaf water potential varied between −0.5 to −0.9 MPa. On average, the transpiration rate (E) showed values less than 3 mmol m^{-2} s^{-1} and only in a few cases exceeded 5 mmol m^{-2} s^{-1}. The net assimilation rate (A) was on average between 2 and 6 µmol m^{-2} s^{-1}, whereas the stomatal conductance (GS) generally resulted less than 200 mmol m^{-2} s^{-1}. Water use efficiency (WUE), expressed as the ratio between A and E, was on average between 2 and 4 µmol $mmol^{-1}$, 'Black Magic' being less efficient than 'Matilde' and 'Victoria' (Table 2).

Table 2. Average values of some eco-physiological parameters in 'Victoria', 'Matilde', and 'Black Magic' table-grape soil-less cultivation [z].

Parameters	Average	±s.e.
Transpiration rate (E) (mmol m^{-2} s^{-1})	2.33	0.10
Stomatal conductance (GS) (mmol m^{-2} s^{-1})	165.82	11.80
Net assimilation rate (A) (µmolm^{-2} s^{-1})	5.27	0.23
Water use efficiency (WUE) (µmol $mmol^{-1}$)	2.46	0.10
Leaf water potential (Ψl) (MPa)	−0.68	0.28

[z] Source: modified from [22].

As a whole, from this research it emerged that both the plastic cover and the high plant density (in this test equal to 16,000 plants ha^{-1}) contributed to the worsening of several eco-physiological grape parameters leading to significant unsatisfactory values of net assimilation and transpiration rates, compared with the standards reported in the literature [39]. This behavior was reputed mainly due to insufficient light intensity values rather than to air temperature values and led the authors to conclude that more attention must be paid to the light transmission features of the covering plastic materials and, consequently, also to the need to adjust and modernize the greenhouse typology and technology [22,38].

Nevertheless, the encouraging results of these first trials have shown that it was possible to obtain good productions with TGSC, both in terms of grape quality and yield and overall have highlighted the high potential offered by this type of production in terms of advancing grape maturity and harvest.

Another interesting research approach was carried out based on the principles of the so-called 'dormancy avoidance' technique, currently applied in the warm winter areas of the tropics and subtropics for temperate fruit species cultivation, including grape [40,41]. This practice generally consists of the application of a number of single or combined treatments, such as defoliation, severe water stress imposition followed by irrigation, or the application of dormancy breaking agents to induce an artificial initiation of a new growth cycle prior to the normal onset of bud endodormancy. By means of this practice, i.e., triggering budbreak in a programmed moment, it is possible to begin a second bearing cycle just 6–8 months after the previous one and just one month after the first harvest, thus allowing de facto two crops per year. Through this so called 'double cropping viticulture system' technique, a second out-of-season wine grape crop has been successfully obtained in South Brazil and China [42–44], with the advantages of minimizing the impact of unfavorable weather conditions in subtropical climates but also improving the quality and yield of out-of-season grapes [45–47]. Following previous trials conducted on soil-grown table-grape greenhouse cultivation [48], a research study was performed in Sicily on a TGSC system for obtaining off-season double production by the manipulation of the rest period [18,23,49]. The trials were conducted in a modern multi-tunnel greenhouse on plants of 'Black Magic' and 'Victoria' grown on perlite in 10 L containers at a planting density of 1.56 plants m^{-2}. For the second out-of-season cropping cycle, two types of plant materials were utilized:

(i) same 'old' plants that had already produced in the regular first cropping cycle (winter to spring), which after harvest were intensively pruned on 8 July to a single vigorous well lignified cane with 6–7 buds and (ii) cold stored (from March to July) dormant 'new' plants introduced into the greenhouse on the same date (8 July). Budbreak occurred in both cases just in about one week (15–18 July). For both the cultivars, whereas the first cropping cycle had lasted on average about 128 days, the second cycle (summer–autumn) was completed in about 90 days due to the shorter duration of both the intervals budbreak to flowering and veraison to harvest (Table 3 and Figure 3). This is to be related to the warmer more favorable temperature regime of the development period in the second cycle, especially between budbreak and flowering.

Table 3. Vine phenology during two consecutive cropping cycles in 'Black Magic' and 'Victoria' table-grape soil-less cultivation submitted to double-cropping system [z].

Cropping Cycle	Start	Budbreak	Flowering	Veraison	Harvest
			'Black Magic'		
1st	5 January	12 February	5 April	10 May	21 June
2nd	9 July	15 July	10 August	16 September	16 October
			'Victoria'		
1st	5 January	14 Feb.	10 April	10 May	21 June
2nd	9 July	18 July	14 August	12 September	16 October

[z] Source: modified from [18].

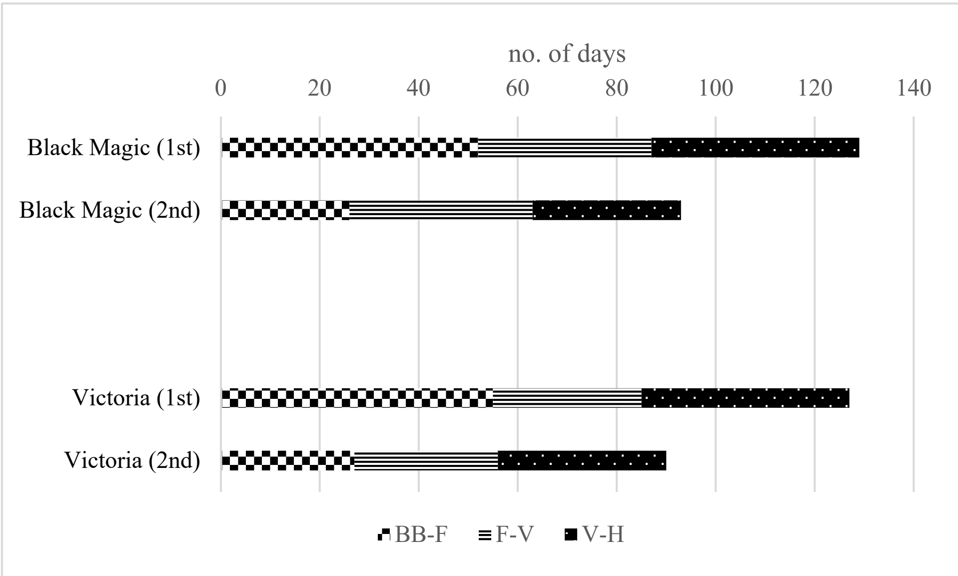


Figure 3. Length of intermediate phenological intervals and total duration (days) of 'Black Magic' and 'Victoria' berry development during two consecutive cropping cycles in TGSC submitted to double-cropping system. Phenological intervals: budbreak–flowering (BB–F); flowering–veraison (F–V) and veraison–harvest (V–H). (Source: modified from [18]).

This technique allowed obtaining a combined production of over 60–75 t ha^{-1} $year^{-1}$, i.e., 6.7–7.5 kg m^2, from the two cropping cycles, depending upon the cultivar and the plant material utilized (Table 4). Furthermore, it is noteworthy that by this system, in the second cropping cycle very early varieties are induced to grow and thereafter are marketed in an unusual late period (autumn) that is normally reserved to late-ripening varieties, highlighting otherwise unexplored phenotypic plasticity with potential grape quality and market benefits. On the contrary, with the same system, medium-late ripening varieties such as 'Red Globe', normally harvested in September–October, can be harvested in July.

Table 4. Vine yield (t ha^{-1}) during two consecutive cropping cycles in 'Black Magic' and 'Victoria' table-grape soil-less cultivation at a theoretical plant density of 15,600 plants ha^{-1}, submitted to double-cropping system ^{z}.

	New (Cold Stored) Vines		Same Vines of 1st Cycle	
	'Victoria'	*'Black Magic'*	*'Victoria'*	*'Black Magic'*
Cropping Cycle	**t ha^{-1}**			
1st	39	45.2	39	45.3
2nd	23	29.6	39	21.8
Total	*62*	*74.8*	*78*	*67.1*

^{z} Source: modified from [18].

These productive results can be considered very interesting, especially when compared with the results obtained in the first application of the double-cropping system in conventional soil-grown greenhouse conditions [48], where 'Matilde' at a planting density of 1111 plants per hectare averaged a total production (first plus second cycle) of about 30 tons per hectare. In these conditions, similar results with respect to the TGSC double-cropping system were obtained in the second cycle in terms of shortening the entire berry development, equal to about 99 days, even if the effect exerted by the application of Dormex® was essential (Table 5).

Table 5. Phenological stage intervals (number of days) in the 1st (winter–spring) and 2nd (summer–autumn) cropping cycle and yield (t ha^{-1}) of 'Matilde' table grape under conventional soil-grown greenhouse cultivation at a planting density of 1111 plants per hectare ^{z}.

Crop Cycle	**Budbreak-Setting**	**Setting-Veraison**	**Veraison-Harvest**	**Budbreak-Harvest**	**Yield**
	Interval (No. of Days)				**t ha^{-1}**
1st	65	62	30	157	20
2nd	33	48	18	99	10
			(%)		
2nd/1st	50.8	77.4	60.0	63.1	50.0

^{z} Source: modified from [48].

With the aim of improving the qualitative characteristics of 'Red Globe' produced in soil-less cultivation in term of evenness of ripening and coloring, the effect of different intensities of bunch trimming on berry quality has been tested [50] in a TGSC plot in Naro (Sicily, 37°24′20′′ N–13°67′70′′ E).

The vines, grown in 10 L pots, filled with a coconut fiber and perlite mixture at a density of 15,600 plants ha^{-1}, were vertically trained and cane pruned. Bunch trimming performed at veraison (approx. 14 mm berry Ø) significantly increased the weight of the berry (min. +4.8–max. +16.7%) and bunch compactness, although decreased the bunch weight (Table 6).

Further, bunch trimming significantly improved berry firmness, intensified skin color, and promoted its uniformity and enhanced the total soluble solids (TSS) content (min. +17.8–max. +24.4%) and the total soluble solids/titratable acidity ratio (TSS/TA) (+14.2 to +21.6%), ultimately indicating the clear effect of advancing fruit ripening, i.e., the primary goal of this growing technique, with positive consequences on the farmer incomes (Table 7).

Table 6. Effect of bunch trimming on bunch and berry characteristics of 'Red Globe' table-grape vines at a theoretical plant density of 15,600 plants ha^{-1} under soil-less cultivation ^{z}.

Bunch Treatment (z)	Bunch Weight	Berry/ Bunch	Berry Weight	Berry Diameter	Rachis Length	Compactness Index
	g	n°	g	mm	cm	
9 shoulders	1175 c	91 c	12.7 a	25.8 a	18.9 c	4.8 a
13 shoulders	1201 b	103 b	11.5 b	24.7 b	27.7 b	3.7 b
Untrim. Control	1424 a	128 a	10.9 c	24.9 b	36.7 a	3.5 b

^{z} Bunch trimming was performed when the berry diameter was ≈14 mm–BBCH 79 (17 June). Different letters denote statistically significant differences (Tukey's HSD test, $p \leq 0.05$). Source: modified from [50].

Table 7. Effect of bunch trimming on berry ripening, and physical and chromatic properties of 'Red Globe' table-grape vines at a theoretical plant density of 15,600 plants ha^{-1} under soil-less cultivation ^{z}.

Bunch Treatment (z)	TSS	TSS/TA	Berry Firmness	a* Chroma
	Brix	Brix/g L^{-1}	N	
9 Shoulders	13.9 a	21.9 c	16.4 a	8.1 a
13 Shoulders	14.7 a	23.3 b	14.4 b	8.8 a
Untrim. Control	11.8 b	19.2 a	12.6 c	6.3 b

^{z} Bunch trimming was performed when the berry diameter was ≈14 mm–BBCH 79 (17 June). Different letters denote statistically significant differences (Tukey's HSD test, $p \leq 0.05$). Source: modified from [50].

TGSC systems have also been successfully tested in other areas of southern Italy (Apulia) in PVC or EVA covered greenhouses. From this research, carried out on 10 L pots with 2:1 (*v:v*) perlite:peat, Buttaro et al. [51], obtained an average yield of 21.7 t ha^{-1}, with a bunch weight of 419 g and 14.9 °Brix with 'Cardinal' and 'Victoria' cultivars at a density of 11,111 plants ha^{-1}, and an average of 29.4 t ha^{-1} with a cluster weight of 686 g, with 'Victoria' and 'Black Magic' at a density of 9259 plants ha^{-1}. Grape quality was found in all cases to be fully responding to the international market quality standards. Interestingly, when comparing four nutrient solutions characterized by different macronutrient concentrations, they also found that it was possible to reduce the mineral concentration of the nutrient solution without affecting the yield and quality of soil-less table-grapes. They also found other considerable advantages of TGSC compared with soil-grown greenhouse systems both in terms of water saving (1144–1565 vs. 1600–1800 m^{3} ha^{-1}) and pesticide reduction (2 vs. 10–16 insecticide and fungicide treatments), respectively.

Additionally, in a study aimed at comparing the postharvest performance of table grapes cultivated in soil-less and soil systems [52], the effectiveness of TGSC was clearly demonstrated for improving table-grape quality by the production of cleaner and firmer (+30%) berries with a 60% higher antioxidant activity and total phenol than those conventionally soil grown. Moreover, TGSC promoted the preservation of visual quality and controlled rachis browning and weight loss. These results led the authors to conclude that TGSC, due to its potential for producing higher nutritional quality table grape, can also be conveniently practiced to produce health-promoting fruits.

3. The Research Activity on TGSC Systems in Other Countries

Most of the scientific literature regarding pot fruit trees deals, not surprisingly, with the nursery production of plant material for open-field orchards or with container-grown ornamental trees [53,54]. Other studies on fruit tree species' soil-less cultivation are exclusively designed for experimental purposes aiming at studying, in a controlled environment, physiological or morphological aspects in response to specific treatments imposed on the plants [55,56]. On the other hand, very few reports dealing with soil-less fruit species intensive cultivation for commercial and productive purposes are available; these regard fig trees [57,58], stone fruits [59–62]), and table grapes [18].

Considerable research interest on table-grape soil-less systems can be retrieved in the recent Turkish scientific literature on the argument, although most of these works are available only in the original language. In this country, thanks to the large extension of favorable areas with a Mediterranean climate, the protected cultivation industry is largely diffused, especially on the south coast, and even protected fruit production is expanding at a steady pace with an increasing interest in the use of soil-less culture techniques to overcome soil-specific problems [63]. Bahar et al. [64], working with the table-grape seedless cv. 'Tekirdag' grown in large trays (5 $\times$ 0.5 $\times$ 0.45 m) in a perlite-based substrate, reported no significant differences in terms of cluster and berry characteristics when compared with grape production from conventional soil-grown 'Tekirdag' vineyards. Sabir et al. [65] tested a TGSC system consisting of big (60 L) pots, filled with peat and perlite, comparing the performances of the cultivars 'Perle de Csaba', 'Pembe Cekirdeksiz', and 'Italia' at a density of 2000 vines per 1000 m^2 under controlled glasshouse conditions in the central Turkish area (Konya). Reportedly, satisfactory results were obtained with this TGSC system, showing grape characteristics, especially in the case of 'Perle de Csaba', similar to those obtained in conventional soil-grown vineyards.

Very recently, Tangolar et al. [66], working in the southeast Turkish area (Adana) under greenhouse conditions, studied the effect of three different substrates (cocopeat, mixture of perlite and peat, and basaltic pumice) and two different levels of crop load (10 and 15 clusters per grapevine) on self-rooted 'Early Sweet' cv. grown in soil-less culture in 32 L pots. Grapevines were trained to a single cane system (Guyot) at a theoretical density of 11,250 plants ha^{-1}. They observed that the highest grape yield (38 t ha^{-1}) was obtained from the perlite:peat medium and 15-cluster crop load treatment, but with a lower value of TSS than with cocopeat. The cluster weight ranged between 263.9 g (cocopeat) and 346.2 g (perlite:peat), with the former having higher berry weight and volume. Furthermore, the adopted substrates showed significant effects on K and Ca leaf concentration at veraison, which resulted higher with cocopeat and perlite:peat media for K and with basaltic pumice for Ca, whereas the effect of crop load on leaf macro nutrients was not significant. The satisfactory results obtained in terms of yield and quality and the grape ripeness advancement (11 days) led the authors to conclude that a soil-less culture could be recommended to local farmers for profitable production.

Commercial interest in TGSC has also emerged in recent initiatives carried out in Mexico (Figure 4) in the Hermosillo area (Sonora), and in Tunisia in the Gabes area. In both cases, these initiatives, which are the result of collaborations with the research group of the University of Palermo, involved the adoption of seedless cultivars such as 'Early Sweet' and others.

Figure 4. Table-grape soil-less cultivation in polyethylene containers under high-technology greenhouse in the Hermosillo area (Mexico).

4. Establishing and Managing the Table-Grape Soil-Less System

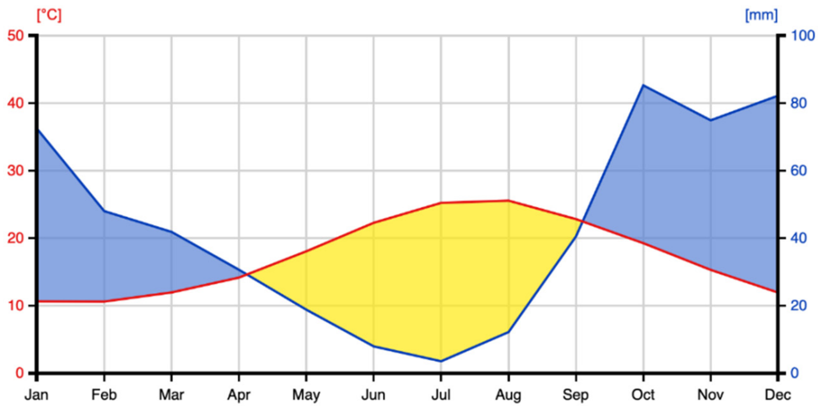
The successful establishment and management of TGSC systems largely relies on the correct choice and application of several environmental, genetic, and technical issues, which in turn determine the overall advantage in terms of flexibility, potential productivity, and earliness of the production system, ultimately determining its profitability.

4.1. The Climate

Site selection is a key factor for profitable and sustainable greenhouse production [67]. First, when considering the environmental suitability for the establishment of a TGSC system, careful attention must be paid to the climatic aspects of the selected site. Thus, a preventive full assessment of the potential table-grape development cycle is necessary to understand whether and when berries of a given genotype can reach maturation under the local climate conditions. Overall, the winter and spring temperature regime is crucial for the proper site selection [68]. Climate charts, or climograph charts when available, are potentially useful tools for the primary suitability assessment for covered crop cultivation [69] and particularly for TGSC systems.

The agricultural areas located on the south coast of Sicily, facing the Mediterranean Sea, from Naro (37°24′20′′ N–13°67′70′′ E) to Vittoria (36°56′54′′ N–14°32′14′′ E) passing from Gela (37°51′71′′ N–14°15′10′′ E), are known to be the earliest for grape ripening in Italy. In this area, rainfall usually ranges between 385 and 548 mm per year. The potential evapotranspiration (ETP) ranges from 870 mm to 1000 mm.

The climate chart of Gela (Caltanissetta district), which can be considered representative of the prevailing climatic conditions of the southern Sicily table-grape area, is reported in Figure 5 [70].



Month	Temp	Precip
Jan	10.6	72.5
Feb	10.6	48.0
Mar	12.0	41.9
Apr	14.2	30.7
May	18.1	18.8
Jun	22.3	8.0
Jul	25.2	3.6
Aug	25.6	12.2
Sep	22.8	40.5
Oct	19.3	85.3
Nov	15.3	74.9
Dec	12.0	82.2

Temperature Mean: 17.3 °C Precipitation Sum: 518.5 mm

Figure 5. Climate chart for Gela, Sicily, Caltanissetta district, 37°51′71′′ N–14°15′10′′ E, elevation: 77 m; Climate Class: Cfa; Years: 1963–2019. Source: see [70].

Secondly, it has to be evaluated how the greenhouse (structural design, orientation, and cover type) at the selected location can influence the indoor microclimate in accordance with the eco-physiological requirements of the selected table-grape cultivars and the grower's expectations.

To correctly characterize a given site, the application of specific phenoclimatic models may be very helpful for determining how and when the thermal requirement of a given specific grape cultivar can be fulfilled and also for detecting the frequency and the intensity of temperature excess (>30 °C) [71]. Particularly, the calculation of chilling unit (CU) availability, together with the estimation of growing degree days (GDD) potential accumulation (>10 °C) and the estimate of growing season (start, end, and duration), defined as the period of the year with daily mean temperature equal to or higher than specific thresholds, have to be determined. The temperatures that effectively contribute to the chilling fulfillment in grapevine are believed to be between 7.2 °C and 0 °C [72], and the European grapevine cultivars tend to be generally characterized by a low chilling requirement (50–400 CU) to complete endodormancy [73]. A comprehensive review of the available phenological models and of their efficacy is given in Fila et al. [74], whereas a critical revision of using GDD is given in Bonhomme [75]. A sound example of the application of different degree-day methods and various temperature thresholds for each grapevine development stage is reported by Prats-Llinàs et al. [76], who demonstrated the existence of different upper temperature thresholds (T_U) for each developmental stage, where the highest T_U value coincided with bloom (29.8 °C) and the lowest was observed at veraison (20.9 °C). Therefore, since the final aim of TGSC is the obtainment of very early production, for a given cultivar the thermal regime of the protected environment must promptly comply with the specific optimal heat requirement of each phenophase. In theory, budbreak, flowering, fruit set and development and, finally, ripening, should be all conveniently anticipated with respect either to open-field or, moreover, to greenhouse conventional soil-grown cultivation. Indeed, it has been observed [36] that most of the gain in terms of harvest earliness in TGSC is largely due to an earlier date of budbreak (Table 8). In fact, the overall length of the budbreak–harvest cycle and the length of the intervals between budbreak and flowering and flowering and veraison may be even longer than those of conventional soil-grown greenhouse cultivation due to the different dates, and thus the prevalent thermal regime, in which they occur (Figure 6).

Table 8. Vine phenology (dates), total duration of the intervals budbreak to harvest and maturity gain (no. of days) in 'Matilde' and 'Victoria' table grapes in conventional soil-grown cultivation (CSG) and in soil-less cultivation (TGSC) [z].

Cult. System	Budbreak	Flowering	Veraison	Harvest	Tot. Duration	Maturity Gain
		'Matilde'			(no. of days)	
CSG	3 February	4 April	16 May	6 June	134	
TGSC	16 December	3 March	2 May	20 May	145	−17
		'Victoria'				
CSG	1 March	28 April	6 May	28 June	119	
TGSC	20 December	7 March	2 May	23 May	154	−36

[z] Source: modified from [36].

In fact, the advanced growing cycle in TGSC is more winterly than that of soil-grown cultivation and, therefore, takes place predominantly during the cold season when the prevailing indoor temperatures are usually suboptimal due to low night-temperature values. On the contrary, the length of interval between veraison-berry maturity, accelerated by the more favorable spring temperatures, is shorter in 'soil-less' cultivation (Figure 6). Furthermore, it must be considered that whereas greenhouses cause the indoor increase of daytime temperature, sometimes even to very high values, on the other hand, night temperatures only increase slightly in relation to the outside ones (2–4 °C, at the most) and, in some cases, are lower as for thermal inversion phenomena [67]. Taken together, these considerations underline the importance of continuous monitoring of the thermal regime inside the greenhouse, especially in order to avoid, through appropriate interventions, the exceeding of the upper temperature thresholds [76].

An example of climatic parameters variation inside the greenhouse along the growing seasons is reported in Table 9, where the climatic parameters in correspondence to the main phenophases are compared in terms of differences between the second and the first cropping cycle.

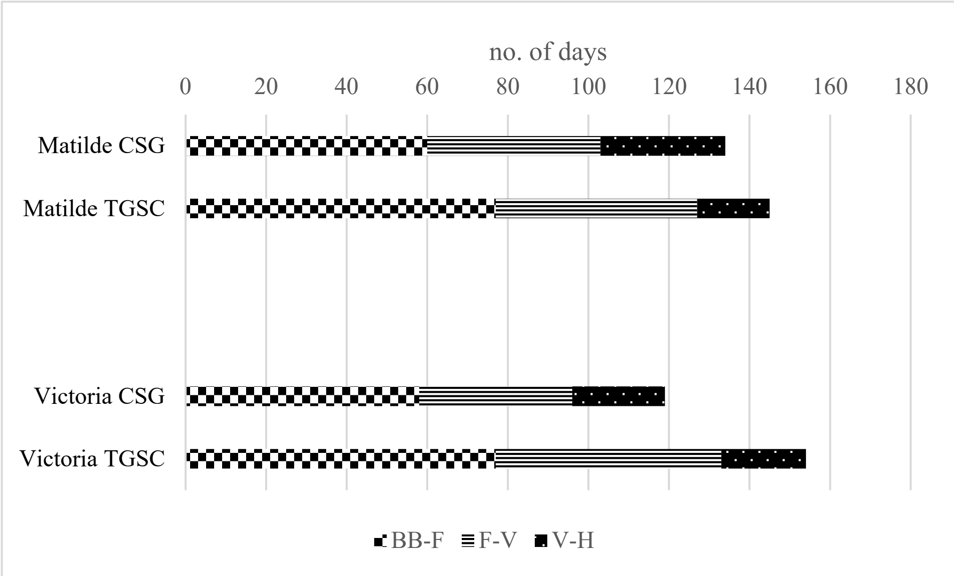


Figure 6. Length of intermediate phenological intervals and total duration (days) of 'Matilde' and 'Victoria' berry development in conventional soil-grown (CSG) cultivation and in soil-less (TGSC) cultivation. Phenological intervals: budbreak–flowering (BB–F); flowering–veraison (F–V) and veraison–harvest (V–H). Source: modified from [36].

Table 9. Climatic differences inside the greenhouse between the second and the first growing cycles' phenophase occurrence in TGSC double-cropping system [z].

	Budbreak–Flowering	Flowering–Veraison	Veraison–Harvest	Budbreak–Harvest
		Climatic Parameter		
Air temperature (°C)	+9.7	+3.5	+2.0	+5.7
Relative humidity (%)	−1.7	−12	+11.4	−0.20
Global radiation accumulation (W/m^2)	+1272	−28	−916	+165
VPD (kPa)	0.65	+12.68	−0.20	+0.40

[z] Source: modified from [23].

The advancement as much as possible of the budbreak date has been made possible and empowered using rest-breaking agents such as hydrogen cyanamide (H_2CN_2-Dormex®). Dormex® has been extensively utilized in a wide range of temperate fruit tree species to effectively overcome inadequate winter chilling [77–79] (and references therein). It has long been utilized as well in table-grape protected cultivation since it has allowed to obtain earlier budbreak and, consequently, earlier grape ripening of about 30 and 20 days, respectively [31,48,80,81]. Similarly, in TGSC the use of Dormex® (4%) found wide application [38,49] until 2008, when it was withdrawn from the market and its use was banned in Europe (according to the European organic regulation EC 834/2007 and 889/2008, Annex I and II) and in other countries. Hence, there is an urgent need to develop dormancy release agents that pose no health risks to humans.

Looking for new alternatives to promote early budbreak, several solutions have been proposed [82]. Kubota et al. [83] found that fresh garlic paste (*Allium sativum* L.) applied to the cross-sectional cut surface of several grapevine canes immediately after pruning was more efficient than calcium cyanamide. Similar positive results were also obtained in hot regions without (or with limited) exposure to chilling by using garlic-derived compounds [84–86]. El-Kaed et al. [87] reported the successful use of a mixture of isolates of *Bacillus subtilis* in multiple soft brushing applications as a biological method to replace Dormex® in 'Flame' seedless grape vine organic farming.

Fructose and methionine have been utilized as alternative budbreak agents as they are safer than cyanamide [88]. According to these authors, spraying fructose at 3% showed potential for use as a commercial budbreak and improved yield and quality of 'Superior' grapevines.

Sabry et al. [89] used jasmine oil at different concentrations as a bud dormancy breaking agent alternative to Dormex® for 'Flame' seedless grape vines. The best results were obtained when 0.2% jasmine oil was in combination with Dormex® 3%, compared with the control treatment (Dormex® 5%).

Ahmed et al. [90] examined plant extracts of turmeric, cinnamon, ginger, colocynth, nigella, olive oil, clove, garlic, red chilies, and coffee, as well as four chemical agents (H_2O_2, salicylic acid, thiourea, and Dormex®) to break dormancy of 'Superior' grape buds in Egypt. This study evidenced that plant extracts of coffee, red chilies, garlic, and clove can be used as natural safe substances to break bud dormancy, although with different efficacy.

A comprehensive and updated review of the latest alternatives of dormancy breaking agents for table grapes has recently been offered by Novello et al. [91].

In addition to the temperature regime, another aspect to be considered to correctly evaluate the climate suitability of a region for protected cultivation is represented by the seasonal pattern of the total PAR at canopy level under covering and in open-field conditions, which is strictly related both to seasonal heliophany (average sunshine hours) and to light transmittance characteristics of the covering material [38].

4.2. The Cover

The most common polymers diffusely used in horticulture are low-density polyethylene (LDPE) and ethylene-vinyl acetate (EVA). Greenhouse cladding film thickness ranges from 80 to 200 µm. Single-layer or multi-layer films are widely used in horticulture, and the latter are often preferred for combining good mechanical resistance with good light transmission. The current greenhouse film life span is reputed to approach to approximately 45 months, depending upon the additives, the geographic location, and the exposure to pesticide treatments [92]. However, economic considerations concerning both the costs of the different materials and the relative installation are to be taken carefully into consideration.

Additionally, at a given location, the prominent role exerted by plastic cover characteristics on the vine eco-physiological response should be carefully evaluated since, as revealed by covered conventional systems' experiment results, it can affect the leaf area and growth rate, the percentage of fertile buds per shoot, the number of bunches per shoot, and ultimately yields [93]. Furthermore, both the advance of berry ripening and the bunch and berry mass, are also affected, as demonstrated by Novello et al. [94], who showed the better performance of 'Matilde' grapes grown under LDPE (low density polyethylene) and EVA, compared with LDPE and HDPE (high density) plastic sheet covering.

Generally speaking, in a passive (unheated) greenhouse for early production, the optimum material to advance grape maturity must have high transparency to solar radiations (80–90%) to increase the internal air temperature, high transmissivity in the PAR wave-length range to increase potential photosynthesis, high transmissivity in the ultraviolet ranges to promote fruit color and nutraceutical compounds, but low transmissivity (20–60%) in the long wave to reduce the thermal radiative losses [32,33,94]. Polyethylene films are very transparent to long-wave IR radiation; therefore, IR-absorbing additives are commonly used to improve the thermal properties of the films [92].

The search for covering plastic films with optimal features still represents a major challenge [14] for protected cultivation. The research is constantly addressed to find new materials and additives with lightweight and good mechanical resistance, easy installation, use and management, lower costs in relation to other materials, good durability and limited decay of the mechanical and radiometric properties, and stable anti-dripping or anti-dust properties [92]. Several, either conventional [95] or environmentally friendly, new materials [96] (and references therein) have been recently proposed such as innovative biodegradable or compostable materials, presenting mechanical and physical properties similar to plastics derived from conventional sources.

In table-grape protected cultivation, the use of differently colored photo-selective films having different transparency to sunlight and increased mechanical strength has been recently tested on 'Italia' and 'Red Globe' table-grape cultivars [97]. In both cultivars, the reduction of light intensity induced by yellow and red plastic films did not significantly affect vegetative growth and yield but, in turn, enhanced grape nutritional value with a much higher total antioxidant activity (in the average +88 and +60% under the yellow and red film, respectively) with respect to those grown under the white one. Further, photo-selective films are reported to positively determine greenhouse cooling by NIR-reflection, thus improving greenhouse microclimate control during warmer periods [98].

With the aim of further advancing berry maturity in conventional covered table-grape vineyards, the effects of new agrotextile transparent plastic fabrics on vineyard microclimate and grape yield/quality have been tested, showing improved IRlong retention, UV transmittance, and light diffusivity [99]. In the same research, positive effects of white reflective woven inter-row groundcover were detected in terms of intensified PAR reflection, lowered soil temperature, improved soil humidity, and bunch weight and productivity.

Plastic coverings are expected to induce indoor temperature increase by reducing losses due to radiative and convective energy exchange [100], in order to ultimately determine a significant advancement of grape maturation and harvest. This temperature increase is an effect of both the air movement reduction and the passive thermal energy stored inside the greenhouse. Depending upon the season and the location, this temperature increase may attain excessive daytime values (>30 °C). In southern regions, during summer, high sunlight intensity combined with high crop temperatures and vapor pressure deficit (VPD) can negatively affect photosynthesis [101,102] at various stages of the vine's entire fruiting process including its lengthening; this probably compromises the earliness of the harvest, but it is also the cause of a significant reduction in the development and quality of the berries. Overheating must be appropriately prevented or reduced by ensuring correct indoor ventilation, which positively also counteracts the excessive humidity, together with CO_2 depletion. Indoor ventilation is obtained through opportunely combining sidewall and roof vent air exchange, preferably in automatized systems. The effects of natural ventilation and current trends of related research are extensively reviewed in Montero et al. [92]. In addition to air exchange (ventilation), the indoor air temperature can be reduced by shading and/or evaporative cooling techniques [69]. Noteworthy, an external shading screen, normally used in the daytime for cooling purposes, also offers a positive effect of increasing nighttime temperature, thus reducing the risk of thermal inversion under clear sky conditions [103]. To promptly prevent excessive daytime temperature, active monitoring of the microclimatic condition and an adequate degree of automation are, therefore, requested, especially in the new designed protective structures. In our experience, positive results were obtained in TGSC through the evaporative cooling technique with a rapid thermal drop effect (up to 3 °C) intervening up to ten times during the day. At the same time, the evaporative cooling technique is useful to favor the budbreak by reducing the percentage of blind buds by approximately 15–20%, (unpublished data) thanks to the improvement of VPD conditions inside the greenhouse.

Therefore, well-designed greenhouses for TGSC conveniently include a fog system, which in turn can also be opportunely utilized for applying the evaporative cooling technique for the reduction of excessive daytime temperature.

The use of shading nets in combination with plastic sheets, as well as in protected open-field cultivation [96], is also increasingly widespread in the TGSC to take advantage of the obtainable combined benefits in different phenological moments characterized by different thermal needs.

4.3. The Genetic Factor: Proper Cultivar Selection and Plant Material

As detailed before, the first Italian experiences with TGSC systems were carried out using early black and white varieties ('Matilde', 'Victoria', and 'Black Magic') and other seedless cultivars such as 'Centennial', 'Superior seedless', and 'Perlon'. All the mentioned seeded cultivars have proved during the time course to be well adapted for their precocity to the Sicilian viticulture environments, both in open-field cultivation and under greenhouse cultivation (in soil and soil-less), resulting as well suited to the cultural environments. On the contrary, seedless cultivars have consistently shown less adaptation to soil-less systems, presenting lower basal bud fertility (0.2–0.4 cluster per node), generally lower (−70%) yields (1–1.2 kg per vine), and lower cluster weight, compared with open-field cultivation [30,36]. More recently, seedless cultivars such as 'Regal seedless' have been shown to be well adapted to TGSC conditions without presenting shoot fertility problems.

Table-grape cultivars well suited to the TGSC must have good fertility, regular from year to year, that is little influenced by external factors. Especially in the TGSC environment, the growth rate of the sprout can in fact affect fertility very negatively in some cultivars. However, it must be noted that the new seedless cvs are generally characterized by good and constant fertility, as in the case of 'Sweet Celebration', 'Allison', 'Early Sweet', etc.

Additionally, in the last years a growing interest has emerged for displacing harvesting time of late varieties by the means of TGSC techniques. This is the case, for example, of early maturity in soil-less cultivation of the cultivar 'Red Globe', 'normally' medium-late ripening. In this context, interesting results, even if sometimes with ripening unevenness and coloring defects, have been reported [50,104].

As far as starting plant material for the TGSC system is regarded, in our experiences, grapes are easily and economically propagated as a double-node hardwood cutting (0.7–1 cm diameter) obtained from the pruning wood of the selected cultivar, temporarily cold-stored for about 20 days. From February to April, they are treated with NAA and/or IBA, then usually planted in plastic bags or in Jiffy® pots (approx. 0.4 L volume) filled with peat (Figure 7), and preferably placed in greenhouses under mist with basal heating (25 °C air temperature and 22 °C substrate temperature). Cuttings root readily (35–40 days) and, afterward, when the shoot is about 10 cm long, they are transplanted into larger pots (4–10 L) with various potting mixtures (e.g., peat and perlite 1:2) and then submitted to the successive phase of training in the open field or directly in the greenhouse.

Figure 7. Table-grape hardwood cuttings ready to the successive phase of training in the greenhouse: in plastic bags (**left**); in alveolar tray (**right**).

Trellis design generally adopted in TGSC is extremely simplified and the vine can be trained on a vertical trellis, on a pergola, or a big V (gable) (Figure 8). Most commonly, the plants are trained to a vertical trellis and pruned to a single shoot that will form the cane during the production phase and are trained by bending the branch on the horizontal wire (Guyot). The height of the support wire and the arrangement of the vegetation must be chosen according to the cultivar, its fertility along the cane, and the climatic conditions within the greenhouse [37]. At the end of the training cycle (October–November) the plants present a single well lignified cane 150 cm in length and 0.8–1.2 cm in diameter [30,36].

Figure 8. Trellis design generally adopted in TGSC: (**A**) pergola; (**B**) V (gable); (**C**) vertical trellis.

In the productive phase and with the Guyot pruning system, both the number of clusters per node and berry weights are strongly dependent on the vigor of the cane. In fact, a hyperbolic significant relationship (R^2 = 0.85) was found between the cane circumference and the number of clusters per node (Figure 9), highlighting that vines with a cane circumference less than 2.5 cm and more than 3.0 cm produced shoots with a lower value of fertility [36].

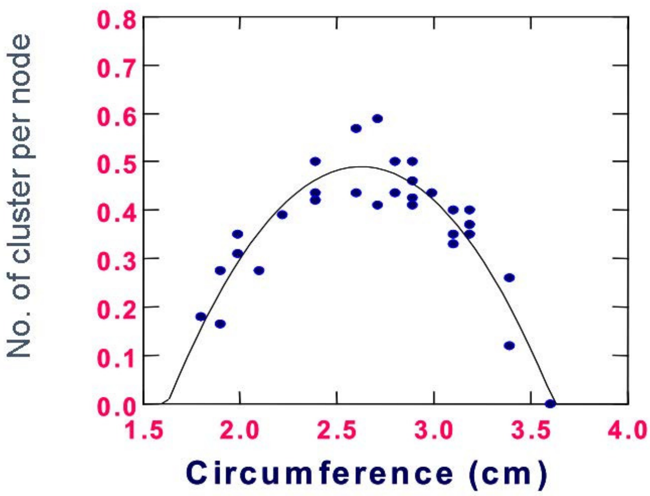


Figure 9. Quadratic regression between fertility (no. of cluster per node) and cane circumference measured at 600 mm from the collar. Source: see [36].

Finally, it must be stressed that TGSC allows the adoption of such a simplified trellis system with significant advantages in terms of management and related costs with respect to all other table-grape production systems.

A schematic representation of the main above-described activities regarding plant obtainment, training, and the subsequent production phase is resumed in Figure 10.

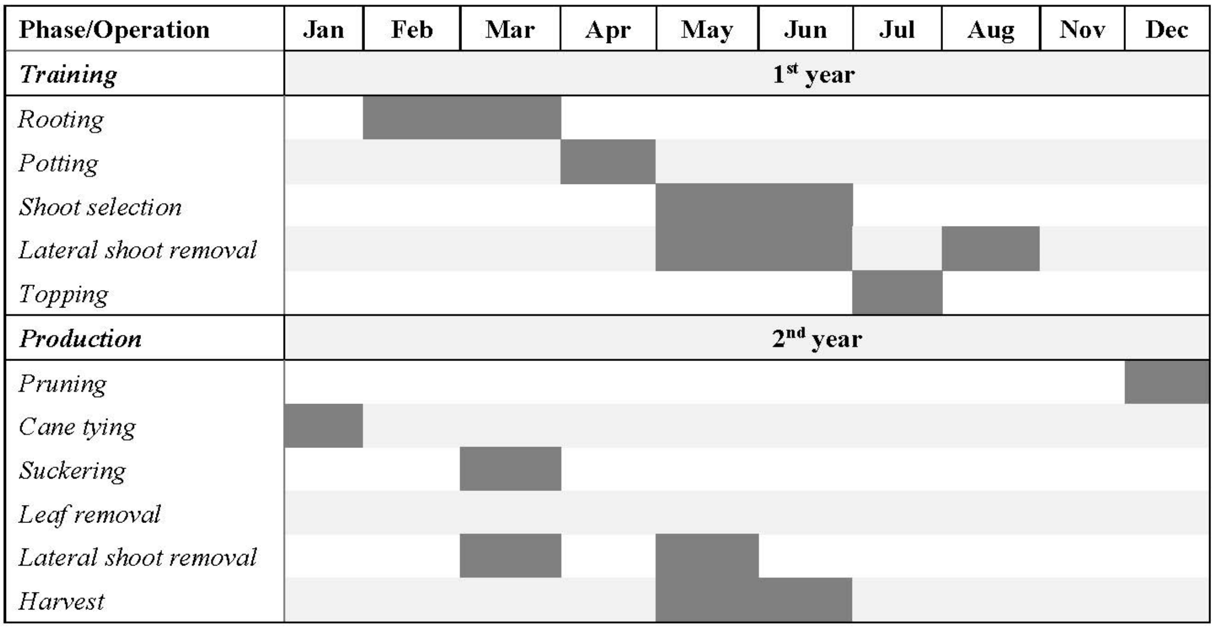


Figure 10. Operational schematic representation of the TGSC plant training and production phases.

4.4. The Substrate

Basically, the ideal substrate must ensure different functions: (i) supports the plant; (ii) favors air, water, and nutrient supply to the roots in a balanced manner in order to prevent root asphyxia and drought stress. Furthermore, it must be free from phytotoxicity and soil diseases, affordable, easy to obtain and to manage, and even more sustainable and environmentally friendly [105]. In theory, almost any organic or inorganic material can be used as a substrate, provided that it meets the above conditions. However, organic materials are generally preferred for their low cost, widespread availability, renewability, and ease of disposal [106]. Recently, organic materials alternative to peat, such as compost, coir, bark, and wood fiber are considered preferable to reduce the carbon footprint in horticulture [107]. There is no universal substrate or mixture that fits all solutions. It is, therefore, appropriate to carefully select the single materials according to the different environment, cultivation phase, and cultivation system, taking advantage of their beneficial properties in blends. In each case, it must always be remembered that growth on a substrate in a container occurs in conditions of a reduced thermal flywheel, limited water reserve, and possible waste of water and nutrients [18]. Hence, to ensure better water:air ratios, materials with high porosity (optimally 75%), and with the right balance between micro (40–60%) and macro (15–35%) pores should be preferred [108]. However, apart from the already reported (ch. 3) results from Tangolar et al. [66], there is a general lack of scientific information on the comparative characteristics and the effects of substrates under TGSC. In the last years, mixtures of different substrates or coir with different grain sizes have become ever more popular in TGSC, trying to exploit the advantages of each type of substrate. However, our observations have shown the need to avoid an excessive stratification of the different substrates in the pot, which may cause uneven effects on roots distribution. In the last decade, a general trend towards the use of natural resources and renewable raw materials has been reported [109]. Further investigation is needed with regards also to environmentally acceptable solutions for growing media materials and constituents [107]. On the other hand, the enormous potential offered by organic waste products [105] such as composts produced from pruning residues, shredded branches, or plant debris must be considered. It has been estimated that soil-less horticultural systems generate approximately 2 t ha^{-1} per year of exhausted mineral (rock wool, perlite) or organic (peat) substrates to be disposed of [110]. In Italy, other readily available recycled or waste materials can be represented for instance by rice husk and almond or hazelnut shells [18]. Growing media used in soil-less culture in Mediterranean countries, including reuse and recycle issues, are thoroughly examined and reviewed in Gruda [107] and in Gruda et al. [111], and general sustainability of protected cultivation in a Mediterranean climate in De Pascale et al. [112] and in Fernández et al. [14]. A comprehensive assessment of potential alternative substrate materials (biochar, biosolids, compost, wood chips, and fertilizer) is reported by Sax and Scharenbroch [113].

4.5. The Container

Potted plant growth is inevitably affected by the limited volume of plant roots in a container. As a consequence, a reduced root system is expected to support the aerial part of the plant, with potential imbalances of the entire system. Furthermore, containerized plants present generally higher water and nutrient requirements compared with conventional open-field cultivated plants, due to the environmental conditions of greenhouses where growth rate is enhanced [107]. Therefore, it is essential to properly select the particle size of the growing media used and the container size and shape to balance water and nutrients availability and aeration in the root zone [25]. Plastic bags were used in the first experiences with TGSC due to their low cost; however, problems of plant handling, stability on the ground, and lack of uniformity in the distribution of the nutrient solution and consequently of the roots, quickly suggested to discard this option. Similarly, the use of long plastic trays (28 L in volume) initially tested was thereafter discontinued due to being more difficult to manage in comparison to plastic pots [37]. Regardless of the type of container used, it is essential to ensure the plants have good drainage to avoid any damage from root asphyxia. To this end, innovative containers specifically designed to maximize drainage and oxygen uptake have been recently developed by the industry. There is growing interest in sustainable alternative containers made from compostable materials, such as bamboo, coconut fiber or wood pulp, rice husks, and recycled paper [107], but as far as we know none of these have been tested in TGSC.

4.6. The Table-Grape Soil-Less System Management: Water and Mineral Nutrition

In addition to the cultural practices already resumed in Figure 10, the soil-less system requires adequate attention to the issue of water and mineral nutrition adapted to the peculiarities of the in-pot vine growing environment, as influenced by the greenhouse typology, the varietal needs, the phenological stage, and the yield expectations. An accurate management and monitoring of all factors involved, such as water supply and quality (EC and pH), nutrient solution composition, concentration, and temperature, dissolved oxygen concentration, etc., is mandatory for the optimization of nutrition in soil-less systems [114]. Further, it must be considered that in containerized production systems, special attention must be paid to the regularity and frequency of irrigation; this must be applied more frequently compared to field soils, due to the limited volume of the containers, the consequent restricted root volumes, and the high porosity of the soil-less substrates. In turn, if the recovered water is adequately treated it may be, at least in part (≈30%), conveniently reused [115].

In our first testing of the TGSC system, when the adopted 'open cycle' system did not include the reuse of the nutrient solution, a total amount of 580 L of water per plant was supplied along the entire vegetative–productive cycle. The total amount of nutrients supplied, the composition of the nutrient solutions, and the dosage applied are summarized in Table 10. The concentration of the nutrient solution and its daily dosage varied depending on the phenological phase, according to an increasing dosage criterion from budbreak until the harvesting phase and subsequently decreasing (Figure 11).

Table 10. Mineral concentration (mg L^{-1}) of the three different nutrient solutions applied according to the different phases of growing cycle and total amount (g) of supplied elements per plant [z].

Mineral Element		N	P	K	Mg	Fe	Mn	Zn
Nutrient Solution (Z) (mg L^{-1})								
	1	44.25	10.98	42.50	25.66	5.31	0.66	0.33
	2	103.50	30.60	137.0	52.71	0.53	1.06	0.53
	3	36.86	9.18	44.39	30.43	0.16	0.32	0.16
Total amount per plant(g)		29.20	7.80	34.80	18.30	1.00	0.30	0.20

[z] Application period of nutrient solutions: (1) from budbreak to the beginning of veraison (onset of grape ripening); (2) from veraison to harvest time; (3) from the end of harvest time to the end of vegetative period. Source: modified from [36].

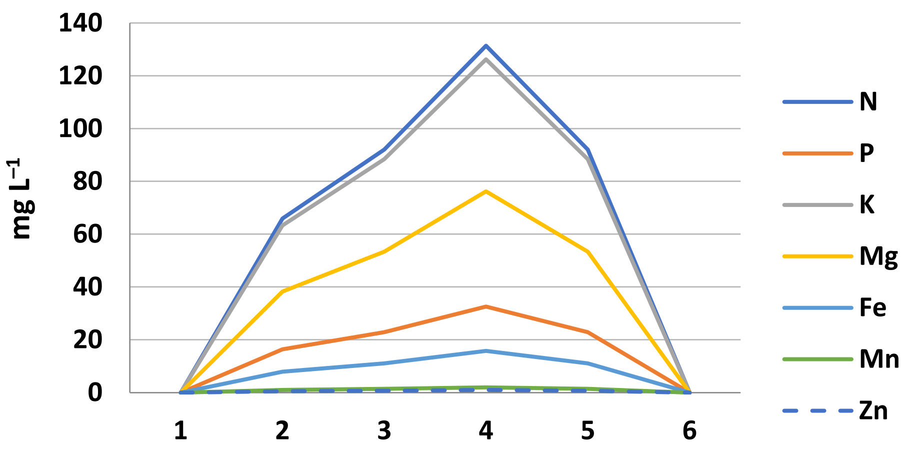


Figure 11. Different amount of supplied mineral elements (mg L^{-1}) per plant, according to the different phenological stages of growing cycle. Stage (1) until budbreak; (2) from budbreak to flowering; (3) from flowering to the beginning of veraison; (4) from veraison to harvest time; (5) from the end of harvest time to the end of vegetative period; (6) from the end of vegetative period onward. Source: modified from [36].

In successive refinement of the TGSC technique carried out under greenhouse tunnels designed for a total recovery of drainage irrigation water (semi-closed cycle system), the total amount of water was conveniently reduced and each plant received on average about 320 L of water and about 34 g N, 12.7 g P, 85 g K, 72.8 g Ca, and 26.7 g Mg during the entire productive cycle (Tables 11 and 12).

Table 11. Number and frequency of irrigations, and amount of water supplied per period and per plant (minimum and maximum values) [z].

Phenophase	Irrigation per	Water Supplied per			Water Recycled per
	Day	Irrigation	Day	Period	Day
	(No.)	(mL)	(L)	(L)	(L)
BB-F	4–5	220–280	1.12–1.40	57.2–72.8	0.33–0.42
F-V	7–8	233–333	1.80–2.66	65.2–93.2	0.70–0.94
V-H	10–15	333	3.33–4.99	139.9–209.6	0.99–1.49
BB-H				262.3–375.6	

[z] Cv. Victoria in 9 L pot at a planting density of 1.56 vines m^{-2}. Phenological intervals: budbreak–flowering (BB–F), flowering–veraison (F–V), and veraison–harvest (V–H). Source: Di Lorenzo, unpublished data.

Table 12. Amount (min.–max.) of nutrients supplied per period and per plant [z].

Phenophase	N	P	K	Ca	Mg
			(g)		
BB–F	8.7–9.1	2.6–5.8	17.0–21.4	11.2–19.6	3.6–7.3
F–V	6.4–9.8	1.4–4.2	13.4–17.3	13.0–25.1	3.5–10.0
V–H	13.2–20.7	4.8–6.5	35.4–66.3	30.7–46.0	12.7–16.4
BB–H	28.4–39.5	8.8–16.5	65.7–105	55.0–91.0	19.8–33.6

[z] Cv. Victoria in 9 L pot at a planting density of 1.56 vines m^{-2}. Phenological intervals: budbreak–flowering (BB–F), flowering–veraison (F–V), and veraison–harvest (V–H). Source: Di Lorenzo, unpublished data.

In this condition (TGSC semi-closed cycle system), about one third of supplied irrigation water was recovered.

The issue of water reuse and remediation in container-grown crops has been thoroughly revised by Majsztrik et al. [115], who report several management practices for this end, including various forms of efficient water filtration and disinfection. The issue of nutrient solution in soil-less systems has been recently and extensively revised by Savvas et al. [116].

5. Concluding Remarks: Lessons Learned in the Last 20 Years

Since its inception in the late nineties, the soil-less technique applied to table-grape production has made several steps forward. Studies over the past two decades on TGSC have indicated that the degree of success of this technique is strictly linked to the optimization of genetic, environmental, and agronomic factors, which in turn require a multidisciplinary approach. Eco-physiological aspects such as bud dormancy release and growth cycle manipulation, together with environmental modification obtained inside the greenhouse and the proper water and nutrient management, as conditioned by the pot culture, are all factors that can strongly affect the TGSC results.

Several greenhouse effects conditioning the main indoor environmental characteristics such as air temperature and humidity, substrate temperature, vapor pressure deficit, and photosynthetic photon flux density (PPFD), together with proper cultivar selection, have shown to be key to the success of TGSC. Particularly, PPFD decay along the canopy as influenced by the plastic material used for covering and excessive temperature control inside the greenhouse still represent issues of major concern that deserve further research and technical innovation. Innovative recyclable covering materials with improved radiometric properties and stable anti-dripping properties and more automation of the greenhouse, including fogging and sublimation systems, together with automatic control of the EC and pH of drainage water, are needed to further improve the success of TGSC. Since the main aim of TGSC relies on taking advantage of the further advancement of berry maturity that enables premium pricing, the role of proper site selection remains of paramount importance, and all the TGSC initiatives carried out so far have confirmed unequivocally that climatic suitability must be previously taken into careful consideration. On the other hand, there has been sound evidence that the soil-less cultivation technique can be helpful for controlling and reducing the amount and the costs of pesticides and water and nutrient applications, thus contributing to the overall sustainability of table-grape production and quality in compliance with the increased environmental awareness [116].

The number of commercial initiatives from different countries of both hemispheres that have shown interest for TGSC is on the rise. This is certainly due to the numerous main advantages of TGSC over other in-soil protected systems. Many of these have been revised in this review and can be considered peculiar to TGSC. Nevertheless, some of them are generally recognized for all kind of protected cultivation in comparison to the open field crops. Readers are referred to the excellent review of De Pascale et al. [108], who inter alia report (i): a greater water-use efficiency especially in closed soil-less systems due to lower solar radiation, less wind, and greater relative humidity inside the greenhouse and (ii) a higher crop productivity due to the better control of plant diseases and climatic parameters, in particular global radiation and air temperature.

It is hardly necessary to observe that specific expertise and technical skills are required to address particular challenges posed by the TGSC technique.

Based on these long-term observations and by properly evaluating all the caveats already mentioned, we now have access to solid guiding principles and specific examples of the many benefits potentially offered by TGSC, including techniques for achieving quality off-season double production by manipulating the rest period.

Nevertheless, since many of the results obtained so far have been borrowed from on-soil trials in protected cultivation it is therefore evident that such acquisitions must be tested and confirmed under TGSC conditions. Additionally, further research is needed for reliable bud-breaking agents, for greenhouse structure with better light transmission and better ventilation, for innovative substrates with excellent chemical, biological, and hydraulic properties, and, above all, in the field of varietal adaptation to TGSC technique. As already reported before, especially newly released seedless cultivars with different vigor, fertility, water and nutrient requirements, phenology, etc., must be carefully tested for their adaptation to the soil-less system before making big investments. For these reasons, an adequate experimentation period is mandatory to determine the overall suitability of new cultivars and new climatic environments to TGSC.

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