D3.2. Case studies

THEGREEFA

Thermochemical fluids in greenhouse farming

Document references

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Executive Public Summary

The following public document is the deliverable report for Task T3.2 – Case Studies of TheGreefa Project. Its main objectives are to analyse different boundary conditions in terms of two representative European climate regions selected in the project. Spain, with the largest extension of horticultural greenhouses in Europe, and Italy, with a robust greenhouse industry, were identified as potential initial markets for TheGreefa in the previous Task T3.1 – Market evaluation.

UAL have analysed in detail the farming system in Almeria, which includes the largest concentration of greenhouses in Europe and one of the key intensive agriculture poles in the world. For this reason, the Almería case study represents an ideal example of the challenges of intensive Mediterranean agriculture, particularly in the important areas of water use efficiency and the employment of low-energy climate control systems. The case study in Almería has been supported by the network of farmers' associations that the University of Almería is linked to. A survey with 43 questions has been carried out among 220 growers of the association AFE *Sociedad Cooperativa Andaluza* OPFH totalizing 610 ha of greenhouses to characterize Almería greenhouses. Production costs for the seasons 2021-22 and 2022-23 have been analysed for *Almería*-type unheated greenhouses for seven different alternatives of crops cycles, based upon regional governmental data. Production costs, energy and water consumption have been measured, during seasons 2020-21, 2021-22 and 2022-23 for unheated multispan greenhouses of the University of Almería. Energy and water consumption were measured in heated multispan greenhouses in a commercial farm of Almería, estimating the productions cost for tomato and pepper crops.

The second case study analysed has been the production of tomato in Italian greenhouses. Production costs of unheated multispan greenhouses have been obtained from governmental data and energy and water consumption have been measured in a commercial heated multispan greenhouse, estimating the associated production costs.

The main utility of TheGreefa technology in unheated greenhouses of Spain and Italy could be cooling inside air in summertime during exceptional hot days of spring-summer and remove excessive humidity during autumn-winter, helping to recover water that can be used for irrigation.

In a heated greenhouse, TheGreefa systems primarily serve to decrease the need for heat energy, thereby reducing reliance on fossil fuels. This contributes to lower CO2 emissions and lessens the environmental footprint of greenhouses.

1. Introduction

1.1 Overview of Task 3.2

The main objective of this deliverable is to present the current situation of horticultural production in greenhouses in Europe and especially in Spain and Italy. In order to analyse the possibilities of using the systems developed in The Greefa project, energy consumption data published in various European countries is presented. Similarly, energy consumption has been measured in unheated and heated greenhouses in Almería (Spain) and has been estimated for greenhouses in Italy. To be able to estimate the investment capacity of the farms, the production costs in greenhouses in Almería and Italy have also been calculated.

The task is led by the University of Almeria with participation of Sfera Agricola, Strane and Meyer. The activities have been proceeding as scheduled and are still ongoing. The primary goals of the case studies were successfully met by identifying three varieties of greenhouses and three key crops. This allowed for a comparison between current production methods and the solutions suggested by the project.

The task began in ninth month of project's development, preparing a survey with 83 questions including greenhouse structure, climate-control systems, crops management, machinery, soil management, irrigation system and the marketing of product to characterize the greenhouses of Almeria (Spain) and Italy. A survey was carried out at the beginning of 2022 among 220 growers of greenhouses of Almería belonging to the association AFE Sociedad Cooperativa Andaluza OPFH.

1.2. Scope and purpose

Based on the analysis of these data, five cases have been selected for modelling, simulation and environmental and socioeconomic evaluation. In Spain, two types of greenhouses have been selected as case of studies:

- The simple Almeria type greenhouses with side and roof ventilation, without the use of heating systems. These greenhouses represented in 2021 55.5% of the 72 151 ha of greenhouses in Spain and corresponded with the 79% of the growers surveyed in 2022.

- The high-tech unheated greenhouses, which are characterized by multispan structure without use of heating systems, representing about of 1.8% of total area in Spain in 2021.

- The high-tech heated greenhouses, using multispan structures with heating systems, representing 1% of growers surveyed in Almería in 2022.

- The fourth case analysed correspond to multispan greenhouse in Italy without the use of heating systems.

- The last case studied corresponds to multispan high-tech greenhouses with heating system in Italy (Sfera Agricola).

The three most important crops in the greenhouses have also been selected to analyse the feasibility of incorporation of the technology proposed in the project:

- Pepper totalizing 12 574 ha in Andalusia (979 604 t) in 2021/22, with an average price of 0.84 €/kg.

- Tomato with surface of 11 316 ha and a production of 1 04 353 t in 2021/22, with an average price of 0.94 €/kg.

- Cucumber with an area of 6 657 ha, a production of 693 370 t in 2021/22 and a price of 0.80 €/kg.

Climatic data has been collected in 5 experimental greenhouses in Almeria with different passive climatic controls systems from October 2020 to July 2023, with tomato, cucumber and pepper crops to obtain the boundary conditions and for the validation of CFD models.

The development of two 3D model of multispan and Almería greenhouses, has been carried out to include the different solutions of the project and compare it with naturally ventilated greenhouses. In 2022, the temperature inside the greenhouses has exceeded 40°C for several days. The analysis of climate data in 2021 and 2023 shows an evolution of the climate of Almeria that will require the use of cooling systems to be able to produce during a large part of the year. Production data for four crops has been analysed, observing the increase in production losses (nonmarketable fruits) in the summer of 2022 due to high temperatures.

The CFD model include plant photosynthesis and transpiration of plants. As a result of CFD modelling, 3D distribution of temperature, humidity, CO_2 concentration and radiation has been simulated for naturally ventilated greenhouses.

Production cost of Almería greenhouses (season 2021/22) have been obtained by UAL from the Spanish Agricultural Ministry and the Andalusian Agriculture Department. From the five experimental crops developed in the University of Almería, the production costs have also been estimated for 2020/21, 2021/22 and 2022/23 seasons.

2. Climate conditions for greenhouses cultivation

Greenhouses function as a production system is designed to regulate the environmental conditions affecting crop growth. Photosynthesis is the main physiological process that drives plant growth and crop productivity. This physiological process is strongly influenced by environmental conditions (Yin *et al.,* 2009). The indoor climate is mainly defined by the level of net radiation, *photosynthetically active radiation* (PAR), air temperature and velocity and its concentration in water vapor (moisture) and CO_2. All these factors directly or indirectly affect the photosynthesis of horticultural crops (Zhang and Wang, 2011; Li *et al.,* 2012) and determine in one way or another their productive capacity. Therefore, one of the main objectives in the design and management of greenhouses should be to enhance those environmental conditions that improve photosynthesis and the productive potential of crops (Sales *et al.,* 2021).

2.1. Net radiation

Net radiation, *Rn*, is the difference between the radiation that reaches the greenhouse and that leaves it and constitutes the main component of the energy balance that determines the energy that heats the soil, plants and air (Dugas *et al.,* 1993; Molina-Aiz *et al.,* 2017b; Reyes-Rosas *et al*., 2017), as well as evapotranspiration processes (Jiang and Liang, 2018; Saadon et al., *2021) and photosynthesis and carbon assimilation (Sellers* et al.*,* 1997). Net radiation can be measured using a net radiometer that measures the upward and downward fluxes of short- and longwave radiation (Allen, 2005; Liang, 2018; Jiang and Liang, 2018). The net radiation inside the greenhouse is a climatological variable whose value depends on the temperatures, reflection coefficients and geometry of the greenhouse cover, soil and plants (Monteith and Unsworth, 2013). During winter, there is a shortfall in net radiation, leading to temperatures that are lower than desired, particularly at night when net radiation becomes negative (Fig. 1).

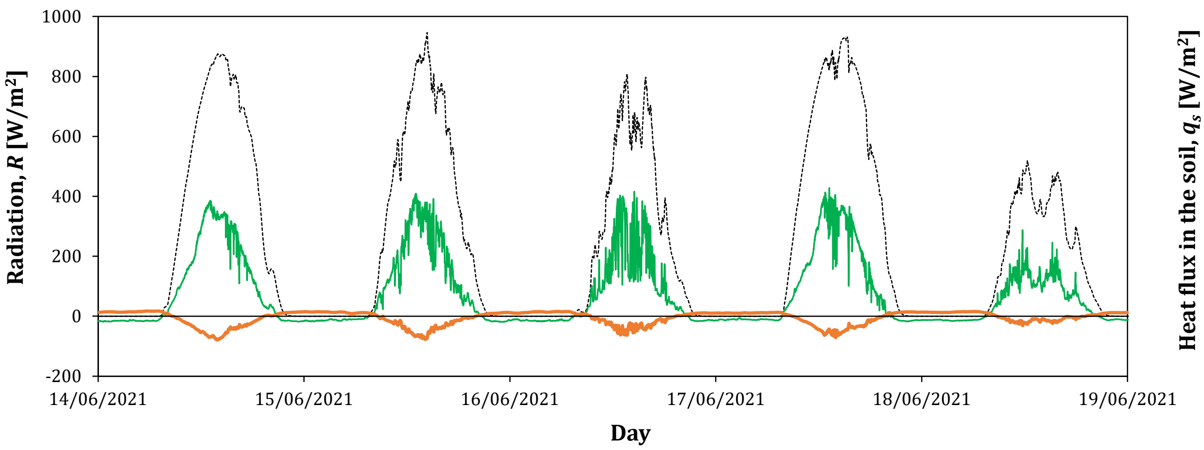


Figure 1. The diagram depicts the changes outdoor solar radiation (---), net radiation (—) and heat flow (–) through a floor with black plastic padding in a multispan greenhouse in Almería with tomato cultivation inside

Net radiation is the main component of the energy balance both at the level of the greenhouse as a whole and of the plants themselves. In the case of the greenhouse, there will be a balance between radiant energy gain and conduction-convection losses through the greenhouse structure, energy exchange with outside air through ventilation, heat absorption from the soil, and evapotranspiration of water generated from soil and plants (Molina-Aiz *et al.,* 2017b; Reyes-Rosas *et al.,* 2017). Net radiation primarily affects crop transpiration, so many automated irrigations control systems rely on Rn evapotranspiration estimates (Saadon *et al*., 2021).

In warm climates, such as the Mediterranean region, or in arid areas, such as North Africa or the Arabian Peninsula, excessive solar radiation is available during a significant part of the year. The increase in maximum intensity and the longer duration of the solar period causes an excessive rise in air temperature in solar greenhouses with passive air conditioning systems. In many greenhouses, the net available radiation is reduced by liming the greenhouse cover (Valera *et al*., 2016). An aqueous solution with calcium carbonate that remains on the cover plastic is applied, drastically reducing its transmissivity, because of the increase of the reflection coefficient (López-Martínez *et al*., 2019; Moreno-Teruel *et al.,* 2020).

In cold areas, such as northern and central Europe, or during the winter period in the Mediterranean region, there is a light deficiency, both from the energy point of view (net radiation) and from the needs of the crop (PAR radiation). To maximize the net radiation available inside the greenhouse, the transmissivity of the roof can be increased by new materials with higher transmissivity (Moreno-Teruel *et al*., 2021) or by using greenhouses with a geometry that improves radiation capture (greenhouse with Gothic-type roof or glass Venlo greenhouses). Increasing the width of the greenhouse modules also improves light harvesting, although this can reduce the structural strength of windows when their size is proportionally increased.

2.2. Photosynthetically active radiation (PAR)

PAR radiation is the fraction of light with a wavelength between 400 and 700 nm used by plants for photosynthesis (Carruthers *et al*., 2001; Kalaji *et al*., 2014). Photosynthetic photon flux density (PPFD) is defined as the photon flux density of PAR radiation. PAR radiation sensors measure the rate at which moles (6.02 × 10^{23} quanta) of PAR impact a unit area (μmol·m^{-2}·s^{-1}) (Carruthers *et al*., 2001). Greenhouse cover plastics and the use of whitewashing that reduce light intensity tend to attenuate certain wavelengths more than others, so they can affect light quality (Fig. 2).

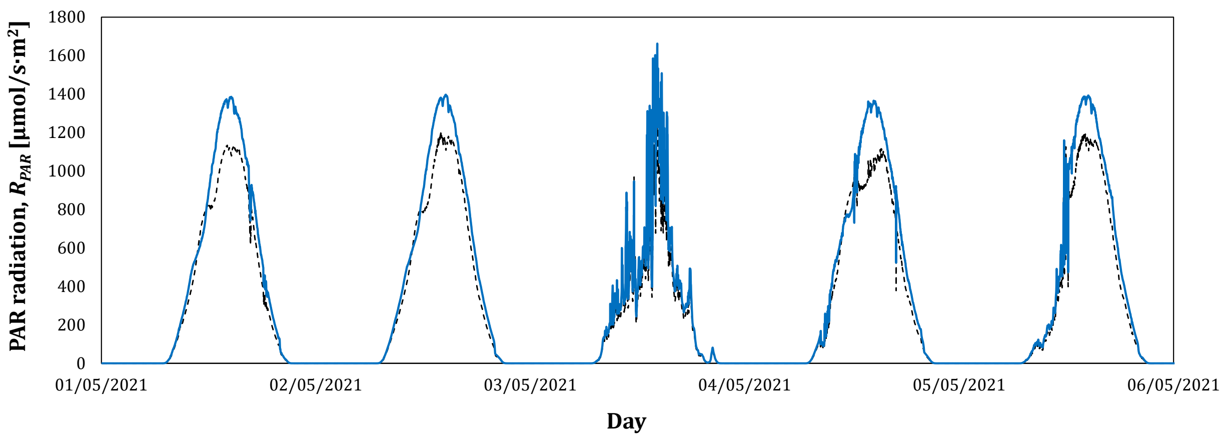


Figure 2. Evolution of PAR radiation in a greenhouse with a standard double-roof (---) and one with a plastic spectrum photoconverter (—), two days before and after liming the roof of a multispan greenhouse in Almería.

PAR radiation is the most important energy source for plants, although if its intensity is too high or too low it can become a stressor, causing photoinhibition and altering the photosynthetic process (Howarth and Durako, 2013). During the day, PAR radiation changes constantly and plants try to maintain a balance between the conversion of radiant energy and the protection of the photosynthetic apparatus against photoinhibition (Demmig-Adams *et al*., 1995; Bertamini and Nedunchezhian, 2003).

The proportion of radiation intercepted by the crop, called *Radiation Interception Efficiency* (RIE), changes during the crop cycle with plant growth (Lecoeur and Ney, 2003), as it is proportional to the *Leaf Area Index* (LAI) and canopy architecture (Lake *et al.,* 2021). The selective absorption of different wavelengths of PAR by photosynthetic pigments, together with the heterogeneity in the spectral distribution of light, make the effect of radiation dependent on light quality (Hill, 1996).

2.3. Air temperature

The inside air temperature depends mainly in the outside temperature (Fig. 3), related to geographical location, and on the energy balance inside the greenhouse, depending mainly on design factors as roof geometry and material, ventilation capacity, and soil characteristics (Molina-Aiz *et al*., 2017b; Reyes-Rosas *et al.,* 2017). The geometry of the greenhouse cover affects the capture of solar energy that heats the surfaces inside the greenhouse (mainly plants and soil). The covering material doubly affects the temperature inside the greenhouse.

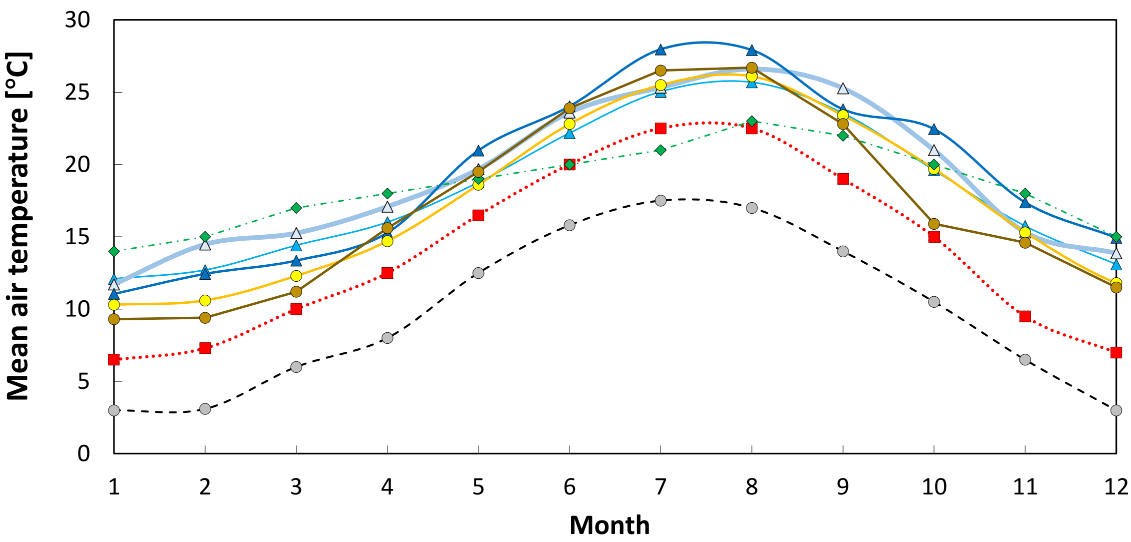


Figure 3. Evolution around the year of mean outside temperature corresponding to the cities of: Almería in Spain (—▲—) during the period 1934-2003 (Molina-Aiz, 2010) in 2021 (—△—) and in 2022 (—▲—); Agadir in Morocco (♦) during the period 1971-2000 (Hassan, 2013); Toulouse in France (···■···) over the period 1980-2009 (Felten et al., 2011); De Bilt in the Netherlands (- -○- -) between 1976 and 2005 (Klein Tank and Lenderink, 2009), Catania in Italy (—○—) during the period 1953-1990 (Lavagnni and Jibril, 1991 and) and Levano in Italy (—●—) during the period 208-2012 (D'Arpa *et al*., 2016).

On the one hand, its spectral characteristics affect the transmissivity of solar radiation (which heats the greenhouse during the diurnal period) and the emission of infrared radiation (which cools the greenhouse, mainly at night in the absence of sunlight). On the other hand, cover material influences the heat exchange by conduction-convection through the walls and roof of the greenhouse. Therefore, the covering material is a determining factor in the thermal balance of the greenhouse (Molina-Aiz *et al*., 2017b; Reyes-Rosas et al., 2017) and its heating and cooling needs (Kim *et al*., 2022). To reduce heating needs, roofing materials with low thermal conductivity, such as inflated glass or double plastic covers, and structures that are as airtight as possible should be used.

Inside air temperature (Fig. 4) affects not only growth, but also the nutritional metabolism of plants, which is related to photosynthetic activity (Liu *et al*., 2017). For most horticultural crops, their yield is adequate over a wide range of temperatures, although the net equilibrium of photosynthesis decreases when the temperature rises excessively due to increased respiration. An increase in temperature between 5 and 10 °C above the optimum can have a significant impact on net photosynthesis (Carnejo *et al.,* 2005). The optimum temperature of the crop is closely related to its yield and can be an important variable when selecting one variety or another crop (Santiago *et al.,* 1998).

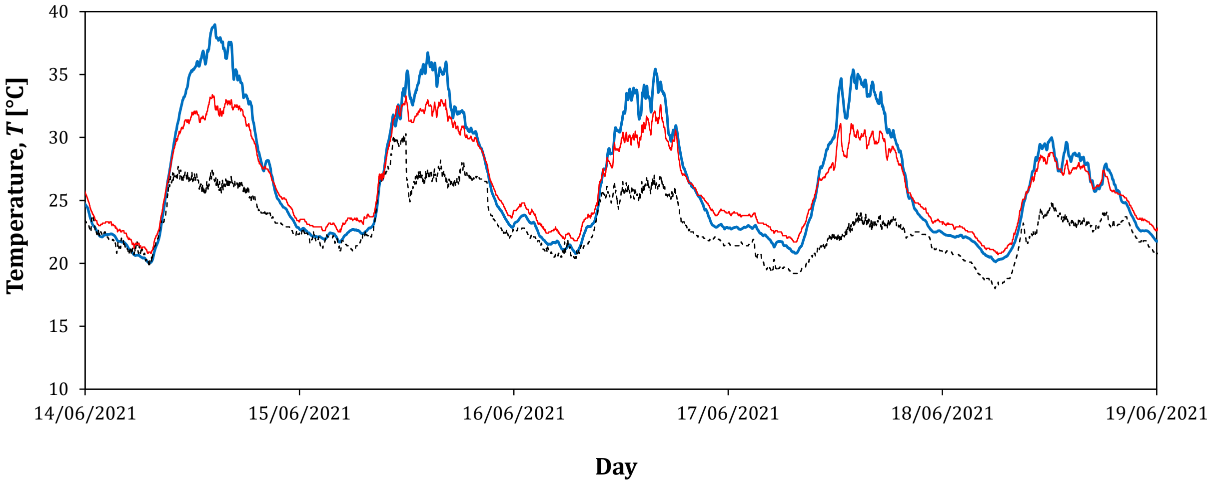


Figure 4. Evolution of the temperature of the exterior (----) and interior air in a multispan greenhouse of Almería at 1 m (–) and 2 m height (—)

The average temperature is essential in the development of horticultural crops, since at average daily temperatures close to 30 °C there are reductions in the number of fruits, the percentage of fruiting and the weight of the fruits. This reduction in yield is mainly attributed to decreased pollen viability due to excess temperature (Sato *et al.,* 2002-2006).

In the Mediterranean area, excess temperature from spring to autumn can reduce the productive capacity of crops (Kittas *et al.,* 1995). For this reason, it is necessary to reduce the temperature inside greenhouses by different cooling systems that will depend on climatic conditions, technology and available resources (Bakker *et al.,* 2008). The greenhouses in the province of Almería that use water evaporative cooling systems are around 20%, the most used being nebulization, due to the peculiarities of greenhouses in the area, such as excessive width and lack of hermeticity (Valera *et al.,* 2016). Water evaporative cooling systems are also associated with an increase in relative humidity within the greenhouse, being desirable in dry climate zones (Arbel *et al.,* 1999; González-Real *et al.,* 2007).

The combination of temperature reduction and increased relative humidity makes refrigeration systems more efficient than other climate control systems such as shade screens or forced ventilation

(Luchow and Von Zabeltitz, 1992). Misting systems are less efficient than evaporative panel and fan systems (Katsoulas *et al.,* 2009). However, their lower installation cost makes them more attractive for use in greenhouses (Luchow and Von Zabeltitz, 1992). The use of evaporative panel systems with extractors allows the temperature inside the greenhouse to be reduced by up to 3 °C compared to the outside (López *et al.,* 2012). However, this system produces uneven climatic conditions, with temperature gradients of 0.10–0.27 $°C·m^{-1}$ in the direction of air flow (Arbel *et al*., 2003) especially when the crop is transplanted in late August (López *et al*., 2010).

2.4. Crop temperature

The temperature of the crop is one of the main parameters that determine its physiological behaviour. This temperature depends on the energy balance in the leaves of the crop, so that the plant adapts its temperature depending on the radioactive energy it intercepts (Fig. 5). During the day, plants receive a large amount of solar energy and lose heat by the process of transpiration by which the tissues of the plant release water that when evaporated absorbs a large amount of latent heat. At night, the plant loses energy in the form of infrared radiation (also called thermal radiation) and reduces the transpiration process.

Depending on the environmental conditions, the value of the sum of these two terms of energy exchange of the plant with the environment can generate an excess of energy or a deficit. When the radiation is excessive and the plant cannot eliminate much latent heat by transpiration, because it does not have enough water in the soil (lack of irrigation) or because the leaf surface is scarce (in the early stages of development), a situation of thermal stress can be generated in which the plant increases its temperature a lot (above that of the environment) in order to lose excess heat in the form of heat sensitive.

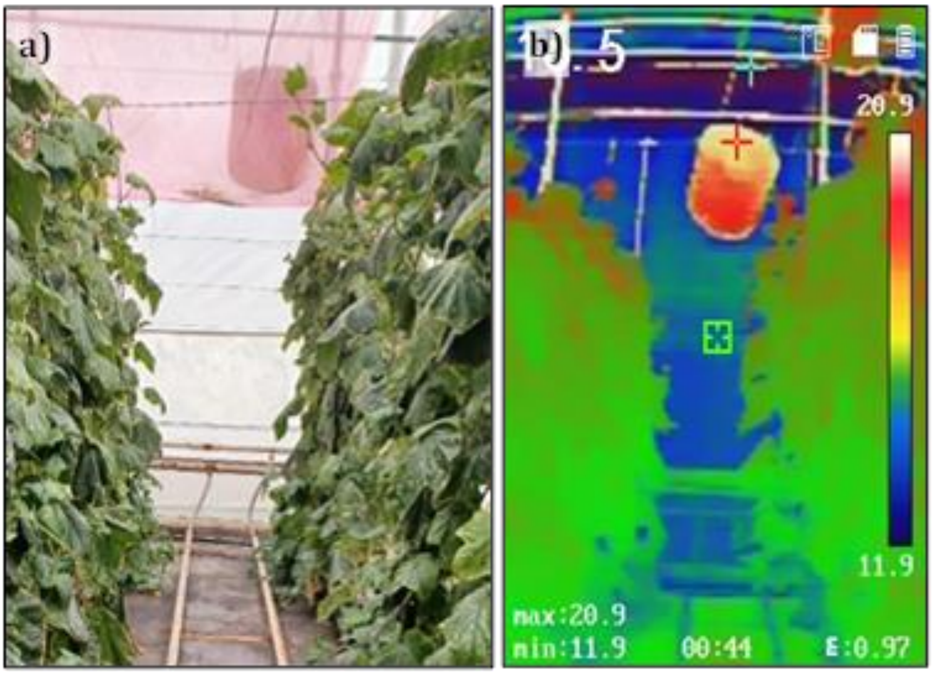


Figure 5. Real image (a) and thermography (b) of cucumber plants in a multispan greenhouse in Almería in the winter period (10/12/2021).

In the winter period, when the ambient temperature is low, the crop reduces transpiration, in order to maintain its temperature as high as possible (Figs. 5-6). This means that the plant closes the stomata (increasing stomatal resistance) to prevent water loss, which has a negative impact on lower photosynthetic activity, and therefore on a lower productive capacity. Under conditions of adequate irrigation and crop development, the leaves can have a temperature lower than that of the environment when solar radiation is not excessive (Fig. 6).

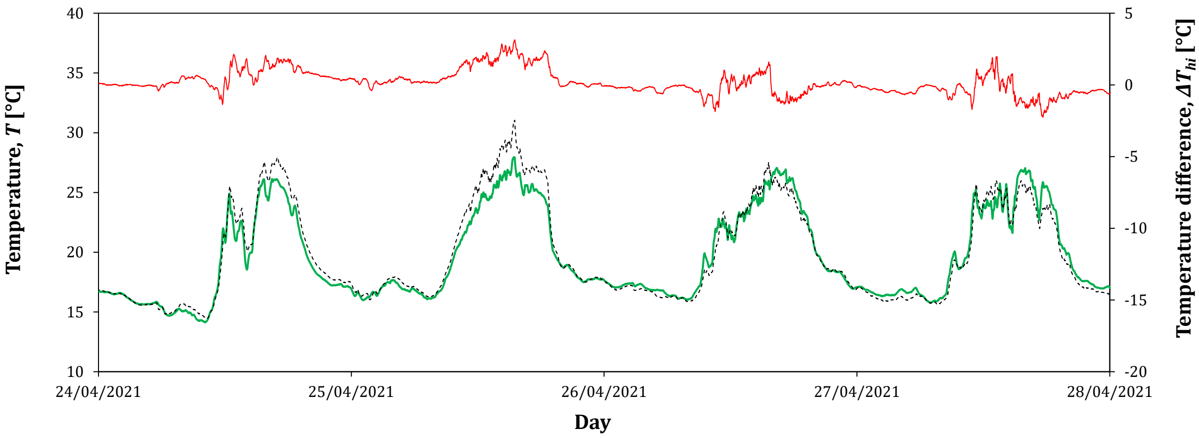


Figure 6. Evolution of the temperature of tomato leaves (–), air (----) and difference between crop temperatures and air represented in the secondary axe of the right side (—) in a multispan greenhouse in Almería.

About half of the solar energy available at the top of a canopy can be intercepted and absorbed by the leaves of a crop with LAI leaf area index < 2 $m^2 \cdot m^{-2}$ (Yang *et al*., 1990). Baille *et al*. (2001) observed how the use of bleaching in greenhouses can halve the mean transmissivity τc of the cover (from τ_c=0.62 to 0.31), resulting in a proportional decrease in the stomatal resistance of the plant canopy. As a result, the transpiration rate increases slightly (about 18%) while the temperature difference between plants and the air changes drastically (from 3 to –2 °C).

Thus, in a whitewashed Almeria-type solar greenhouse (τ_c=0.40-0.47), the temperature of a melon crop fell 6-8 °C below that of the air due to insufficient solar radiation (Molina-Aiz, 2010). Fargues *et al*. (2005) also observed values of the mean temperature in the leaves of a tomato crop of 0.8 to 2.8 °C lower than that of air.

The temperature profile of the crop is usually reversed in the morning because most of the solar energy is intercepted and absorbed by the leaves at the top of the canopy (Tchamitchian, 1993). This situation usually lasts only a short period of time in the morning due to evaporative cooling of the leaves at the top (Yang *et al*., 1989). At high levels of solar radiation, the energy absorbed exceeds the latent heat, resulting in an increase in crop temperature (Stanghellini, 1987; Marcelis, 1989). However, at low levels of radiation the leaves are cooler than air (Figure 5), since the energy absorbed by radiation is less than that lost by transpiration. In the case of tropical crops such as papaya, one way to increase the temperature of the crop is to surround it with thermal blankets, which allows the minimum temperature to be increased by 1 °C (Honoré *et al*., 2020a).

2.5. Soil temperature

Soil temperature is also a microclimatic parameter of great interest for greenhouse cultivation, due to the diverse and complex interactions that occur between plants and soil (Ehrenfeld et al. *2005; van der Putten* et al. 2013; Heinze *et al.,* 2017). In the soil, many abiotic (physical, chemical and biochemical) and biotic (living soil organisms) factors interact with roots (Mokany *et al*. 2006). As a result of the effect of soil temperature on soil physicochemical and biological processes (Heinze et al., 2016), and on gas exchange with the atmosphere (Onwuka and Mang, 2018), soil temperature affects crop growth and development (Sabri *et al.,* 2018). Soil temperature also influences seed germination and dry matter accumulation in early crop shoots. The optimum soil temperature varies depending on the crop, being 25 °C for tomatoes and between 25 and 30 °C for peppers and eggplants (Chermnih, 1971).

Soil temperature varies daily and throughout the year (Onwuka and Mang, 2018) because of changes in radiant energy and air movement across the soil surface, which determines convection heat exchange (Elias *et al.,* 2004; Molina-Aiz *et al.,* 2017b). The main factors influencing soil temperature are the amount of radiation reaching the soil surface (Geiger et al., *2003), soil color (Sándor* et al., 2012) or the type of mulch used (Martias and Musil, 2012; Elizaberashivili *et al.,* 2010; Reyes-Rosas et al., *2017), the content of organic matter (Abu-Hamdeh and Reeder, 2000) and the amount of water evaporated (Lu* et al.*,* 2019).

Soil constitutes an important heat storage, acting as an energy reservoir during the day and a source of heat to the surface at night (Onwuka and Mang, 2018). Two of the factors that determine the amount of heat dissipated in the soil are moisture content and bulk density (Abu-Hamdeh, 2003). Thus, soil temperature can be increased by using micro-tunnels, by 0.5-1.2 °C at the soil surface and by 0.5-0.6 °C at 20 cm depth (López-Martínez *et al*., 2021). The temperature of the soil surface can also be increased by placing black plastic padding, with a large absorption coefficient to solar radiation (Figure 6). On the contrary, the use of a mulch with sand, traditionally used in the sandblasted soils of the greenhouses of Almeria, allows to increase the reflection of the soil and thus decrease the temperature of its surface. In contrast, heat flow through the floor (downward during the day and upward at night) is not greatly affected using either type of mulch (Fig. 7).

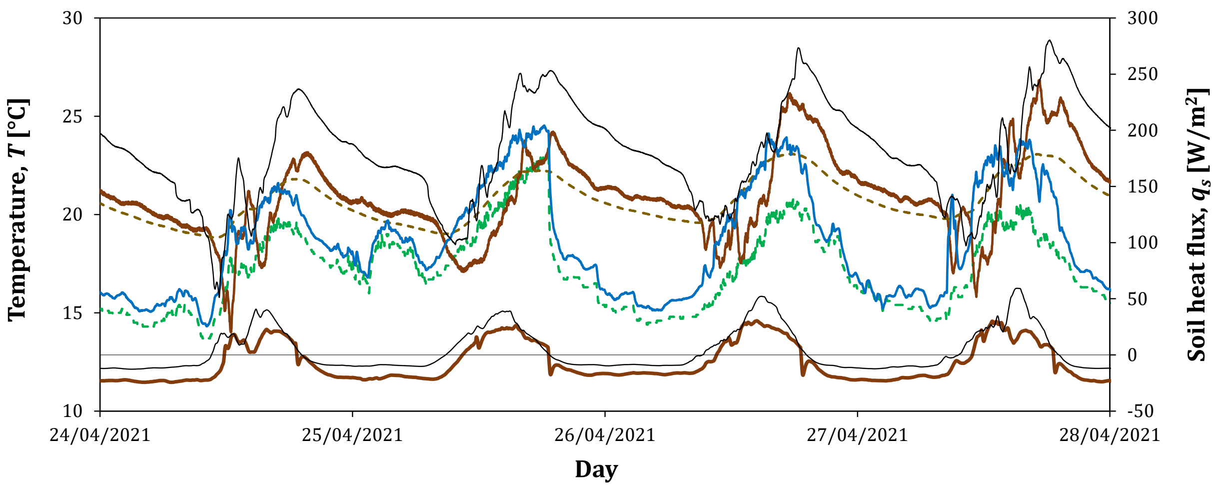


Figure 7. Evolution of soil surface temperature and heat flow in multispan greenhouses with sand mulched soil (—) and black polypropylene mulch (—). Soil temperature at 0.1 m depth in sandblasted soil (---) and outside air temperature at 2 m (—) and 6 m (---) height.

2.6. Air velocity

The movement of air inside greenhouses is produced by the processes of natural convection, due to temperature gradients in the indoor air that cause variations in its density, and by forced convection, when the air moves by the external impulse of the wind (natural ventilation) or by fans (forced ventilation). Under conditions of natural ventilation, air moves inside the greenhouse at speeds between 0.1 and 0.3 m·s^{-1} (Molina-Aiz, 2010), oscillating according to the intensity of the external wind (Fig. 8).

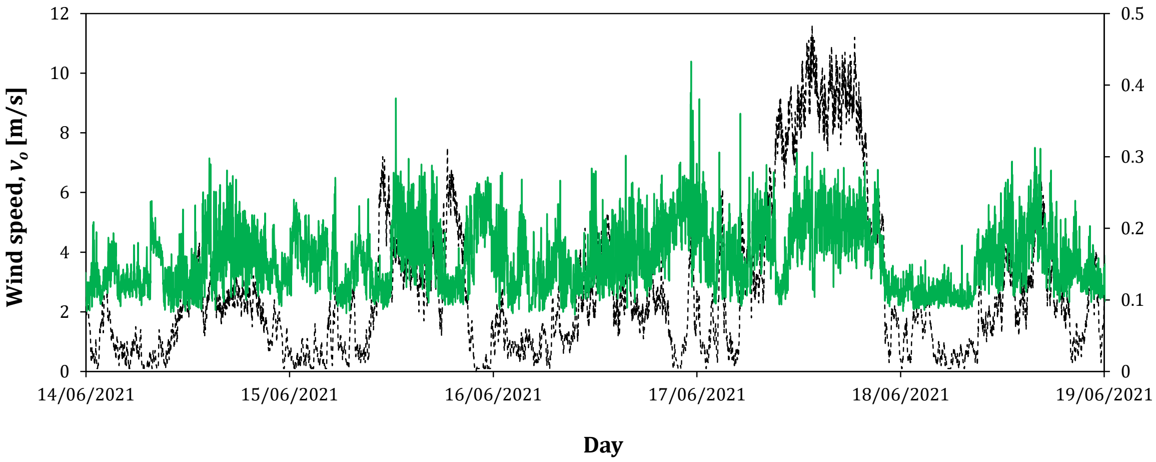


Figure 8. Wind speed measured at 9 m altitude (----) and air speed inside a multispan greenhouse with tomato cultivation inside (—).

The movement of air within the greenhouse is related to all the processes of energy and matter exchange (water vapor and CO_2) between air and plants (Shibuya and Kozai, 1998; Kitaya *et al*., 2003; Molina-Aiz *et al.*, 2020a) so their knowledge is fundamental (Sase, 2006). When the indoor air velocity is insufficient, air stagnation occurs, leading to a reduction in the exchange of energy from the soil and the plant canopy with the air (increasing temperature), water vapor (increasing humidity and decreasing transpiration) and CO_2 (decreasing photosynthesis). Net photosynthesis and transpiration rate increase significantly as air velocity increases from 0.01 to 0.2 m s^{-1} (Kitaya *et al.,* 2003).

However, an excessive increase in air speed can cause high crop transpiration, which in some cases could lead to water stress. As a response of the culture to these situations, a closure of the stomata can occur that reverts to a reduction in the exchange of CO_2 with the air, and therefore a decrease in its photosynthetic activity. In low temperature conditions, increasing air speed can also reduce the temperature of the crop.

2.7. Air humidity

Air humidity is an important factor in the greenhouse climate as it affects the processes of transpiration and photosynthesis and can help the development of fungal diseases. In general, humidity inside greenhouses is controlled based on relative humidity (RH) management, whose evolution is closely related to air temperature. During the central hours of the day, its value drops to values of 20-40%, rising at night to 80-90% (Fig. 9) and even reaching saturation conditions (100%) during the winter in closed greenhouses with well-developed crops.

The combination of values of temperature and relative humidity regulates vapor pressure deficit (VPD), that can affect plant growth, leaf and stem anatomical structure of plant (Devi et al., 2016; Schoppach et al., 2016; Du et al., 2018), transpiration (Devi and, 2018), water use efficiency, fruit production (Zhang *et al*., 2018) and dry matter of plants growing inside greenhouses. The background VPD conditions give different internal structure of muskmelon and cucumber, therefore it can improve the transport capacity of water to the leaf surface under low VPD conditions (Song *et al*., 2021).

Stomatal limitation to photosynthesis was reduced by low VPD under water stress. The reduction in plant growth induced by water stress was moderated by low VPD, partially due to higher photosynthetic rate (Du *et al*., 2018). At low VPD (LVPD), corresponding with high relative humidity conditions, the yield of tomato (Guichard *et al*., 2005) and leaf area can increase whereas leaf thickness decreases (Leuschner, 2002; Carins-Murphy *et al*., 2014).

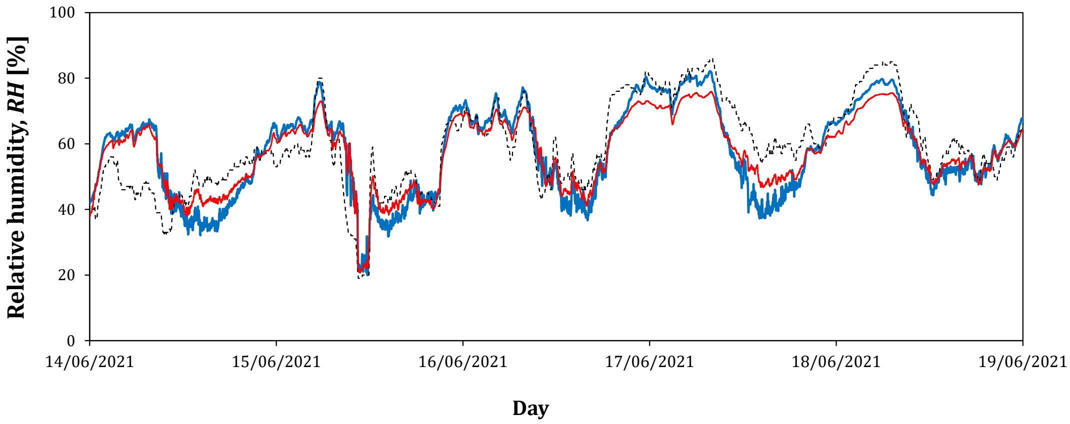


Figure 9. Evolution of the relative humidity outside (----) and inside a multispan greenhouse in Almería at 1 m (–) and 2 m height (—) with a tomato crop inside.

In crops with commercial leaf value, such as lettuce and ornamental plants, increased moisture can contribute to loss of yield, quality and commercial value (Hand, 1988). Since a high level of humidity inside the greenhouse does not usually appreciably affect the growth of most horticultural crops, this climatic parameter is often not taken into consideration, prioritizing the management of ambient temperature (Mortensen, 2000).

However, humidity control is very important to achieve high quality production. Under inadequate humidity conditions, the growth of some crops may decrease (Mortensen, 1986) and anatomical changes and alterations or delays in plant development may occur (Hand *et al*., 1996; Mortensen, 2000). High values of humidity in the air can even adversely affect the assimilation of some macronutrients (Gilsleröd *et al*., 1987). The best way to control humidity in greenhouses is through the vapor pressure deficit (DPV) of the air (difference between the partial pressure existing in the air and that which would be reached in case of saturation at air temperature). The increase in nocturnal DPV (from 0.27 to 0.86 kPa) favours flowering and fruit development, while, in the daytime period, low DPV values favour fruit setting. However, excessive DPV, with too low RH conditions, can lead to water stress of plants (Körner and Challa, 2003).

In general, farmers control the indoor humidity in solar greenhouses only by managing natural ventilation and in very specific cases, reducing crop fertigation or even watering the surface of the corridors. In highly technical greenhouses, with heating systems and automated climate controllers, the heating and opening of the windows can be managed according to the interior and exterior humidity. The main drawback of heating is that humidity control can sometimes counteract energy-saving measures within dynamic temperature regimes (Körner and Challa, 2003).

A relatively low humidity (55-75%) allows to increase the net assimilation rate of plants (van de Sanden and Veen, 1992) due to the increase in stomatal conductance (Torre *et al.,* 2001) that facilitates the processes of exchange of water vapor (transpiration) and CO_2 (photosynthesis) between plants and air. Continuous measurement of transpiration rate improves relative humidity control when using humidification systems (Suzuki *et al.,* 2015).

High humidity (75-95%) can produce beneficial effects, such as an increase in the individual surface area of the leaves (van de Sanden and Veen, 1992), although it can also cause adverse effects on flowering, fruit set and growth of crops such as pepper (Bakker, 1989). Relative humidity between 50-70% is considered optimal for tomato pollination, since values close to 90% can decrease the viability of pollen due to thermal stress (Peet *et al*., 2002).

One of the main reasons for moisture control in greenhouses is to avoid the incidence of fungal diseases (Körner and Challa, 2003). Although fungicides are used by farmers, the development of resistance or the impossibility of its use due to environmental restrictions (Köhl *et al*., 2000) makes it necessary to use alternatives for climate management such as the use of disease epidemiology models (Tantau and Lange, 2003). Using a greenhouse microclimate model, the periods of condensation and drying of the leaves can be estimated, controlling the greenhouse climate to avoid the incidence of fungal diseases (Körner and Holst, 2005).

2.8. CO_2 concentration

Ventilation of solar greenhouses in hot weather is the main method of climate control throughout the year. The flow of air through the windows directly influences the temperature and humidity distribution of the indoor air. However, a fundamental aspect is the distribution of CO_2 generated by the circulation of outdoor air inside the greenhouse. The CO_2 content in the area occupied by the plants (Fig. 10) and the available PAR radiation are the two basic factors that determine the photosynthetic activity of the crop.

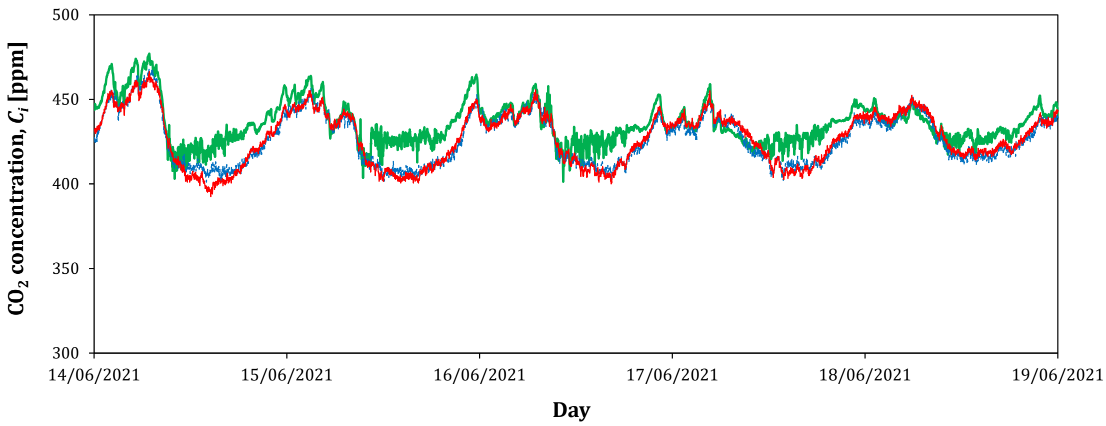


Figure 10. Evolution of the CO_2 concentration in the centre of a multispan greenhouse in Almería at 2 m height (–) and (–) and 1 m (–) with a tomato crop inside.

Increased CO_2 concentration can improve yield and dry matter accumulation in horticultural crops such as tomato, pepper and cucumber (Mortensen, 1987; Hicklenton and Jolliffe, 1978; Vafiadis *et al*., 2012; Segura *et al.,* 2001). Since 2011, the atmospheric concentration of CO_2 has been increasing progressively, reaching an annual average of 410 ppm in 2019 (IPCC, 2021). The increase in the level of atmospheric CO_2 because of anthropogenic emissions is causing a carbonic fertilization effect, that is, an increase in plant photosynthesis (Zak *et al.*, 2011) that improves crop growth and development (IPCC, 2020).

At these atmospheric concentrations, improved natural ventilation can help increase the CO_2 concentration within the greenhouse (Molina-Aiz *et al*., 2020a). In general, with adequate ventilation, concentrations close to the outside can be achieved during the day inside the greenhouse, while, when closing the greenhouse at night, the concentration can reach very high values of 450-470 ppm (Fig. 10), as a result of plant respiration.

Although the average ventilation surface with respect to the ground surface has increased in the greenhouses currently being built, it is still well below the recommended values of 30% (Molina-Aiz, 2010). The increase in the available ventilation surface would mean a substantial improvement in the cooling capacity and natural supply of CO_2, which would undoubtedly positively affect production (Molina-Aiz *et al.,* 2020b).

The distribution of CO_2 (Fig. 11) can be predicted by computational fluid dynamics (CFD) simulations, both in carbon-enriched greenhouses (Roy *et al*., 2014) and naturally ventilated greenhouses (Molina-Aiz *et al*., 2017a).

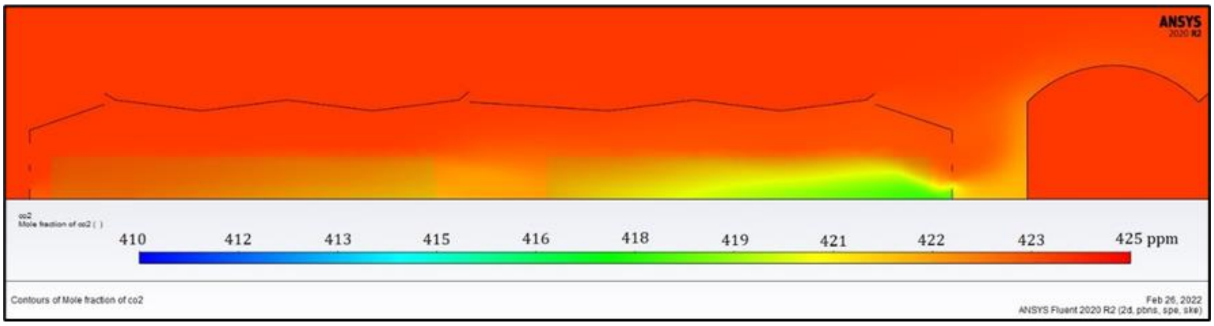


Figure 11. Distribution of CO_2 concentration in a solar greenhouse type Almería simulated by computational fluid dynamics (CFD).

3. Passives technologies to improve crop production

The horticultural sector has been faced in recent years with a difficult economic situation in which the stability in the sale prices of products in the face of the gradual increase in the production costs of greenhouse crops puts at risk the economic profitability of most farms (Valera *et al*., 2017). Thus, in the greenhouses of Almeria, the net operating profit (considering variable costs, fixed costs, amortization and investment costs) became negative for most crops in the seasons from 2015 to 2017 (Honoré *et al.,* 2019b; Molina-Aiz *et al*., 2020c). The main cost of production in the greenhouses of Almeria, and in general in the unheated solar greenhouses, is labour, which in the case of tomatoes represented on average 46% of total costs (Molina-Aiz *et al*., 2020c).

3.1. Passive climate control systems in Solar greenhouses

Solar greenhouses are based on the use of two renewable energies to produce horticultural crops practically all year round. On the one hand, greenhouses are collectors in which solar radiation is used for the development of crops through photosynthesis and for the warming of the environment. On the other hand, greenhouses need a contribution of CO_2 and evacuate excess radiant energy through natural ventilation that is based on a second source of renewable energy, wind. Passive climate control methods involve structural and design changes that do not require external intervention to function (Fig. 12). Greenhouses in the Mediterranean region tend to rely mostly on the use of these passive climate control systems (FAO, 2013).

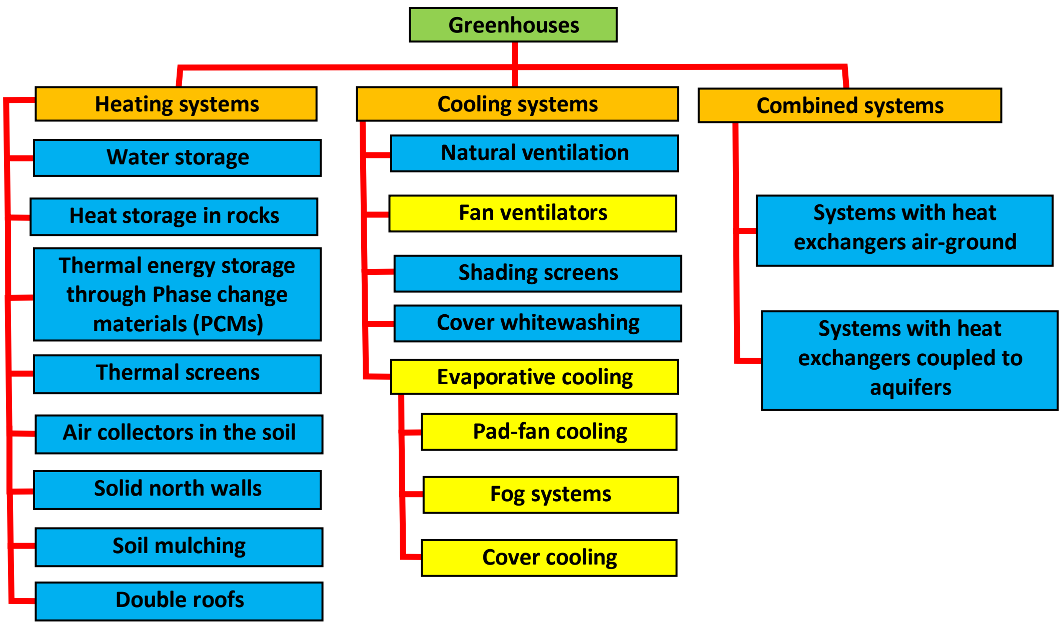


Figure 12. Classification of various climate control systems for greenhouses (adapted from Sethi and Sharma, 2008), highlighting passive methods (■).

The future of solar greenhouses is to face the great challenges of agriculture at a global level and the loss of profitability of the sector at a local level. For this, one of the main tools is the optimization of photosynthesis (de Boer and van Ittersum, 2018). This can be achieved by improving the cooling capacity by increasing the ventilation surface to partially or completely reduce the liming of the roof. Also important is a better interception of light from the structures (greater slope of cover), the use of diffuse plastics and spectrum converters, the optimization of the geometry of the crop lines to allow higher values of leaf area index and a better distribution of the leaves vertically.

3.1.2. Optimisation of ventilation systems

Natural ventilation is based on the movement of air caused by the outside wind (forced convection) and by variations in air density as a result of temperature differences (natural convection), so it does not need an external energy supply (Molina-Aiz *et al*., 2023).

The use of side openings together with roof vents has been confirmed as the best design for proper ventilation in multispan greenhouses (Kittas *et al*., 1997; Kacira *et al.,* 2004; Bournet and Boulard, 2010; López *et al.,* 2011a-b; Espinoza *et al*., 2017) and in the Almería type (Pérez-Parra *et al*., 2004; Molina-Aiz *et al*., 2009-2011-2012). Vanthoor *et al,* (2008) observed through models a productive increase of 0.63% for every 1% increase in the ventilation surface.

The insufficient ventilation surface of most solar greenhouses causes a significant reduction in CO_2 concentration. In the central greenhouse areas of Almeria, where ventilation is poorer, the CO_2 concentration can reach values of up to 370 ppm (Fig. 13), well below the values measured outdoors of 420-430 ppm.

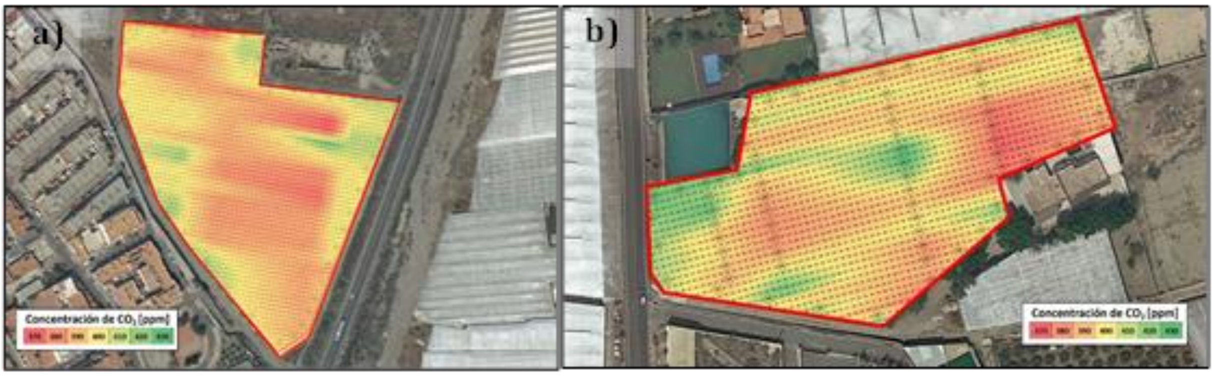


Figure 13. Distribution of CO_2 inside solar greenhouses of Almería of type "*raspa y amagado*" or simple (a) and "*parral plano*" or elemental (b).

The increase in the productivity of tomato crops thanks to the increase in the ventilation surface has also been observed experimentally in solar greenhouses of the Almería and multispan type (Valera *et al*., 2020). A linear relationship was observed between production and ventilation capacity (surface area and type of insect mesh) for the 9 tomato crops tested (Fig. 14).

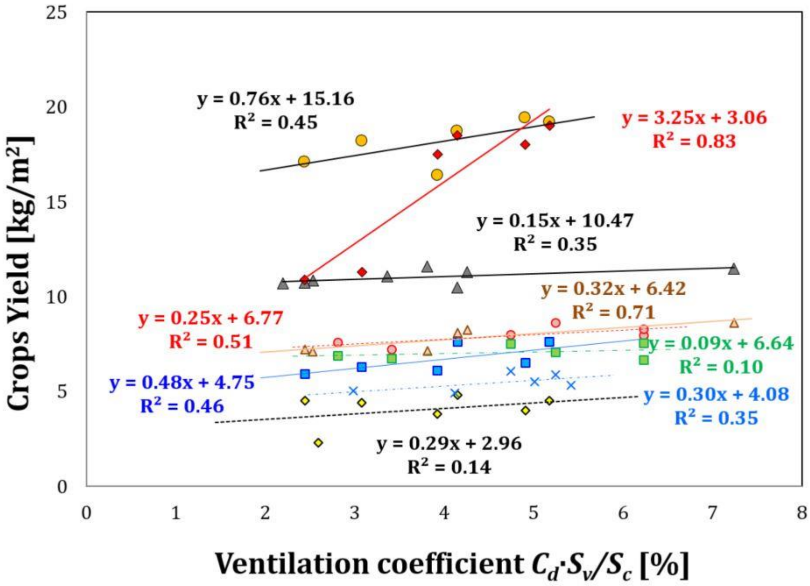


Figure 14. Crop production in function of the ventilation coefficient based in the discharge coefficient of the screened opening C_d and the percentage of ventilation (surface of opening S_v in relation to the soil surface S_c) for 10 cycles of tomato crops developed in multispan greenhouses: spring-summer 2008 (×), autumn-winter 2008-09 (●), spring-summer 2009 (■), autumn-winter 2011-12 (●), autumn-winter 2012-13 (■), spring-summer 2013 (♦), autumn-winter 2013-14 (♦), spring-summer 2017 (▲), autumn-winter 2017-18 (▲).

The increase of ventilation capacity (Fig. 15) affects positively the inside climate reducing hight temperatures, excessive humidity and maintaining CO_2 concentration close to outside value. As consequence, photokinetic activity increased, improving tomato production 4-8% in a multispan greenhouse and 5% in an *Almería*-type greenhouse when area of side vents was enlarged (Molina-Aiz *et al*., 2020b).

Figure 15. Multispan greenhouse in Almería with increased side openings.

3.1.3. Improvement of indoor radiation

Insufficient radiation levels produce significant abiotic stress that limits plant growth and greenhouse crop yields (Jiang *et al*., 2017). In low incident light, canopy leaves have an extremely low net photosynthetic rate and premature senescence (Acock *et al.,* 1978; Xu *et al.,* 1997; Frantz *et al.*, 2000), which results in a decrease in plant growth and productivity (Frantz *et al*., 2000; Steinger *et al*., 2003). Generally, a decrease in accumulated daily light of 1% leads to a yield loss of 0.8-1% for most greenhouse crops (Marcelis *et al.,* 2006).

The use of new cover materials with greater transmissivity and diffusivity allows more PAR radiation to be available (Fig. 16), which translates into higher levels of photosynthesis and crop production (Moreno-Teruel *et al*., 2021).

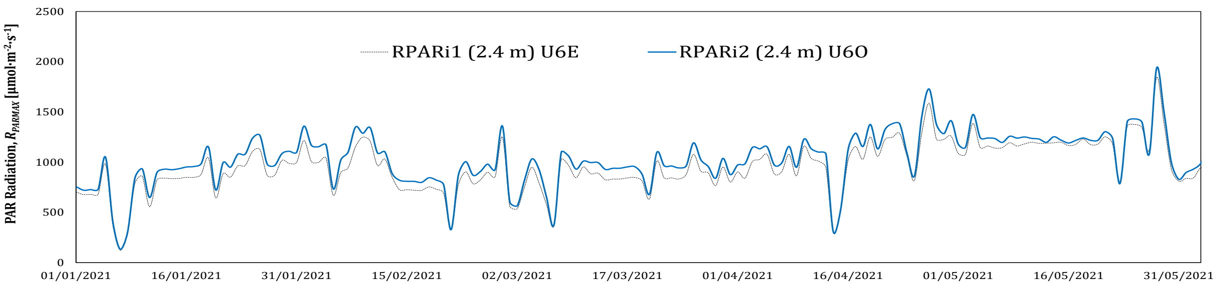


Figure 16. Maximum PAR radiation in sectors with experimental plastic (—) and standard plastic (—) for spring-summer cultivation of tomato in 2021.

On the other hand, the use of coloured plastic sheets that modify the quality of light by converting certain parts of the radiative spectrum (Inada, 1976; Inada and Yasumoto, 1989; Hidaka *et al*., 2008) also allow to increase the photosynthetic activity of plants. Spectrum converter plastics transform less effective wavelengths, such as green or yellow, into the red or blue wavelength range, where photosynthetic activity is the highest (Nishimura *et al*., 2012). The use of spectrum converter plastics as double indoor roofs in solar greenhouses in Almería has been shown to be effective in increasing photosynthetic activity and tomato crop production (Molina-Aiz *et al*., 2021).

3.1.4. Increased radiation reflection in the soil

Albedo, or fraction of incident solar radiation reflected by a surface, influences the availability of shortwave radiation and the energy balance on that surface, which can affect the microclimate, production, and use of water in agricultural systems (Bonachela *et al*., 2020a). The plastic mulching of the soil influences the passive control of the temperature in addition to favouring the fight against weeds and insects, preventing the evaporation of irrigation water and reducing humidity inside the greenhouse (Lamont, 2017). In greenhouses, the use of white plastic mulches to increase soil reflection is widespread, although recently the serious drawback of generating microplastics has been observed (Wang *et al*., 2022; Qi *et al*., 2023). The use of plastic mulching should be done with caution as it can influence the flight patterns of different insects depending on colour (Schalk *et al.,* 1979; Zitter and Simons, 1980). The use of mulching with the aluminized surface produced a reduction in thrip populations in tomato and pepper crops (Ham and Kluitenberg, 1994) as a consequence of the incidence of tomato spotted Wilt Virus (TSEV, *Tomato Spotted Wilt Virus*) whereas silver-coloured mulches may attract tomato miners (Schalk and Robbins, 1987).

In Almería, around 80% of greenhouses used the sand mulching named "*enarenado*" consisting of a layer with the natural terrain covered with an initial half metre-layer of soil with a high clay content, a second layer of manure or organic matter and the surface with a layer of silica sand (Valera *et al*., 2016). The mulching of the greenhouse soil with sand reduces soil evaporation and increases shortwave radiation reflected to plants (Bonachela *et al*., 2020b).

Plastic mulching with the greater reflection coefficient is aluminized and black with the upper face painted in white, with values of 0.39 and 0.48, respectively (Ham *et al*., 1993). In winter, black mulches (with an absorption coefficient of 0.96) that can increase the air temperature in the soil through conduction are usually used (Ham and Kluitenberg, 1994; Ham *et al.,* 1993; Reyes-Rosas *et al.,* 2017).

White marble gravel soil mulching reflects about 40-50% of radiation. White marble gravel mulching together with larger side vent openings reduce the maximum air temperature by –2.1-4.5°C and increase the relative humidity by 5-10%. The use of white marble gravel mulch (Fig. 10) together with larger side openings (Fig. 15) allows to reduce the net solar radiation while increasing the PAR radiation in the leaves of the plants by 6% (Molina-Aiz *et al*., 2023). The production of a first tomato crop developed in autumn-winter in the season 2022/23 increased 5%, whereas a second zucchini crop developed in spring-summer 2023 augmented 20% with respect to the use of standard ventilation and black plastic mulching.

Figure 17. Multispan greenhouse with a new soil mulching with white marble gravel in the University of Almería (Spain).

3.1.5. Reduction of cover whitewashing

The combination of "thermal" plastic covers (low transmissivity to infrared radiation from 0.7 µm to 1000 µm) and an adequate natural ventilation system allows to maintain adequate climatic conditions inside the solar greenhouses of Almeria during most of the year. Inadequate temperature and humidity conditions can cause various physiological disorders in horticultural crops (Savvas *et al.*, 2008). In conditions of high temperature and low air humidity, such as those that occur in the months of June and July in the greenhouses of Almeria, apical rot (*Blossom-End Rot*, BER) can occur in crops such as tomatoes (Bertin *et al.* 2000).

The analysis of climate data in 2021 and 2022 shows an evolution of the climate of Almeria that will require the use of cooling systems to be able to produce a large part of the year (Fig. 18).

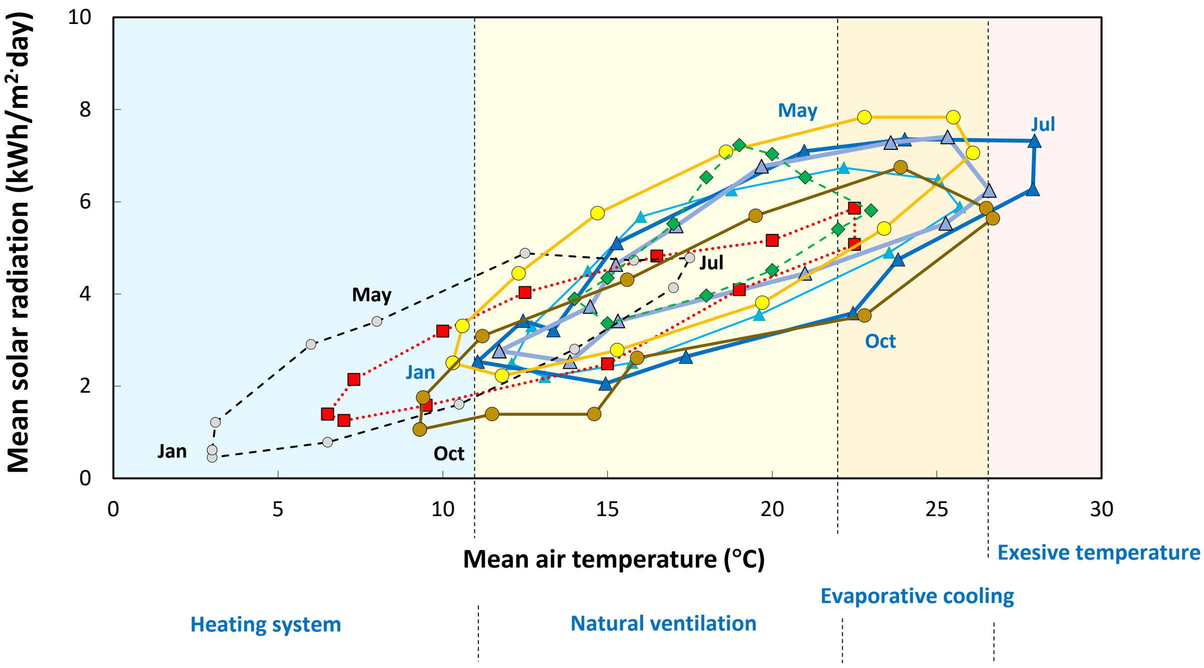


Figure 18. Average daily solar radiation relative to the average daily temperature corresponding to the cities of: Almería in Spain (△) during the period 1934-2003 (Molina-Aiz, 2010) in 2021 (△) and in 2022 (▲); Agadir in Morocco (♦) during the period 1971-2000 (Hassan, 2013); Toulouse in France (■) over the period 1980-2009 (Felten et al., 2011); De Bilt in the Netherlands (○) between 1976 and 2005 (Klein Tank and Lenderink, 2009), Catania in Italy (○) during the period 1953-1990 (Lavagnni and Jibril, 1991 and) and Levano in Italy (●) during the period 208-2012 (D'Arpa *et al.*, 2016).

To avoid this problem, greenhouses are whitewashed with calcium carbonate ($CaCO_3$) (called white of Spain) reducing their transmissivity and increasing their reflection coefficient to solar radiation (Baille *et al.,* 2001). The whitewashing of the cover in the greenhouses of Almería is usually carried out with doses of the applied product of 40/100 kg product/L of water (Valera *et al.*, 2016), which corresponds to transmissivity values of the cover of approximately 0.3-0.4 (López-Martínez *et al.*, 2019). The great drawback of the cover whitewashing is that the transmissivity to PAR radiation is reduced and therefore the photosynthetic capacity of the plants and the productivity of the crop (Moreno-Teruel *et al.,* 2020). In commercial greenhouses in Almeria these values can be reduced to 0.2-0.3 in the warmer months of June and July (Fig. 19).

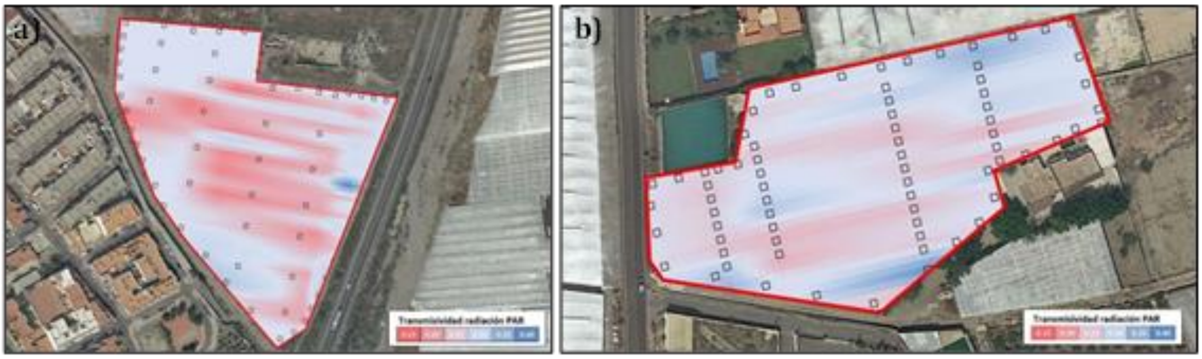


Figure 19. Distributions of cover transmissivity measured in commercial greenhouses of type "*raspa y amagado*" (a) and "*parral plano*" (b) in July 2019.

The low values of PAR radiation caused by whitewashing (Fig. 19) together with the reduction of CO_2 concentration (Fig. 13) and the temperature rises produced by poor ventilation decrease the photosynthetic activity of plants, well below their maximum potential (Fig. 19). This partly explains the significant difference between the productive capacity of greenhouses in Almeria and those in other producing areas with more unfavourable climatic conditions (Fig. 18). Thus, the average level of tomato production in the long cycle in Almeria is 16.8 kg/m^2, although farmers with better yields reach 20.9 kg/m^2, both in hight-tech and simple greenhouses (Valera *et al.,* 2016). These production levels are well below the productions obtained in highly technical greenhouses in Northern Europe or America of 55 kg/m^2 of tomatoes (Hendricks, 2012; Heuts *et al*., 2012*;* van Zundert, 2012) or even the values that are obtained in greenhouses in China of 20-35 kg/m^2 (Costa *et al*., 2004). However, these production systems generate a much higher environmental impact with global energy requirements of the order of 50-80 MJ·kg^{-1}, higher than those generated in Spanish solar greenhouses of 5 MJ·kg^{-1} (Torrellas *et al*., 2012).

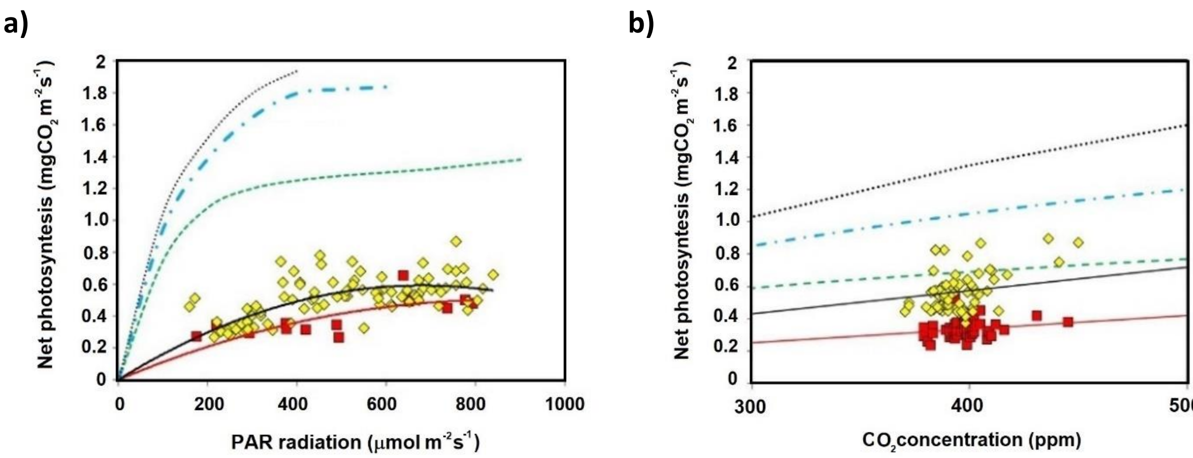


Figure 20. Photosynthesis as a function of PAR radiation (a): measured in tomatoes in greenhouses in Almería for CO_2 concentrations of 370-380 ppm (■) and 400-410 ppm (◊) with temperatures of 20-30 °C and simulated by Gijzen (1992) for 350 (---), 500 (-·-·-) and 700 ppm (····) at 25 °C. Photosynthesis as a function of CO_2 concentration (b) measured for PAR radiation values of 200-300 (■) and 700-800 µmol·m^{-2}·s^{-1} (◊) and simulated for 75 (---), 150 (-·-·-) and 300 µmol·m^{-2}·s^{-1} (····).

3.2. Energy saving systems in heated greenhouses

The Dutch horticultural industry is energy-intensive, based mainly on the consumption of natural gas (van der Velden and Verhaegh, 1992). The energy efficiency of Dutch greenhouses increased by 35% in the decade of the 80s as a result of the 57% increase in crop productivity per unit of cultivated area. The amount of CO_2 emitted into the atmosphere in 1989 is estimated at 6.5 million tons (van der Velden and Verhaegh, 1992). The greatest efforts to improve the energy efficiency of heating systems have been directed mainly at (Liao and Dexter, 2004):

- Increase the thermal insulation of heated buildings.

- Improve boiler efficiency by using condensers to recover heat from exhaust fumes.

- Use renewable energies such as biomass.

- Improve the control of distribution systems.

The main energy-saving measures implemented in greenhouses in the Netherlands were the incorporation of a condenser to the boilers, the installation of hot water storage tanks and the use of thermal screens (van der Velden and Verhaegh, 1992). However, the most important option that has allowed Dutch greenhouses to reduce their environmental impact has been the simultaneous production of electricity and heat (van der Velden and Verhaegh, 1992).

3.2.1. Climate measurement and control systems

The existence of computerized control systems for the management of the microclimate in greenhouses offers the opportunity to improve productivity and save energy. The choice of an appropriate control algorithm and a strategy adapted to local conditions and crop requirements are also essential (Spanomitsios, 2001).

The overall performance of a heating system can also be improved by obtaining a representative value of the air temperature to be controlled (Liao and Dexter, 2004). In the case of greenhouses this can be achieved by increasing the number of sensors that are installed in the greenhouse.

The use of nighttime temperature setpoints related to outdoor climatic conditions together with higher daily temperature regimes can reduce greenhouse energy consumption by 16% and meet the physiological requirements of plant growth and development (Spanomitsios, 2001).

Dieleman *et al*., (2006) studied the effect of temperature control on greenhouse energy consumption, observing how allowing fluctuations around the temperature setpoint can achieve energy savings of 3-13%, depending on the fluctuation bandwidth applied. Lowering the setpoint temperature by 2 °C reduced energy consumption by 16% and production by 3%. Increasing the relative humidity set and reducing plant transpiration by defoliating or applying antiperspirants showed energy savings of approximately 5%, with almost no effect on plant growth.

In the Netherlands, Bontsema *et al.* (2011) made a study on the impact that the accuracy error of the sensors of the climate control system would have on the overall energy consumption of the crop. They showed that this error can increase energy consumption in greenhouse air conditioning by 4.9–5.2%. The largest errors were detected in humidity sensors and solar radiation probes. They concluded that it was much cheaper to perform the annual calibration of the measuring equipment, than the energy cost overrun produced by its malfunction Bontsema *et al.* (2011).

3.2.2. Thermal insulation and double covers

In the specific case of greenhouses, heating oil consumption can also be reduced by including materials inside the greenhouses that reduce on the one hand the movement of air inside them (which reduces heat losses by convection from the air to the inner surface of the roof material) and on the other the emission of longwave radiative energy.

Greenhouses with double walls are also an effective method against low winter temperatures and can be considered as an alternative or a complement to heating systems. They perform better than in single-walled greenhouses (Papadopoulos and Hao, 1997a). Ferare and Goldsberry (1984) observed decreases of 34-40% in fuel consumption when using an inflated double cover (Fig. 21) compared to a single roof, although they found reductions of 10-17% in the level of solar radiation inside the greenhouse.

Figure 21. Use of inflated double cover in an unheated multispan greenhouse in Almería (Spain).

The vegetable varieties have also been selected to be able to use energy-saving systems with optimal yields and quality of production. The use of double cover produces various changes in the microclimate of greenhouses, the most obvious being the reduction of light (Bauerle and Short, 1981). Cucumber crops can be acclimatized to low solar radiation conditions produced by a double inflated polyethylene cover, reducing the specific leaf weight, and increasing their light interception efficiency. In cold climate conditions such as southwestern Ontario (Canada), greenhouses with double polyethylene cover do not produce productivity losses in cucumber and tomato compared to glass greenhouses, while allowing significant energy savings, up to 30% and in the initial investment (Papadopoulos and Hao, 1997a-b). In tomato cultivation, reductions in fruit size were observed during the beginning and middle of the season in the double polyethylene cover greenhouse with respect to glass, obtaining a 6-12% reduction in the size of the fruits of greater calibre (Papadopoulos and Hao, 1997b). In greenhouses without carbon enrichment, decreasing air infiltration can also reduce the CO_2 available to plants (Bauerle and Short, 1981).

3.2.3. Internal double roofs

The use of double roofs in greenhouses is a passive climate control technique normally used for the development of crops in cold periods (Cemek *et al*., 2006). The use of double roof structures over the crops (Fig. 22) produces an increase in the minimum night-time temperature, reduces temperature oscillations and relative humidity, provided it is combined with adequate ventilation management during the day (Salvador, 2015). Double-roofs used inside greenhouses provide better insulation from external climatic conditions (Papadakis *et al*., 2000), which results in energy savings for greenhouse heating of 40% to 50% in active climate systems but affects the transmissivity of light reaching the crop.

The double roof reduces heat losses in greenhouses by 35-40% (Landgren, 1985) and reduces energy inputs to greenhouses to maintain the temperature (Ahamed *et al*., 2019). The use of double roofs increases average summer and winter temperatures around the crop (Ward and Bomford, 2013) and can improves the production and quality of tomato crops (Abak *et al*., 1994).

Figure 22. Double roof with a photoconversion of spectrum film inside a multispan greenhouse in Almería (Spain).

One of the problems of the use of double roof inside greenhouses is the reduction of light transmission. This problem can be attenuated using spectrum converter film that can increase PAR transmission moving radiation to the range where photosynthetic activity is the highest (Nishimura *et al*., 2012). Spectrum convert film modify the solar spectrum reaching crops by modifying plant photosynthesis and the microclimate around crops (Yoon *et al*., 2020). Spectrum converter film can transform blue-green light (450-550 nm) into red light (600-700 nm) or ultraviolet (UV)-violet light (350-450 nm) into the blue-green light range influencing crop development (Hidaka *et al.*, 2008; El-Bashir *et al*., 2016). Spectrum converter film can enhance the photosynthetic activity of crop leaves by 15% (Yoon *et al.*, 2020). In the University of Almería, the use of augmented natural ventilation and a double roof with photoconversion films (Fig. 22) improved crop photosynthesis inside greenhouses.

3.2.4. Thermal screens

Various energy-saving measures are currently being implemented in both the construction and operation of greenhouses to minimize heat losses during heating and to improve the use of solar energy. For this, two systems are usually used, the thermal screens located under the greenhouse gutter (Fig. 23) and which are deployed during the night and removed during the day to allow the entry of solar radiation, or the thermal curtains or blankets (with a high transparency to solar radiation) that are deployed during the coldest season in the space between the crop and the thermal screen (Seginer and Albright, 1980; Bailey, 1981a; Barral *et al*., 1999).

The energy savings provided by the use of indoor thermal screens have been verified both by experimental data (Bailey, 1981b; Roberts *et al*., 1981) and through analytical studies (Chandra and Albright, 1980; Seginer and Albright, 1980). The effect of thermal screens on energy consumption is the mutual effect of physical and biological factors since on the one hand heat losses are reduced but also affects the rate of time needed to produce an amount of plant mass (Amsen *et al*., 1978). Sims (1978) observed that the use of a clear polyethylene thermal screen managed to reduce fuel consumption by 27% for the January-April period without reducing production in a greenhouse tomato crop.

Figure 23. Thermal screen inside a Venlo glasshouse with a pepper crop in Almería (Spain).

The thermal screens are driven by automatically controlled mechanical systems that unfold and fold the screens on top of a network of polypropylene monofilaments (Roberts *et al*., 1981). It is important that the system allows the edges to be hermetically closed to prevent warm air leaks. Although, fully porous materials provided less energy savings, they were easier to manage (Roberts *et al*., 1981).

The use of thermal screens at night can reduce heat losses by 16 to 60% (Roberts *et al*., 1981; Baille *et al*., 1985; Dieleman *et al*., 2006) depending on the type of material used and its properties against thermal radiation (Table 1).

The use of thermal screens reduces heat transfers with the outside both by convection and radiation, and even latent heat transfer (Bailey, 1981). Thermal screens must simultaneously have low transmissivity and emissivity to thermal radiation in the mid- and long-infrared (2.5-40 µm) using aluminized sheets with a high reflection to thermal radiation (Bailey, 1981a), which are either inserted as flat sheets in a polyester or polyethylene net or arranged as braided fibres. The most efficient are those with both aluminized faces and if only one of them is aluminized, it should be placed facing outwards (Baille *et al.,* 1985).

Table 1. Properties of different types of thermal screens: transmission coefficients τ_{IR} and reflection coefficients ρ_{IR} to infrared radiation, heat transmission coefficient K_T and percentage of energy savings achieved with the use of the screen (Bailey, 1981b; Nijskens *et al*., 1984a-b; Baille *et al*., 1985).

Materials	τ_{IR}	ρ_{IR}	*KT* (W/m²·K)	Energy saving (%)
Low density polyethylene	0.18-0.85	0.03-0.05	6.29	32.5
Polypropylene	0.26	-	6.98	35.5
Polyester with aluminized underside	0.01	0.43-0.92	5.34	42.0
Polyester with aluminized upper face			4.99	46.0
With both sides aluminized	0.01	0.95	4.97	46.5

The best time to close or open thermal screens is when the potential increase in photosynthesis when folded is equal to the potential heat energy savings when deployed (Seginer and Albright, 1980). Thermal screens produce the greatest energy savings when deployed just before dusk and collected in the morning (Pirard *et al*., 1994). Some types of thermal screens are designed to allow their use as shade nets during midday, although in general this entails a loss of performance for use as an energy saving system with heating systems.

Baille *et al.* (1984) observed experimentally that the use of acryl-polypropylene thermal screens very effectively reduced convective losses (by 50% or more), radiative losses and even losses due to infiltration of the outside air, which were less affected by wind. At night, they observed significant differences in plant temperature that were up to 2 °C higher in the greenhouse with thermal screen (Baille *et al.*, 1984), this increase being greater with aluminized screens than with polypropylene or polyethylene screens (Baille *et al.*, 1985). During the unheated period, the increase in air temperature in the greenhouses induced by the screen was about 1-2 °C (Baille *et al.,* 1984).

The heat-saving effect of a thermal screen is the result of energy consumption both during the day and at night. Thus, Amsen (1986) observed a 17% increase in heating oil consumption during the day, after retracting the curtains in the morning. This higher consumption was due to the need for extra heat input to readjust the heating system and to heat the structure of the greenhouse. At night, when the curtains are deployed, the opposite happens due to the readjustment of the heating system to the greater insulation of the greenhouse, so that in the first hours energy savings of 44% are achieved, and 33% in the final part of the night period. The total savings after a full day was 27% (Amsen, 1986).

De Graaf (1985) observed that the use of thermal screens causes large changes in the greenhouse climate, which in turn have a great influence on crop transpiration. Thus, they found decreases of between 25 and 60% of the transpiration of a tomato crop as a result of the use of screens, which was greater during the growing period. By opening gaps of about 15-20 cm between the screens it was possible to reduce the negative effect of the screens on perspiration (de Graaf, 1985)

Barral *et al*. (1999) used a system with thermal screens under the cover of the greenhouse and transparent and low-weight synthetic thermal blankets on the crop with the aim of avoiding the arrest of plant growth by concentrating, as close as possible to the plants, the energy stored in the soil during the day and distributing it through polyethylene tubes during the night. The system allowed to maintain satisfactory temperature levels, above 13°C in the area around the plants, which allowed to maintain a continuous growth and fruiting of the tomato and pepper plants (Barral *et al*., 1999).

Gilli *et al*. (2012) in Switzerland, they studied in a Venlo-type greenhouse for tomato production, the effect on energy efficiency and fruit quality, of two types of materials: a thermal screen (SLS 10 ultra plus) and an aluminized shading mesh (XLS *15 firebreak*). In a greenhouse (test), the shading mesh was deployed half an hour after dawn, if the temperature was above 5ºC and if the light intensity was greater than 3 klux, and folded half an hour before nightfall, while the thermal screen was extended in the greenhouse one hour after dawn (if the conditions mentioned above were met) and folded one hour before nightfall. In a second greenhouse used as a witness, the two screens opened just at dawn. The trial showed that 23% to 27% of energy could be saved without adversely affecting fruit and crop quality, or yield (Gilli *et al*., 2012).

3.2.4. Thermal blankets

Another system that reduces heat losses from the soil and plants, by infrared radiation and convection to the air are thermal blankets, which can be placed over plants directly during the first weeks of growth (Fig. 24) and then removed completely or at an intermediate height between the crop and the thermal screens. They can be manufactured by thin filaments of polypropylene stabilized against ultraviolet radiation to reduce their degradation by the direct action of the sun. The blanket is a thin sheet of very light fabric (weighing approximately 17 g m^{-2}) with high air permeability and high transparency to solar radiation, around 95% (Shukla *et al*., 2006), which allows the crop to develop correctly under it. These thermal blankets can also be 50 µm transparent polyethylene sheets (Ghosal and Tiwari, 2004). They can be placed on the crop at 1 m height (Barral *et al*., 1999), which allows to increase the temperature of the air surrounding the plants between 2 and 3 °C during the night and the first hours of the morning, and reduce 3-4 °C its temperature during the central hours of the day (Ghosal and Tiwari, 2004).

Figure 24. Thermal blanket over the plant of fava beans sown in "*arenado*" sand mulched soil in a multispan greenhouse of the University of Almería (Spain).

Arinze *et al*., (1986) built and experimentally analysed a system of thermal screens placed in the middle of the two sheets of a greenhouse of semicircular structure with double cover (an outer sheet of inflated polyethylene and an inner sheet of fiberglass). Both experimental tests and calculations made with a computer model, showed reductions in heating energy consumption of 60 to 80% with the use of thermal screens between the double cover.

Abak *et al.* (1994) studied the effects of a double plastic shell and thermal screens on tomato plant development and greenhouse temperature. When thermal screens were deployed at night, minimum temperatures were 2.5 °C, 3.4 °C and 3.4 °C higher than in a single-deck greenhouse without thermal screens, in a double-decked greenhouse, in a greenhouse with double-deck and thermal screen, and in a greenhouse with thermal shield and single-deck, respectively. On the other hand, the double deck and thermal screens did not affect the early spring yield, although the total production was increased compared to plastic greenhouses without screens. Although thermal screens and double cover did not fully protect the crop from autumn frosts, they did manage to slightly reduce and delay frost damage (Abak *et al.*, 1994).

3.2.5. Energy storage systems

Scientific studies have been conducted on the effect of passive greenhouse heating methods (Abak *et al*., 1994; Santamouris *et al*., 1994). Passive heating can be done by storing heat in water tanks, storing it in bedrock under the greenhouse floor, floor padding, movable insulation and thermal screens or blankets (Shukla *et al*., 2006).

Santamouris *et al*. (1994) designed, built and tested a 1000 m^2 prototype passive solar agricultural greenhouse to reduce heat losses and increase solar energy harvesting on a daily and seasonal basis. The greenhouse was equipped with a wall with a mass for heat storage on the north side and a network of ground-to-air heat exchangers buried in the greenhouse. The two systems together provided 35% of heating needs for a 2-year period (Santamouris *et al*., 1994).

Ozturk and Basçetinçelik (2003) conducted a thermodynamic study of the use of a heat storage system using a volcanic rock bed (54 kg of material per m^2 of soil) located under the floor of a plastic cover tunnel-type greenhouse in Turkey. The bedrock stored the heat captured by solar panels placed on the south side of the greenhouse. The results obtained showed that 18.9% of the energy needs of the greenhouse were provided by the storage unit.

Wang and Liang (2006) studied an underground heat storage system using an 11.2 cm layer of concrete in a double-decked greenhouse designed to reduce energy consumption in greenhouses. Through this system, increases in soil temperature between 2 and 5.2 ºC were achieved, with air temperature and humidity values suitable for plant growth (Wang and Liang, 2006).

De Gelder *et al.* (2012) have developed a novel cultivation system for tomatoes in greenhouses in the Netherlands with the aim of considerably reducing the energy required, by 40% to go from 1.3 G·J m^{-2} $year^{-1}$, without affecting a deterioration in the quantity and quality of production, maintaining it at 60 kg m^{-2} $year^{-1}$ (which would mean an energy consumption of 12.5 MJ/kg). To do this, they made intensive use of thermal screens combined with humidity control, maximizing the integration capacity of the crop by reducing high humidity, improving the efficiency in the contribution of CO_2 by reducing ventilation and the use of refrigeration combined with a heat pump and an aquifer as a thermal storage system. In this system, the main factor was the prolonged use of thermal screens with an elevated level of insulation (greater than 79%) to reduce energy demand, combined with a forced ventilation system that injects relatively dry outside air into the greenhouse (Gelder *et al*., 2012). Maximizing the use of crop integration capacity implies a strong relationship between the sum of daily radiation and average daytime temperatures, and a significant difference between daytime and nighttime temperatures. This reduces energy requirements and ventilation rates (Gelder *et al*., 2012).

Aquifer Thermal Energy Storage (ATES) systems use natural water in a permeable and saturated underground layer as the storage medium. The transfer of thermal energy is done by extracting groundwater from the aquifer and reinjecting it normally at a modified temperature into another nearby well. Being sources or sinks of heat, aquifers have been used to store large amounts of thermal energy to supply water to balance the supply and demand of cooling and heating on both a short- and long-term basis (Lee, 2010).

Palmer *et al*. (1992) conducted hot water injection and thermal storage trials to investigate the feasibility of thermal energy storage in shallow, unconfined aquifers. As a result of the tests they obtained the three-dimensional temperature distribution within the aquifer, observing a good penetration into the physical processes of thermal energy storage of the aquifer (Palmer *et al.*, 1992). Applications of cold storage in aquifers include its use for air conditioning and refrigeration equipment in institutional and commercial buildings and the cooling of industrial processes (Schlaetzle *et* al., 1980). Currently, there are many cold storage systems operating in North America, Europe, and particularly in the Netherlands (Bridger and Allen, 2005).

In the current context of scarcity of fossil fuels and awareness of environmental problems (greenhouse gases), energy saving and conversion to renewable energies have become priorities. Thus, in France, an important development of the concept of "*sustainable greenhouses*" is taking place, using renewable energies and using a reversible air conditioning system through the storage of thermal energy in aquifers. This technique has already been in use for years in other European countries, especially in the Netherlands and France the Ctifl (*Centre Technique Interprofessionnel des Fruits et Legumes*) and the BRGM *(Bureau de Recherches Géologiques et Minières*) are carrying out research projects aimed at evaluating the feasibility of this technique for use in greenhouse air conditioning in France (Courtois *et al*., 2008).

Within these projects Grisey *et al.* (2012) have used the concept of the semi-closed greenhouse to reduce the large energy loss due to ventilation and the high thermal inertia in greenhouses. The *Energy Sustainable Greenhouse* project sought to reduce thermal losses using double plastic cover, double thermal screen on the roof and the installation of thermal screens on the sides. Improving humidity control through the employment of industrial dehumidifiers and developing a semi-enclosed greenhouse equipped with ATES reversible air conditioning systems to store and use excess energy (Grisey *et al.*, 2012).

Turgut *et al.* (2009) also conducted a research project in 2005-2006 with the aim of determining the heating and cooling potential of the ATES system in greenhouses in the Mediterranean climate zone. Similarly Wong *et al*. (2011) carried out a study in 2007 to evaluate the application of ATES technology and a "*closed*" greenhouse in the climatic conditions of Canada by performing simulations of the energy flow in the greenhouse (using the *Transient System Simulation (*TRNSYS) software).

4. Greenhouse production in Europe

4.1. Characteristics of the greenhouse production in Europe

Greenhouse cultivation involves growing crops inside structures covered with a transparent material that protects from extreme weather and unfavourable climatic conditions (Nemali, 2022). Greenhouses can disconnect, to some degree, the inside microclimate and outside climate conditions, that they are getting more extreme and unpredictable as consequence of climate change. Greenhouses can also ensure high resource use efficiency, mainly in water, which is scarce especially in Mediterranean region (EPI-AGRI, 2019). Greenhouses have glass (denominated also as glasshouses) or plastic roofs (and walls) that allow solar radiation to enter the structure and heats the plants and soil (or substrate) faster than the heat is able to escape from the structure (EUROSTAT, 2020).

In addition to greenhouses, there are other forms of protected cultivation, including rowcovers, low and high tunnels, and net houses. A greenhouse differs from others mainly in its higher level of technology and permanent nature of structural components used for construction (Nemali, 2022). Crops under glass or high accessible cover refers to crops that are covered by accessible greenhouses for the whole period of growth or for the predominant part of it and exclude the tunnels not accessible to persons (EUROSTAT, 2020).

4.1.1. Greenhouse area in Europe

The surface of protected cultivation inside greenhouses is increasing around the world because they can provide high-quality products all-year round (EPI-AGRI, 2019). However, the area of vegetables, flowers and permanent crops under greenhouses was significantly reduced in lasts seasons (Table 2). In 2016 the estimated total area in the EU was about 120 930 ha (Table 2), that represents a decrease of 7.1% respect to surface of 130 170 ha in 2005 (EUROSTAT, 2023A).

In the Mediterranean region (Fig. 25), permanent crops under greenhouses constitutes the most productive form of primary agricultural production, with an area of about 86 000 ha in 2022 (Table 2).

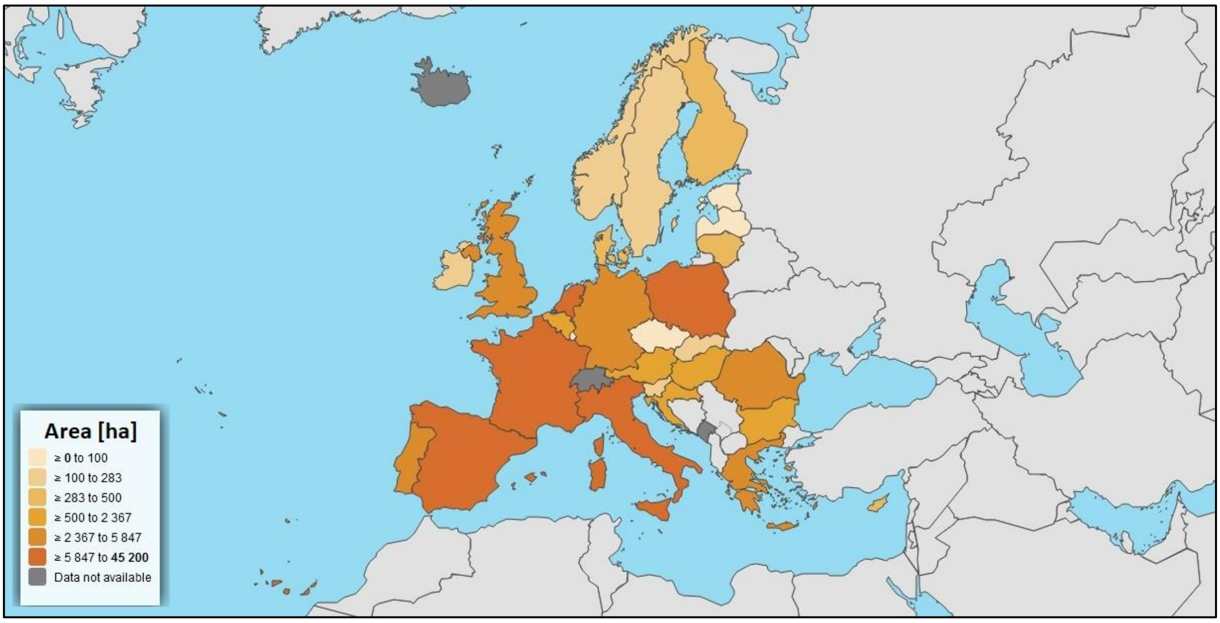


Figure 25. Greenhouse distribution in the countries of the European Union EU-27 (EUROSTAT, 2023A).

The effect of the smaller acreage was aggravated by the Europe-wide summer drought (FL, 2023). Spain, the Netherlands and Italy have increased their greenhouse surface in 2022 with respect to 2016, but other countries as Greece, Germany and France have reduced it (Table 2). The main crops cultivated are vegetables (with tomato and cucumber covering almost 70% of the cultivated area), cut flowers and potted plants.

Table 2. Area of vegetables, flowers and permanent crops under greenhouses EU-27 [ha] ([a] Until 1990 former territory of the FRG.EUROSTAT, 2023A; [b] MAPA, 2023f; [c] ISTAT, 2023b; [d] AFP, 2023; [e] AGRESTE, 2022; [f] ELSTAT, 2021; [g] Draghici *et al.*, 2021; [h] DESTATIS, 2023; [i] Costa *et al.*, 2020; [j] LNV, 2021; [k] STATBEL, 2023).

Country	2005	2007	2010	2013	2016	(2019)	2022
Spain	52 170	52 720	45 700	45 200	43 540		63 390 [b]
Italy	28 640	26 500	39 100	38 910	28 310		30 820 [c]
Netherlands	10 540	10 370	9 820	9 330	8 830		10 636 [d]
France	9 620	9 790	-	11 190	10 300		9 813 [e]
Poland	7 170	7 560	6 630	8 080	6 230		-
Greece	4 670	5 340	4 290	4 730	5 250	(2019)	5 100 [f]
Romania	2 790	3 250	3 020	3 300	3 890	(2019)	1 420 [g]
Germany [a]	3 370	3 430	3 170	3 110	3 540		3 199 [h]
Portugal	2 310	2 220	2 360	2 490	2 310	(2019)	3 000 [i]
Hungary	1 910	1 760	1 960	2 260	1 790	(2019)	3 510 [j]
Belgium	2 140	2 120	2 060	1 800	2 080		2 726 [k]
Bulgaria	900	1 140	1 090	1 080	1 060		-
Austria	290	580	620	720	690		-
Croatia	-	250	410	500	620		-
Cyprus	420	430	450	420	370		-
Denmark	450	470	460	400	380		-
Finland	450	440	420	400	390		-
Lithuania	1010	450	310	330	290		-
Sweden	420	180	200	260	300		-
Ireland	60	30	60	180	270		-
Slovenia	170	180	170	160	210		-
Malta	70	70	80	100	110		-
Slovakia	250	190	150	100	90		-
Estonia	60	60	40	40	30		-
Latvia	110	80	50	40	50		-
Czechia	180	190	0	0	0		-
Luxembourg	0	10	0	0	0		-
Total	**130 170**	**129 810**	**122 620**	**135 130**	**120 930**		**-**

4.1.2. Greenhouse production in Europe

Overall, the vegetable harvest in 2022 was –6% lower than in the previous year in the EU-27 (Table 3). After weak economic results in the previous two years, acreage for the 2022 season had been restricted in key producing countries. Late frosts in the spring then caused additional losses and delays. According to initial estimates, around –11% fewer watermelons and –8% fewer melons were harvested across Europe (FL, 2023).

The sharp rise in energy costs was also reflected in crop volumes (FL, 2023). For the fruit vegetables tomatoes, peppers and cucumbers, the crop volume across Europe was estimated to be around –10% smaller than in the previous year (FL, 2023). According to the Dutch Central Bureau of Statistics (CBS), the gross yield of greenhouse vegetables in 2022, compared to a year earlier, decreased by 7.9% to 1.78 million tons (Table 3).

Table 3. Total [millions of kg] fresh vegetables production ([a] FL, 2023) and inside greenhouses (with the percentage with respect to overall production) in Europe EU-27 ([b] MAPA, 2023b; [c] ISTAT, 2023b; [d] CBS, 2023; [e] AGRESTE, 2022; [f] DESTATIS, 2023; [g] ELSTAT, 2021).

Country	2019 [a]	2020 [a]	2021 [a]	2022 [a]	In greenhouses 2022
Spain	10 391	9 971	10 430	9 497	4 757 (50.1%) [b]
Italy	7 211	7 212	7 862	7 600	1 477 (19.4%) [c]
Poland	5 354	5 240	5 369	5 549	
Netherlands	5 484	5 383	5 695	5 017	1 780 (35.5%) [d]
France	5 263	5 160	4 981	4 935	712 (14.4%) [e]
Germany	3 707	3 693	4 057	3 499	229 (6.5%) [f]
Belgium	1 777	1 726	2 007	1 836	
Romania	1 865	1 957	1 941	1 748	
Greece	1 445	1 583	1 601	1 563	469 (30.0%) [g]
Hungary	1 303	1 264	1 260	1 190	
Portugal	794	1 101	1 201	1 010	
Austria	611	644	675	674	
Sweden	346	395	409	413	
Denmark	300	303	287	292	
Finland	294	297	284	290	
Czechia	226	252	275	261	
Bulgaria	313	256	262	249	
Lithunia	230	220	238	226	
Ireland	219	222	231	219	
Croatia	141	182	145	140	
Slovakia	122	119	142	135	
Slovenia	119	134	114	109	
Other EU	222	217	223	212	
TOTAL	**47 737**	**47 531**	**49 689**	**46 664**	

In heated and illuminated greenhouse cultivation in the Benelux region, production periods were shortened to keep costs in check due to the high-energy prices. The energy demand of greenhouse could decrease through energy savings, using new greenhouses, (additional) energy screens, more efficient lamps (LED) and energy-efficient cultivation strategies (Smit and van der Mee, 2022).

Conditions in the Spanish growing regions were also negative, particularly in the spring of 2022, with the result that slightly below-average yields were also achieved here (FL, 2023). Total vegetable production, including open field and greenhouses, decreased in Spain –8.6% between 2019 and 2022 (Table 4). The yields per hectare in the Netherlands also decreased for almost all crops in the cultivation of greenhouse vegetables (CBS, 2023a). The fall in production has been attributed to a combination of declining area and lower yield per ha, both of which were blamed on the impact of high-energy prices on grower's decision making. The gross yields of tomatoes (–12.5 %) and cucumbers (–9.1 %) diminished last year 2022 with respect to 2021 (CBS, 2023a) and the total vegetable production decreased a –8.5% with respect to 2019 (Table 4).

Total production of principal fresh vegetables decreased from 2019 to 2022 2.2% in Europe EU-27's, with reduction of -1.5% in tomatoes and -6.2% in cucumbers, two of the main vegetable crops (Table 4).

In contrast to this decrease in production, the EU consumption of fresh fruit and vegetables is expected to increase by 2031, driven by an increasing consumer awareness of the benefits of adopting a diet rich in fruit and vegetables, as well as public initiatives to promote their consumption (EC, 2021).

Table 4. Total production [millions of kg] (inside greenhouses and in open field) of principal fresh vegetables in Europe EU-27's main producer countries (FL, 2023; [a] CBS, 2023).

Country	Europe		Spain		Italy		Netherlands		France		Greece	
Crops	**2019**	**2022**	**2019**	**2022**	**2019**	**2022**	**2019**	**2022**	**2019**	**2022**	**2019**	**2022**
Tomatoes	6 263	6 169	2 008	1 793	1 049	1 080	910	835	704	706	463	553
Peppers	2 864	2 880	1 312	1 296	250	245	415	420	-	-	155	145
Lettuce	2 513	2 525	1 009	832	487	560	250	260	216	177	70	76
Cucumbers	2 439	2 287	739	668	-	-	410	421	-	-	129	131
Courgettes	1 574	1 731	602	617	569	560	16[a]	15[a]	-	-	66	60
Aubergines	-	-	-	-	301	330	62	61	-	-	55	58
Onions	6 837	6 314	1 600	1 198	478	400	1 699	1 494	494	511	134	146
Other	25 246	24 757	3 121	3 093	4 078	4 425	1 684	1 528	4 383	4 291	373	394
TOTAL	**47 737**	**46 664**	**10 391**	**9 497**	**7 211**	**7 600**	**5 484**	**5 017**	**5 263**	**4 935**	**1 445**	**1 563**

4.2. Greenhouse energy consumption in Europe

Greenhouses are complex structures used to improve climatic conditions affecting plant growth and production throughout the year, by controlling temperature, humidity, water, light, and carbon dioxide (Von Elsner *et al*., 2000a) and protecting from rain, wind, hail and snow (Bibbiani *et al*., 2016).

The greenhouse farming sector in Europe is facing a tendency as consequence of the varying consumer demands in a society that, globally, is increasingly wealthy (Bibbiani *et al*., 2016). Consumers consider greenhouse production as the most intensive agricultural production (Tittarelli, 2020) as compared to energy use in traditional open-field agriculture (Paris *et al*., 2022b). The substitution of the production in the open field by that of the greenhouses generates concerns in the consumers. Intensive production is associated with negative consequences, such as high energy consumption, with increasing demand of fossil energy, augmentation of environmental impacts and emissions of carbon dioxide (CO_2) and others Greenhouse Gas (GHG) (Bibbiani *et al*., 2016).

However, greenhouses have been extremely successful in providing abundant, cheap and high-quality vegetables and fruits, by using more efficiently natural resources (sun, wind and water) and input (minerals and pesticides) than open field cultivation. Greenhouse technology has allowed to rapidly convert marginal agricultural land into protected cultivation in many (semi-arid) regions of the world, improving primary and secondary activities (Stanghellini *et al*., 2003).

Greenhouse structures and equipment vary significantly around the EU, ranging from intensive structures with sophisticated actives climate control systems and a high-energy consumption, to simple structures covered with a plastic sheet, with production inputs similar to open-field crops and low-energy requirements. In between are a large part of the greenhouses in the Mediterranean region, with simple structures and passive climate control systems, without the need for the use of energy for their operation.

Greenhouse type is choice depending on the local climate conditions, the specific crop cultivated, the environmental control technologies and the workforce available in the region (EPI-AGRI, 2019). The design of the greenhouse structure is also determined by the type of covering materials used. Mechanical and radiometric properties of cladding materials determine the transmittance and the insulation performance of the greenhouse (Bibbiani *et al*., 2016) and consequently the energy consumption.

4.2.1. Energy consumption and gas emissions in European greenhouses

Total energy consumption in greenhouse production in Greece, Spain, Italy and The Netherlands was estimated in 2008-09 as 42 891 GWh (Table 5), corresponding to a fossil energy of 3.69 Mtoe, with calculated yearly direct emissions of 24.46 $MtCO_2eq$, and a total yearly economy value in products and structures in the range of 12.5 billion € (Bibbiani *et al.*, 2016).

Table 5. Average energy consumption of greenhouse agriculture in Europe (Bibbiani *et al.*, 2016).

Country	Greenhouse area (ha)	Energy consumption (MWh)		Average consumption (GJ/ha) [a]		Total energy		Gas emission	
		Heating	Electricity	Heating	Electricity	(GJ/ha)	(kWh/m²)	(toe/ha) [b]	(tCO_2eq/ha) [c]
Greece	5 646	87 644	1 700	56	1.1	57	1.6	1.4	9.3
Spain	43 964	989 627	33 623	81	2.8	84	2.3	2.0	13.6
Italy	30 000	8 432 500	112 866	1 012	13.5	1 025	28.5	24.5	168.2
Netherland	10 311	29 510 800	3 723 000	10 303	1 300	11 603	322.3	277.2	1 819.6
Total/Average	**89 921**	**39 020 571**	**3 871 189**	**1 562**	**155.0**	**1 717**	**47.7**	**41.0**	**272.0**

[a] 1 MWh=3.6 GJ (Krey *et al.*, 2014).

[b] 1 GWh = 8.60×10^{-5} Mtoe - Mega tonne oil equivalent (Krey *et al.*, 2014).

[c] Using a factor emission corresponding to 2010 of CO_2 for electricity of 0.594 tCO_2eq/MWh and for heat production of 0.331 tCO_2eq/MWh. CO_2-equivalent emissions (CO_2eq) are aggregated using global warming potentials (GWPs) over a 100-year time horizon (Krey *et al.*, 2014).

In the warmest Mediterranean areas, the greenhouse technology is normally based on the principle of minimizing capital investments, running costs and energy consumption (Giacomelli et al., 2012; Castilla and Montero, 2008). Thus, most of greenhouses in countries of the Mediterranean area as Spain, Italy and Greece are commonly characterized by simple structures, use of low technology, reduced energy inputs without heating systems and labour intensive (EPI-AGRI, 2019; Blanco *et al.*, 2022). In these unheated greenhouses, the climate is controlled passively using natural ventilation in spring-summer and energy saving systems that allow the interior temperature to increase during autumn-winter such as double roofs or thermal blankets (Valera *et al.*, 2016). In these countries the average energy consumption of greenhouses ranged between 57 GJ/ha in Greece, with few greenhouses equipped with heating, and 11 603 GJ7ha in Italy, where a part of the greenhouses is equipped with heating systems, mainly in northern regions with a colder climate. The equivalent emissions produced in greenhouses of Mediterranean areas ranged from 9.3 to 168.2 tCO_2eq/ha (Table 5).

In Central and North Europe, greenhouses are mainly high-tech with active climate control using heating and artificial lighting systems that involve high-energy consumption. Although these high-tech greenhouse farming allows maintaining optimal conditions for year-round production, they are the most expensive option in terms of energy consumption, running costs and capital investment (Vanthoor *et al.*, 2012; EPI-AGRI, 2019). In the Netherland, average consumption of energy is 11 603 GJ/ha, with emissions of 1 819.6 tCO_2eq/ha (Table 5).

In temperate and northern European countries, greenhouses try to optimize the indoor environment to maximize crop production (Baille, 2001; Castilla *et al.*, 2004). Greenhouses in these cold regions have been evolving following the development of new technologies advanced as the automation of the environment control, soilless cultivation and agro-robot systems (Stanghellini *et al.*, 2003; De Pascale and Maggio, 2005).

In the last years, the technology associated with greenhouses production has progressed considerably with significant changes in design, materials, climate control and irrigation systems, growing techniques, crop protection and vegetal materials (Valera *et al.*, 1999; Valera *et al.*, 2016). As a consequence, the maximum potential yield in greenhouses has increased for most crops, and actually the production of tomatoes in greenhouses with intensive use of technology can reach up to 60 kg/m^2 in recent years (Aznar-Sánchez *et al*., 2020).

A large proportion of greenhouses, especially in Southern Europe, are not heated and the total energy requirement ranges between 125 and 273 GJ/ha equivalent to 3.5-7.6 kWh/m^2 (Table 5). In South Europe, about 3-6 toe·ha^{-1}·year^{-1} are required for keeping the air temperature inside unheated greenhouses at around 15°C-20°C in low energy intensity tomato production systems (Table 6).

In North and Centre Europe, greenhouses often have large heating requirements ranging from 12 600 to 15 000 GJ/ha, equivalent to 350-420 kWh/m^2 (Table 6). In Germany and The Netherlands 300-360 toe·ha^{-1}·year^{-1} is required for maintaining optimal air temperature inside the greenhouses using heating systems. In the Mediterranean countries as Greece and Spain, the heating energy necessary to maintain similar conditions inside greenhouses are lower, between 8 100 and 10 000 GJ/ha. When cooling systems are also used in spring-summer, the total energy requirement can reach values similar to those of colder countries, about 14 000 GJ/ha, equivalent to 390 kWh/m^2 (Table 6).

Table 6. Energy inputs in low and high-energy intensity tomato production systems ([a] Campiglia *et al*., 2007; [b] Alonso and Guzman 2010; [c] de Visser *et al*., 2012; [d] Baptista *et al*., 2012; [e] Kittas *et al*., 2014).

Country	Chemical	Electricity	Irrigation	Heating	Cooling	Others	Total energy		Gas emission	
	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(kWh/m^2)	(toe/ha) [f]	(tCO$_2$eq/ha) [g]
Low energy intensity tomato production systems										
Italy [a]	23.7	65.62	1.97	-	-	34.3	125.6	3.5	3.0	11.6
Spain [b]	46.4	-	13.91	-	-	140.6	201.0	5.6	4.8	18.5
Greece [c]	105.5	-	53	-	-	98.5	257	7.1	6.1	23.5
Portugal [c]	89.5	-	92.5	-	-	91.0	273	7.6	6.5	25.2
High energy intensity tomato production systems										
Greece [e]	58.8	-	-	8 138	328	25.2	8 550	237.5	204.3	786.1
Spain [d]	-	-	-	10 080	3 816	0	13 896	386.0	332.0	1 277.7
Germany [c]	42	-	-	12 612	-	-	12 654	351.5	302.3	1 163.5
Netherlands [c]	119	-	-	14 990	-	-	15 110	419.7	360.9	1 389.2

[f] 1 GWh = 8.60×10^{-5} Mtoe - Mega tonne oil equivalent (Krey *et al*., 2014).
[g] Using a factor emission corresponding to 2010 of CO_2 for heat production of 0.331 tCO_2eq/MWh (Krey *et al*., 2014).

The weight of each input in the energy consumption of greenhouses (Table 7) varies greatly between the different production systems with significant ranges in function of the geographical area and climate conditions, the type of greenhouse, the climate control system and agricultural practices and techniques-conventional, organic, conservation, soilless cultivation, hydroponic, etc., employed (Palmitessa *et al*., 2020; Paris *et al*., 2022a).

Table 7. Range of energy consumption per category in EU greenhouses (Paris *et al*., 2022a).

Energy consumption per category	Range of total energy consumption
Heating and cooling	0–99%
Irrigation	1–19%
Fertilizers	1–27%
Pesticides	0–6%
Lighting	1%

Energy consumption is mainly depending on the use of heating systems. There are a large variety of options for heating a greenhouse, including central heating through boilers and water pipes, air heaters or heat pumps (D'Arpa et al., 2016). Energy sources vary, with small systems often running on direct fossil fuels, such as gas or oil, while larger systems may run on cogeneration/combined heat and power from power plants, or geothermal heat pumps (Paris *et al*., 2022a).

The quality and the production level in Spain could be improved by using high-tech greenhouses with heating and CO_2 enrichment systems (Van der Velden et al., 2004). The surface of greenhouses incorporating these technologies in Spain is lower than 3% (Valera et al., 2016; JA, 2022a), and majority of Spanish greenhouses are usually unheated. The efficient use of energy is important to maintain competitiveness by reducing the energy costs and the environmental impacts. Generally, energy requirements in high-tech greenhouses with active climate control are around 8–12 times greater that in low-cost greenhouses with passive energy control (Paris *et al*., 2022a). Primary fuel consumption per kg of tomatoes, peppers and cucumbers is estimated to be 13, 14-17 and 9 times greater respectively in the Netherlands than in Spain (Van der Velden *et al*., 2004).

The annual energy greenhouse heating requirements mainly depend on the temperature difference desired between external environment and the inside microclimate. Thus, in mild climate regions of Mediterranean countries greenhouses need between 4 800 and 7 300 GJ/ha for the heating system, whereas in north and central European countries or cold regions (as Lombardía in Italy) the requirements range between 8 600 and 16 300 GJ/ha (Table 8).

Table 8. Comparative representation of the annual energy greenhouse heating needs in different European countries ([a] Tataraki *et al*., 2020; [b] García *et al*. 1998).

Country	Total energy [a]		Gas emission		Locations	Total energy [b]		Gas emission	
	(GJ/ha)	(kWh/m²)	(toe/ha)	(tCO_2eq/ha)		(GJ/ha)	(kWh/m²)	(toe/ha)	(tCO_2eq/ha)
Spain	5 688	158	135.9	523.0	Almeria	3 168	88	75.7	291.3
Greece	4 824	134	115.2	443.5	Central Greece	7 128	198	170.3	655.4
Italy	7 308	203	174.6	671.9	Lombardia	14 616	406	349.2	1 344
France	9 648	268	230.5	887.1	South France	8 604	239	205.5	791.1
Netherlands	11 700	325	279.5	1 076	De Bilt	15 264	424	364.6	1 403
Germany	14 472	402	345.7	1 331	Central Germany	16 308	453	389.6	1 499

4.2.2. Energy consumption in greenhouses in Spain

In Spain, there is high variation in the use of energy in greenhouse production, with a mixture of intensive and non-intensive greenhouses, while the average holding sizes are relatively small (Valera *et al*., 2016; Paris *et al*., 2022a). The heating and cooling energy requirements vary considerably in the Iberian Peninsula in function of the outside temperature. Thus, estimated power and energy consumption for heated greenhouses heavily climatically controlled in different locations of Spain and Portugal ranged from 5 360 GJ/ha in Almería (Southern Mediterranean coast) with an average outside temperature of 21.3 °C to 16 272 GJ/ha in Navarra (north) with a mean temperature of 15.5 °C (Table 9). This last value is comparable to energy consumption in North and Central Europe (Tables 8).

Table 9. Computed maximum heating and cooling power and energy consumption in high energy intensity tomato greenhouse production in Spain and Portugal using a Greenhouse Climate Simulator (GCS) (Baptista *et al*., 2012).

Location	Average Outside Temperature (°C)	Maximum heating power (W/m²)	Maximum cooling power (W/m²)	Heating consumption		Cooling consumption (GJ/ha)	Total energy consumption (GJ/ha)
				(GJ/ha)	(kWh/m²)		
Spain							
Almeria	21.3	108.1	269.4	5 630	156	5 610	11 240
Huelva	22.6	105.2	282.6	5 760	160	6 192	11 952
Castellon	20.6	134.6	269.8	8 700	242	5 340	14 040
La Coruña	17.5	124.5	141.5	9 756	271	1 368	11 124
Madrid	19.3	165.0	266.8	13 644	379	4 536	18 180
Navarra	15.5	168.8	149.3	16 272	452	1 512	17 784
Portugal							
Madeira	17.3	64.0	181.4	2 174	60	3 334	5 508
Azores	17.3	78.0	209.8	2 880	80	3 960	6 840
Faro	17.0	97.3	287.6	5 220	145	6 156	11 376
Torres Vedras	16.3	102.8	231.9	5 652	157	4 356	10 008
Vila do Conde	11.0	113.8	244.2	6 768	188	4 788	11 556

More than 95% of Spanish greenhouses have low climate control without heating systems and require considerably less energy inputs (Table 10). The most important consumption of electrical energy is related to the drive of the motors that control the opening of the windows.

Table 10. Energy consumption in low energy greenhouse production in Spain (Alonso and Guzman, 2010).

Crop	Fertilisers	Pesticides	Irrigation	Others	Total	
	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(kWh/m²)
Tomato (average)	25.0	21.5	13.9	140.6	201.0	5.6
Lettuce	2.7	0.9	3.0	138.5	145.0	4.0
Pepper	12.1	1.0	21.0	166.1	200.2	5.6
Beans	5.3	0.2	4.7	145.1	155.4	4.3

Only 8.4% of the greenhouses in Almería use heating systems, which in most cases consist of indirect combustion air heaters equipped with a heat exchanger and chimney for the evacuation of gases outside the greenhouse (3.3%). Secondly, the greenhouses have direct combustion air heaters (2.8%), which release combustion fumes inside the greenhouse (Valera *et al*., 2016). In general, these air-heating systems, which use diesel or propane as fuel, are used as safety systems to prevent damage from frost during the winter period. On the other hand, heating systems using boiler and hot water pipes distribution system represented only 0.5 % of the greenhouses in Almería (Valera *et al*., 2016).

These facilities are used throughout the winter period to maintain interior temperatures around 16-18 °C with the aim of significantly increasing production. Air heaters are used to maintain indoor temperatures between 12 and 16 °C, resulting in energy consumption of 500 to 2 500 GJ/ha, whereas systems with hot water pipes generate much higher energy consumption, about 4 500-6 000 GJ/ha (Table 11). In any case, these consumptions represent less than half of those needed in the countries of central and northern Europe (Table 8).

Table 11. Maximum power and energy consumption of water and air heating systems measured in greenhouses in Spain ([a] Valera *et al.*, 2008a-b; [b] Honoré, 2014; [c] López *et al.*, 2006).

Location	Productivity (kg/m²)	Set-point Temp. (°C)	Greenh. type	Crop	Power (W/m²)	Heating consumption	
						(GJ/ha)	(kWh/m²)
Air heating system							
Almería	-	14.9	Almería	Green bean	240	1 200	33.3
Almería	-	15.5	Almería	Green bean	240	1 810	50.3
Almería	-	16.2	Almería	Green bean	240	2 580	71.7
Almería	-	12.0	Almería	Cucumber	240	510	14.2
Almería	-	15.0	Almería	Cucumber	240	2 040	56.7
Water pipes heating systems							
Navarra [a]	-	15.5	Multispan	*Lilium* flowers	130.5	5 630	156.4
Almería	18.9	18.7	Venlo	*California* Pepper	129.0	5 630	156.4
Almería	13.5	18.7	Venlo	*Ramiro* Pepper	129.0	6 055	168.2
Almería	15.4	18.7	Venlo	*Cherry* Tomato	129.0	6 058	168.3
Almería	21.0	18.7	Multispan	Cucumber	115.0	4 632	128.7
Almería	8.2	18.7	Multispan	*Cherry* Tomato	115.0	4 632	128.7
Almería	18.9	18.7	Multispan	Tomato branch	115.0	4 632	128.7

One important contribution to energy consumption for vegetable in southern provinces of Almería and Murcia It is road transport on roads to the wholesale markets of central Europe, that account for 65% of total requirements (Table 12). Maritime transport from Almería to Rotterdam or train transport through the future Mediterranean corridor have been studied as possible alternatives to reduce the carbon footprint associated with the production of this region. In any case, the total energy consumption (including that associated with transport), around 250-330 GJ/ha (Table 12) is still much lower than that heated greenhouses in Spain or central Europe, from 3 000 to 16 000 GJ/ha (Tables 8-9), around 10-50 times greater.

Table 12. Primary energy consumption (fuel and electricity) in Spanish greenhouses (Van der Velden *et al.*, 2004).

Region	Productivity (kg/m²)	Cultivation tasks			Transport	Total		
		(m^3_{gas}/m^2)	(kWh/m²) [a]	(GJ/ha) [b]	(m^3_{gas} /kg)	(m^3_{gas}/kg)	(GJ/ha) [b]	* (kWh/m²) [a]
Tomato								
Almería	9	0.3	3.3	118	0.0592	0.09	318.7	8.9
Murcia	8	0.3	3.3	118	0.0538	0.089	280.2	7.8
Sweet pepper								
Almería	6	0.3	3.3	118	0.0774	0.124	292.8	8.1
Murcia	8	0.3	3.3	118	0.0703	0.105	330.6	9.2
Cucumber								
Almería	9	0.3	3.3	118	0.042	0.073	258.5	7.2

[a] 1 m³ natural gas ≃ 10.931 kWh. [b] 1 kWh/m²=36 GJ/ha.

4.2.3. Energy consumption in greenhouses in Italy

Due to the better climatic conditions, more suitable for the development of plants, greenhouse vegetable crops are located mainly in the south of Italy, while the cultivation of ornamental plants is carried out in the northern regions (Pardossi and Tognoni, 1999). In southern regions with favourable climatic conditions, greenhouses are built with inexpensive structures for winter cropping of warm season species that are usually equipped with simple heating systems (Paris *et al*., 2022a). However, in the northern regions with colder weather, greenhouse structures covered with glass use heating systems associated to other climate control equipment (Bibbiani *et al*., 2016). Approximately 20–30% of the Italian greenhouses are equipped with heating and cooling systems. Greenhouses have considerable economic importance in Italy and are a major consumer of energy (Campiglia *et al*., 2007). It was estimated that energy requirement for the climate control is around 140 000 toe, approximately 90–95% of global energy demand for greenhouse production (Carlini *et al*., 2012).

In unheated single greenhouses in the coastal area of Lazio region (Central Italy), the total energy requirements for vegetable production ranged between 62 and 140 GJ/ha in function of the crop (Table 13). Electricity and diesel consumption represents the highest contribution to total energy inputs for producing vegetable crops inside greenhouses (Campiglia *et al*., 2007).

Table 13. Energy consumption low-energy intensity greenhouse production in Italy (Campiglia *et al*., 2007).

Crop	Energy consumption (GJ/ha)						Total energy	
	Seeds	Fertilizers	Pesticides	Diesel	Electricity	Irrigation	(GJ/ha)	(kWh/m²)
Lettuce	20.7	8.2	1.5	11.1	20.5	0.9	62.9	1.7
Parsley	0.0	7.2	1.4	21.8	62.1	0.9	93.4	2.6
Zucchini	2.3	12.4	2.7	26.4	59.1	1.3	104.1	2.9
Tomato	5.5	22.0	1.8	28.8	65.6	2.0	125.6	3.5
Melon	1.4	13.6	2.1	36.3	85.1	1.4	139.9	3.9

Power energy load necessary for heating in greenhouses varies mainly in function of the different climatic areas in the Italian peninsula, from 30 W·m^{-2} in southern regions to more than 175 W·m^{-2} in northern regions (Bibbiani *et al*., 2016). Average energy consumption in greenhouses was estimated in the range from 10 kWh·m^{-2}·year^{-1} in the southern regions of Sicilia (Table 14) and Puglia (Table 15) to 262.8 kWh·m^{-2}·year^{-1} in the northern region of Veneto (Table 14). Moreover, the CO_2 enrichment in greenhouses from the exhaust gas of a biomass heating system can bring benefits for greenhouse plant production, along with optimal management strategies to reduce fuel consumption (Bibbiani *et al*., 2016).

Table 14. Estimation of energy consumption of most important greenhouse areas in Italy (Campiotti *et al*., 2011).

Regions	Greenhouse area (ha)	Energy consumption (MWh)			Mean consumption (GJ/ha)			Total energy		Gas emission	
		Heating	Cooling	Electricity	Heating	Cooling	Electricity	(GJ/ha)	(kWh/m²)	(toe/ha)[a]	(tCO_2eq/ha)[b]
Sicilia, Sardinia	2 200	220 000	42 768	14 331	360	0.70	1.2	362	10.1	8.6	33.3
Campania	3 000	4 312 500	28 350	19 542	5 175	0.02	2.5	5 178	143.8	123.7	476.0
Liguraia, Tuscany	400	870 000	1 800	2 606	7 830	0.01	5.2	7 835	217.6	187.2	720.4
Veneto	400	1 050 000	864	2 606	9 450	0.00	10.9	9 461	262.8	226.0	869.9
Total - Average	**6 000**	**6 452 500**	**73 782**	**39 085**	**3 872**	**0.04**	**1.9**	**3 873**	**107.6**	**92.5**	**356.1**

[a] 1 GWh = 8.60×10^{-5} Mtoe - Mega tonne oil equivalent (Krey *et al*., 2014).
[b] Using a factor emission of CO_2 for heat production of 0.331 tCO_2eq/MWh (Krey *et al*., 2014).

The total energy requirements for producing the greenhouse vegetable crops cultivated in low energy intensity greenhouses in the southern region of Puglia were found in the range of 314–487 GJ/ha in function of the surface of the greenhouses (Table 15). The calculated hourly heating requirements per unit area for the greenhouses in the districts of Leverano and Taviano in the region of Puglia were between 0.7 and 2.7 kWh/m^2 for the small-size greenhouses, 0.5 and 3.0 kWh/m^2 for the medium-size greenhouses, and 0.5 and 2.2 kWh/m^2 for the large-size greenhouses (D'Arpa *et al.*, 2016).

Table 15. Heating requirements computed over the monthly average day for the Leverano and Taviano greenhouse districts in Italy (D'Arpa *et al.*, 2016).

Surface (m^2)	Inside temperature (°C)	Greenhouse type	Heating consumption	
			(GJ/ha)	(kWh/m^2)
Leverano dictrict				
1360	18/20°C	Multispan	425	11.8
10 200	18/20°C	Multispan	338	9.4
40800	18/20°C	Multispan	314	8.7
Taviano dictrict				
1360	18/20°C	Multispan	487	13.5
10 200	18/20°C	Multispan	385	10.7
40800	18/20°C	Multispan	357	9.9

The consumption of fossil energy generated by horticulture in greenhouses can be reduced through various measures such as increasing the energy efficiency of heating and cooling systems, the application of renewable energy, greater insulation of structures and adequate maintenance of the equipements (Valera *et al.*, 2008a; Campiotti *et al.*, 2011; Honoré, 2014).

To support the innovation of greenhouses in Italy, the ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) made at national level some specific evaluations in order to define the energy consumptions in terms of heating, cooling and electricity. Based on 6 000 ha equipped with permanent structures, the ENE estimates the energy requirement in 0.72 Mtoe for heating and cooling (Campiotti *et al.*, 2011; Bibbiani *et al.*, 2016). The total equivalent CO_2 emissions from Italian greenhouses was estimated as 2.8 M tCO_2eq, with average values for greenhouses between 33.3 tCO_2eq/ha in greenhouse of Sicily and Sardinia and 870 tCO_2eq/ha (Table 14). Calculated total energy requirements of tomato crop cultivated soil-less in glasshouses of different regions was very similar (Table 16). In the northern region of Piamonte, heating consumption was estimated to 1 668 GJ/ha, whereas in the southern region of Sicilia the heating requirement was 11.8 GJ/ha. However, cooling requirements were greater in the South, with an estimated value of 3 279 GJ/ha, so that the final calculation of energy needed in climate control is quite similar in all the country, between 3 200 and 3 400 GJ/ha (Table 16).

Table 16. Calculated energy consumption in glasshouses in Italy with soil-less tomato (Carlini *et al.*, 2012).

Location	Greenhouse area (m^2)	Energy consumption (MWh)		Average consumption (GJ/ha)		Total energy		Gas emission	
		Heating	Cooling	Heating	Cooling	(GJ/ha)	(kWh/m^2)	(toe/ha)[a]	(tCO_2eq/ha)[b]
Roma (Lazio)	3842.7	41.0	305.5	384.0	2 862	3 246	90.2	77.5	298.5
Ragusa (Sicilia)	3842.7	1.3	350.1	11.8	3 279	3 291	91.4	78.6	303
Turin (Piamonte)	3842.7	178.1	183.3	1 668	1 717	3 386	94.1	80.9	311.3

[a] 1 GWh = 8.60×10^{-5} Mtoe - Mega tonne oil equivalent (Krey *et al.*, 2014).
[b] Using a factor emission of CO_2 for heat production of 0.331 tCO_2eq/MWh (Krey *et al.*, 2014).

4.2.4. Energy consumption in greenhouses in France

One of the main objectives of vegetable production in France is to limit the effects of seasonal overproduction on the markets, inherent to field crops (Mauguin, 2006). In 2022 the surface of tomato, cucumber, melons and strawberries was 5 463 ha (AGRESTE, 2023). The regions in which the largest vegetable greenhouse area is concentrated were Nouvelle Aquitaine with an area of 1 122 ha (20.5% of the total), Provence-Alpes-Còte d'Azur – PACA (1 047 ha – 19.2%), Bretagne (725 ha – 13.3%), Occitanie (613 ha – 11.2%), Auvergne-Rhône-Alpes (540 ha – 9.9%) and Pays de Loire (361 ha – 6.6%). Between 2000 and 2010 the two northwestern regions increased the greenhouse area, decreasing in the rest (FranceAgriMer, 2013).

In France, the total area of cucumber and tomato in heated greenhouses was 1 081.6 ha in 2016 (FranceAgriMer, 2020). In 2010 the area of heated greenhouses for tomato production was approximately 915 ha, which was only 12.3% of the total (FranceAgriMer, 2013) and in 2022, 73% of 495 ha of greenhouses cultivating cucumber in France are heated (AGRESTE, 2022). In flowers and ornamental plants, 42% of greenhouses were heated in 2013 (FranceAgriMer, 2020). Most greenhouses in France are glass (63.5%), followed by small tunnels (30.4%) and plastic roof greenhouses with multispan type structure (6.1%), using heating systems in 69.6% of them (AGRESTE, 2008; Boulard *et al*., 2011).

Energy costs are the second largest input in the budget, after labour, representing 25 to 40% of total costs for French heated greenhouse growers (Grisey *et al*., 2014). In the last years French government have support the investment in new greenhouse structures and heating systems and encouraged the use of renewable energy to heat greenhouses (Mauguin, 2006; ADEME, 2019; FranceAgriMer, 2020).

The average energy consumption for heating and dehumidifying greenhouses with tomato crops in France is between 297 and 317 kWh·m^{-2}·year^{-1}, corresponding to 10 700-11 400 GJ/ha (Table 17). In greenhouse of regions in north-western France as Bretagne and Pays de Loire energy is used year-round for greenhouses heating. In regions of the south of France, as PACA and Occitanie, heating is not necessary in the summer period (Grisey *et al*., 2020). The average power necessary for cooling the greenhouse of the "Energy Sustainable Greenhouse" project for a tomato crop was 100 W·m^{-2} (Grisey *et al*., 2014), with a consumption of 10 to 166 kWh·m^{-2}·year^{-1} (Table 17).

Table 17. Calculated energy consumption in tomato and cucumber [a] greenhouses in different regions of France ([a] Sabatier, 2010; [b] FranceAgriMer, 2013; [c] Grisey, 2013 - Grisey *et al.*, 2014; [d] Brazeau, 2015; [e] Grisey *et al.*, 2020).

Location	Greenhouse type	Area (m²)	Energy consumption (kWh/m²)		Total energy		Gas emission	
			Heating	Electricity	(GJ/ha)	(kWh/m²)	(toe/ha) [f]	(tCO_2eq/ha) [g]
Cucumber crop								
Occitanie [a]	Venlo – Double cover	5 900	224.7		8 091	224.7	45.8	354.1
Tomato crop								
Occitanie [a]	Venlo	18 000	265.5		9 558	265.5	45.6	463.2
Occitanie [a]	Venlo	100 000	277.0		9 972	277.0	66.7	567.6
Pays de Loire [d]	Venlo	1 037	298	4.4	10 886	302.4	260.1	1 000.9
Pays de Loire [d]	Venlo - Fan	1 037	259	6.4	9 554	265.4	228.2	878.5
Pays de Loire [d]	Venlo - Semiclosed	1 037	249	14.6	9 490	263.6	226.7	872.5
Provence [c]	Venlo	960	218	10	8 208	228.0	196.1	754.7
Provence [c]	Venlo – Semiclosed	960	5	166	6 156	171.0	147.1	566.0
France [b]	Average	-	297	-	10 692	297.0	255.4	983.1
France [e]	Average	-	317	-	11 412	317.0	272.6	1 049.3

[f] 1 GWh = 8.60×10^{-5} Mtoe - Mega tonne oil equivalent (Krey *et al.*, 2014).
[g] Using a factor emission of CO_2 for heat production of 0.331 tCO_2eq/MWh (Krey *et al.*, 2014).

By using biomass boilers, significant reductions in emissions into the atmosphere can be achieved. Thus, in three greenhouses in the Mediterranean region of Occitanie, wood-fired boilers were used to cover between 70 and 80% of the energy needs and the rest with gas boilers (Sabatier, 2010). This allowed a total contribution of between 8 000-10 000 GJ/ha with emissions of only 350-570 tCO_2eq/ha, well below the 750-1 050 tCO_2eq/ha generated with fossil fuels (Table 17).

4.2.5. Energy consumption in greenhouses in Greece

The total area of vegetables cultivated in greenhouse in Greece in 2019 with tomato, cucumber and pepper was about 5 100 ha. Nearly 96% of the greenhouses in Greece are covered with plastic films, used for vegetables, and glasshouses are used mainly in floriculture (Savvas *et al*., 2016).

The main vegetable crops in the Greek greenhouses are tomato (2 445 ha), cucumber (1 270 ha), pepper (1 013 ha) and eggplants (372 ha). More than half of greenhouses are is concentrate in the region of Greece (55.5%), followed by Peloponnese (14.9%), Central Macedonia (8.9%), Western Greece (5.1%) and Thessaly (3.4 %). Majority of greenhouses are high tunnels used for cultivation of vegetables, whereas low tunnels are used mainly for strawberry, early melon and watermelon (Savvas *et al*., 2016).

In Greece most vegetable greenhouses are not heated and only 17% of the greenhouses are heated, and exceptionally use computer-controlled automation systems. However, heating systems are necessary to achieve appropriate temperatures during the winter and obtain high yield and good quality products (Savvas *et al*., 2016).

For low energy intensive greenhouses, the energy inputs requirements due to the manufacture and transport of fertilizers, pesticides, materials and electricity in the functioning of irrigation suppose 63-95% of the around 250 GJ/ha (Table 18). In the other hand, heated greenhouses have high energy intensity requirements, heating leads the consumption, corresponding to 69-95%. For high energy intensity production in multispan greenhouses, covered with polyethylene (PE) plastic film in Thessaly (Central Greece), fuel and electricity for heating tomato were the major contributors to the total energy demand, with a weight of 87.7% and 8.9% respectively (Table 18). In these greenhouses natural gas was used for heating, while electricity was mainly used to operate the heating and irrigation system in greenhouses in Greece (Ntinas *et al*., 2017). For vegetable crops growing in high energy intensity greenhouses, the total energy inputs are 7 200-8 500 GJ/ha, in a similar way for flowers the total energy requirement was about 8 200 GJ/ha. These values are 29-34 times greater that for low intensity energy use (Tabla 18).

Table 18. Energy consumption in low and high energy intensity greenhouse production in Greece ([a] De Visser *et al*., 2012; [b] Ntinas *et al*., 2017; [c] Kittas *et al*., 2014; [d] Trypanagnostopoulos *et al*., 2017; [e] Vourdoubas, 2015).

Location	Crop	Fertilisers, pesticides and materials	Diesel	Irrigation	Heating	Cooling	Electricity	Total	
		(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(GJ/ha)	(kWh/m²)
Energy consumption in low energy intensity greenhouse production									
Greece [a]	Tomato	190.5	0.5	53	13.0			257.0	7.1
Greece [a]	Cucumber	155.0	1	-	92.5			248.5	6.9
High energy intensity greenhouse production									
Thessaly [b]	Tomato	306	-	120	8 189	-	828	8 507	236.3
Thessaly [b]	Tomato	324	-	130	4 676	-	2 141	7 155	198.8
Thessaly [c]	Tomato	77			8 138	328	7.2	8 550	237.5
Pyrgos [d]	Lettuce	-			5 400	-	1 800	7 200	200.0
Crete [e]	Flowers	-			7 704	-	504	8 208	228.0

4.2.6. Energy consumption in greenhouses in The Netherlands

Of the 10 636 ha covered by glasshouses in the Netherlands (CBS, 2023a), 4 972 ha is devoted to vegetable production (CBS, 2023b), corresponding to 46.7% of this, around 25% to flower production, and 15% to fruit production (Paris *et al.*, 2022a). Production is very intensive, and yields are high, especially as compared to greenhouse production in other countries. The average production was 63.8 kg/m^2 for cucumbers and 47.6 kg/m^2 for tomatoes in 2021 (FAOSTAT, 2023). Due to this high production intensity, The Netherlands produced in 2022 the 17.3% of the cucumbers, 14.7% of the peppers, 13.3% of the tomatoes and 10.3% of lettuce grown in Europe (FL, 2023).

Dutch glasshouses are generally characterized by large permanent structures that are heavily climate controlled, with large scale heating, cooling, lighting, and ventilation facilities. Glass has been the traditional greenhouse covering material in The Netherland as in other countries of Northern Europe. In these countries, greenhouses were extensively used before the development of plastic films for greenhouse cover. The majority of glasshouses are Venlo type, named after the Dutch town Venlo, where they first appeared (Von Elsner *et al*., 2000b). Greenhouses in high latitudes consume vast amounts of energy for heating and supplemental lighting. With an estimated 40 000 ha of vegetable glasshouses worldwide for ornamental production (Stanghellini *et al*., 2019), greenhouses consume more than 880 PJ/year, corresponding to an average comsumption of 22 000 GJ·ha^{-1}·year^{-1}. In The Netherland, heated glasshouses consume energy at a rate of 9 500-22 600 MJ·ha^{-1}·year^{-1} (Hemming *et al*., 2019) as it can be observed in Table 19.

Table 19. Greenhouse energy consumption for different crops in the Netherlands ([a] Vermeulen, 2014 - Stanghellini *et al.*, 2016; [b] de Visser *et al.*, 2012; [c] Van der Velden *et al.*, 2004; [d] Smit and van der Mee, 2022).

Crop	Temperature set-point (ºC)	Fertilizers (GJ/ha)	Pesticides (GJ/ha)	Lighting (GJ/ha)	Heating (GJ/ha)	Total (GJ/ha)	Total (kWh/m²)
Cucumber [a]	20.0	-	-	-	-	11 320	314.4
Cucumber [b]	-	0	0	-	14 245	14 360	398.9
Cucumber [c]	-	-	-	-	-	18 649	518.0
Eggplant [a]	19.0	-	-	-	-	11 320	314.4
Sweet pepper [b]	-	112.6	2.5	-	11 424	11 539	320.5
Sweet Pepper [a]	20.0	-	-	-	-	11 540	320.6
Sweet pepper [c]	-	-	-	-	-	18 181	505.0
Tomato [a]	18.0	-	-		-	11 480	318.9
Tomato [b]	-	119	1	-	14 990	15 110	419.7
Tomato [c]	-	-	-	-	-	22 686	630.2
Zucchini [a]	16.0	-	-	-	-	9 510	264.2
Average 2021 [d]	**-**	**-**	**-**	**-**	**-**	**11 300**	**313.9**

According to the annual publication of the energy monitor of the Dutch greenhouse sector, the total energy-use of Dutch greenhouse horticulture rose 5% to 117.5 PJ in 2021 (Tabla 20). This increase was a result of growth of crop area compared to 2020, as is indicated by the slightly lower energy use after temperature correction from 11 400 to 11 300 GJ/ha (Table 20). As a result of a relatively cold first quarter of 2021 (higher heat demand) and selective energy-use (especially artificial lighting) during the last two quarters, the energy consumption associated with heating rose to around 80%, and electricity dropped to 20% of the total energy-use (Smit and van der Mee, 2022).

Overall, energy use is dominated by energy from natural gas accounting for 88.1% of the total, and the share of renewable energy grew in 2021 by 1.6% to 11.9% (Smit and van der Mee, 2022). Sustainable energy used by greenhouse horticulture consisted of more than 92% heat (mainly geothermal heat and purchase of sustainable heat from parties outside the sector) and almost 8% from electricity (especially purchasing and own generation with solar photovoltaic, PV).

Table 20. Factors influencing the total CO_2 emissions from greenhouse horticulture in 2020 and 2021 [a] (Smit and van der Mee, 2022).

Influence factor	Unit	2020	2021 [a]
Outside temperature	°C·days	2 456	2 804
Total greenhouse area	ha	10 078	10 418
Total energy used	PJ	114.6	117.5
Energy used per surface	GJ/ha	11 400	11 300
Use of sustainable energy	PJ	11.5	14.0
Purchase of electricity [b]	TWh	3.0	2.6
Percentage of sustainable energy	%	10.0	11.9
Purchase of heat [b]	PJ	2.17	2.23
Electricity sales	TWh	6.3	6.7

[a] Figures 2021 provisional. [b] Exclusively sustainable.

The amount of renewable energy used was more than 54% produced by the sector itself and approximately 46% purchased from parties outside the greenhouse horticulture sector (Smit and van der Mee, 2022). Light emitting diodes (LEDs) have been suggested as having great potential for reducing greenhouse energy use, as they are extremely efficient at converting electricity to light (Katzin *et al*., 2021).

In 2021 the total CO_2 emissions of Dutch greenhouse horticulture have risen by 0.35 Mt to 6.5 Mt. The increase was a result of further growth of crop, the increase of electricity sale from gas engines and a decrease of electricity purchase. The increase was partly compensated by the growth of renewable energy use, the increase of non-renewable heat purchase and a lower energy use per m^2. The total CO_2 emissions were at a 4% lower level compared to 1990 and higher than the goal set for 2021 of 6.0 Mt (Smit and van der Mee, 2022).

The share of energy-sources without CO_2-emissions for the greenhouse horticulture sector has almost doubled since 2010. However, due to the use of gas engines for cogeneration (Combined Heat and Power, CHP) in greenhouse horticulture, CO_2 emissions were more than 2.8 Mt higher in 2021, while preventing almost 4.3 Mt of CO_2 emissions nationally (Smit and van der Mee, 2022). The energy-price increases of 2021 as a mixed result of economic activity and geopolitical tensions pushed net-energy-costs up around 25% to an average of 8.50 €/m^2 (Smit and van der Mee, 2022).

4.2.7. Energy consumption in greenhouses in Germany

In Germany only 3 199 ha are cultivated under high accessible protective cover including greenhouses, 60% dedicated to strawberries and about 40% to vegetables (DESTATIS, 2023). However, despite a gradual advance of plastic sheets and foils, mainly used in vegetable growing, most greenhouses are still covered with glass (Ruhm *et al.*, 2007). About 80% are glasshouses, 15% foil and 5% stiff plastics covered greenhouses (Voss, 2011).

The main vegetable cultivated in the German greenhouses are tomatoes (382.7 ha), cucumbers (214.6 ha), peppers (110.9 ha), salads and lettuces (DESTATIS, 2023). Most of the facilities are relatively old, 43.1% of the total number of greenhouses, corresponding to almost 1 600 ha, were built before 1982 (Voss, 2011). Even though some of these facilities were upgraded to comply with the modern-day standards, most of them are still outdated and only 10.6% of the total facilities were built after 2000 (Voss, 2011).

In 2005, almost 90% of greenhouses are heated in Germany, mainly using fuel oil or natural gas, and in some cases also with black coal (Ruhm *et al.*, 2009; Kuntosch *et al.*, 2020). All heated greenhouses have their own heating system (Paris *et al.*, 2022a). More than 99% of the energy input in greenhouses for tomato and cucumber production is relate to heating (Table 21), whereas a small portion of the energy inputs account for fertilizers (de Visser *et al.*, 2012). Energy consumption in the greenhouse cultivation of tomato and cucumber is close to 13 000 GJ/ha (Table 21). Heating in the greenhouse resulted in 20-80% of product carbon footprint (PCF) for strawberries, 38-92% for roses and 10-64% for orchids (Soode *et al.*, 2015).

Table 21. Average energy consumption in the German greenhouses (de Visser et al., 2012).

Crop	Fertilizers (GJ/ha)	Heating (GJ/ha)	Total	
			(GJ/ha)	(kWh/m²)
Tomato	42	12 612	12 654	351.5
Cucumber	53	13 000	13 053	362.6

The use of electricity and heat from renewable energy sources is also becoming increasingly interesting for production horticulture and especially in greenhouse cultivation, as the price situation in the energy sector, especially for fossil fuels, is increasingly threatening greenhouse production. The use of renewable energies in recent years in horticulture has increased in Germany (Dierksmeyer and Fluck, 2013). Biogenic fuels such as wood chips, pellets (Table 22), straw, energy grain or the use of waste heat from a combined heat and power plant (CHP) powered by biogas or oil can represent an economical alternative to fossil fuels (Brökeland *et al*. 2001; Voss *et al*., 2014). The energy consumption in greenhouse can be reduced using energy saving means and using renewable sources for heating, as for example double cover, allowing reduce the standard consumption of around 13 000 GJ/ha (Table 20) to 4000-6800 GJ/ha (Table 22).

Table 22. Cumulative energy demand (CED) of tomato crop heated with wood pellets biomass in Germany (Ntinas *et al*., 2017).

Greenhouse type	Area (m²)	Productivity (kg/m²)	Cumulative energy demand		
			(MJ/kg)	(GJ/ha)	(kWh/m²)
Venlo – Double PE	345.6	14.7	46.1	6 809	189.1
Venlo – Double PE	345.6	12.1	36.5	4 431	123.1
Venlo - Double F-clean	345.6	17.9	22.2	3 981	110.6

4.2.8. Energy cost characteristics in European countries

In the EU, greenhouse structure and cultivation show considerable variation, ranging from complex energy intensive structures that heavily regulate the indoor climate to simple structures that resemble open-field practices. This variation depends mainly on local climatic and socio-economic conditions (Popsimonova *et al.*, 2017). Low-cost greenhouse structures are more common in Mediterranean, with an average cost between 0.2 to 0.6 million €/ha, whereas than in North and Central Europe greenhouse use more technology for climate control, and their costs vary between 0.9 and 1.2 million €/ha (EIP-AGRI, 2019; Tataraki *et al.*, 2020). Low-tech greenhouses have the advantage of no direct dependency of the high volatility of energy prices and are less exposed to similar risks. On the other hand, high-tech greenhouses have the benefit of major independence from weather conditions that can affect their productivity, but operating costs are susceptible to fluctuations (Tataraki *et al.*, 2020).

Minimization of energy costs, which account for up to 40% of final production costs (Marsh and Signgh, 1994; Ahamed *et al.*, 2019), is the main objective of high-tech modern greenhouses (Tataraki *et al.*, 2020). The cost of energy is directly connected to energy prices (Fig. 26 and 27) and the thermal energy required, that depend on the crop requirements, the climatic conditions of the region and the technology used (Tables 5-22).

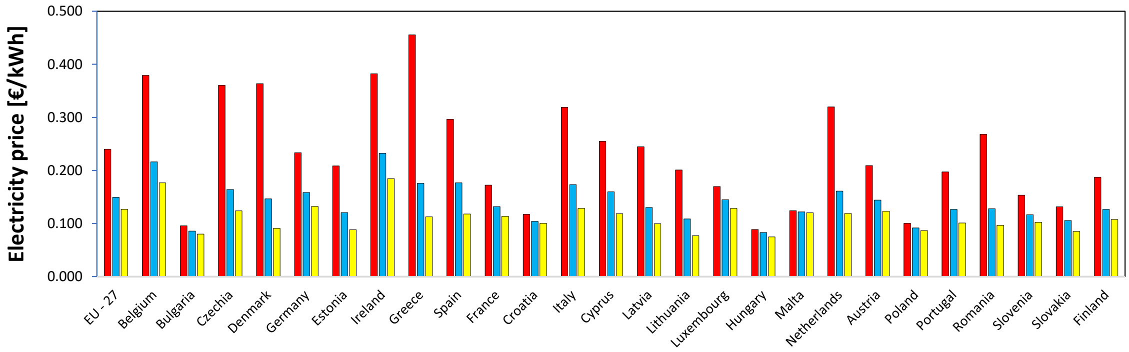


Figure 26. Values for the 2018–2022 time period of the maximum (■), average (■) and minimum (■) electricity prices of European countries (EUROSTAT, 2023b). Consumption from 2 500 kWh to 4 999 kWh.

In the analysed period from 2018-2022 the highest average electricity prices, greater than 0.2 €/kWh occurred in Belgium and Ireland (Fig. 27). Between the main producer of vegetables greenhouses, the higher prices were produced in Mediterranean countries (Greece, Spain and Italy), a little above those of The Netherland and Germany.

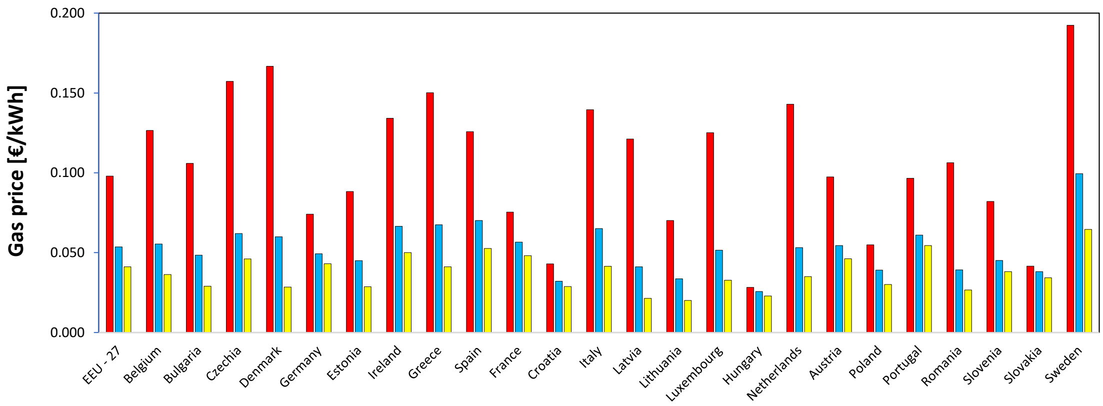


Figure 27. Values for the 2018–2022 time period of the maximum (■), average (■) and minimum (■) gas prices of European countries (EUROSTAT, 2023b). Consumption from 20 GJ to 199 GJ - band D2.

4.3. Environmental impact of greenhouse production in Europe

A Life *Cycle Assessment* (LCA) allows the quantification of the environmental performance of a product with respect to the production subprocesses that integrate it, through the quantitative estimation of all the flows of matter and energy related to the realization of the product (Russo and Scarascia Mugnozza, 2005; Heuts *et al*., 2012).

Greenhouse crops are one of the most innovative examples of modern agriculture and are considered one of the most powerful agricultural systems developed by man, due to their high level of both technology and bio-agronomic (Russo and Scarascia Mugnozza, 2005). Greenhouse crops are characterized both using structures and equipment and by increasing efficiency in the use of water and energy resources in production processes. The LCA method can be applied both to industrial processes and to agricultural production that takes place in greenhouses (Russo and Scarascia Mugnozza, 2005)

Thus, Antón (2004) used a life cycle analysis (LCA) to evaluate the environmental impact associated with the production process of a tomato crop in plastic cover greenhouses of the Maresme (Barcelona) in three different cases: soil cultivation and open and closed hydroponic systems. The main negative effects of greenhouse tomato production are derived from biomass waste and plastics, therefore, proper waste management is the best option to reduce its environmental impact, being the best option for biodegradable materials composting (Antón *et al*., 2005).

Russo and Scarascia Mugnozza (2005) also performed an LCA analysis to objectively compare the environmental compatibility of horticultural production in the three main greenhouse systems used in Italy for growing tomatoes: a structure in galvanized steel with glass cover, a vaulted roof structure in galvanized steel and with plastic sheet cover and a wooden structure with plastic sheet. As a result of their analysis, they concluded that hydroponics, compared to growing in soil, reduces environmental impact due to lower levels of fertilizers and pesticides in the environment. In terms of raw material selection, the use of wood instead of galvanized steel structures reduces environmental impact, as does the use of recycled plastics for pipes and crop banks (Russo and Scarascia Mugnozza, 2005).

Boulard *et al.* (2011) compared the environmental impact of the main types of greenhouses and plastic tunnels in France for tomato production using a life cycle assessment. The analysis was developed after making a complete database on the set of flows of matter and energy, with respect to the structure of the system, inputs for production and waste products. The results obtained showed that heating greenhouses produces the greatest environmental impacts, including toxicological impact. For example, the average environmental impact of crops heated under plastic or in greenhouses was 4.5 times greater than in tunnels (Boulard *et al.*, 2011).

Recently, the EUPHOROS (*Efficient Use of imputs in Protected Horticulture*) project has been developed, whose objective was to improve horticultural production systems in Europe by developing environmentally and economically clean production alternatives (Montero *et al*., 2011). Within the framework of this project, Torrellas *et al*. (2012) conducted an environmental assessment, using an LCA, and an economic assessment, using cost-benefit analyses of current agricultural practices for greenhouse crops, both in cold and warm climates in Europe. They used four scenarios as reference systems: tomato crops in plastic multispan greenhouses in Spain (Table 23) and glass Venlo greenhouses in Hungary and the Netherlands and rose cultivation in Venlo greenhouses in the Netherlands (Table 24). In the latter country, greenhouses were equipped with combined heat and power (CHP) cogeneration systems. The main environmental loads in all four scenarios were energy consumption, greenhouse structure and fertilizers (Tables 23-24). The environmental impacts produced by energy consumption can be reduced by using geothermal water or by cogeneration in greenhouses.

Table 23. Values the potential environmental impacts of tomato production systems in different types of greenhouses in Italy and Spain according to various authors: *P*, production; *GER*, Global Energy Requirement; *C*, percentage of heating requirements; GWP, Global Warming Potential; *ADP*, abiotic *depletion*; *AAP*, Air acidification; *EUP*, eutrophication; *POP*, photochemical oxidation; *W*, water requirements ([a] Cellura *et al*., 2012; [b] Bartzas *et al*. 2015; [c] Torrellas *et al*., 2012; [d] Perez-Neira *et al*., 2019; [e] Honoré, 2014; [f] Antón, 2004).

Country	Type of greenhouse	*Crop*	*P* [kg/m^2]	*GER* [MJ/kg]	*C* [%]	*GWP* [kg CO_2eq/kg]	*ADP* [kg Sb eq/t]	*AAP* [kg SO_2 eq/t]	*EUP* [kg PO_4^{-3} eq/t]	*POP* [kg C_2H_4 eq/t]	*W* [m^3/t]
Italy [a]	Unheated plastic multispan	Tomato	9.6	16.2	0	0.74	-	5.70	2.10	0.30	88.90
Italy [a]	Tunnel with unheated plastic cover	Pepper	6.3	18.0	0	0.92	-	6.90	3.40	0.30	111.80
Italy [a]	Unheated plastic multispan	Cherry	4.1	23.0	0	1.24	-	9.80	3.70	0.50	77.70
Italy [a]	Unheated plastic multispan	Melon	3.6	24.0	0	1.43	-	11.20	4.30	0.50	147.80
Italy [a]	Tunnel with unheated plastic cover	Courgette	2.7	29.0	0	1.57	-	13.00	6.70	0.50	172.40
Italy, Sicilia [b]	Tunnel with unheated plastic cover	Lettuce	0.54	3.7	0	0.21	-	1.35	0.28	-	-
Spain, Almería [c]	Plastic multispan	Tomato	16.5	4.0	0	0.30	1.70	1.00	0.49	0.05	28.80
Spain, Almería [d]	Unheated plastic multispan	Tomato	8.5	4.4	0	0.34	-	-	-	-	-
Spain, Almería [d]	Heated plastic multispan	Tomato	15.3	13.1	67.7	0.92	-	-	-	-	-
Spain, Almería [e]	Heated double PE cover multispan	Cucumber	21.0	25.1	90.6	1.40	11.89	1.50	0.20	0.11	91.50
Spain, Almería [e]	Heated double PE cover multispan	Tomato	19.8	26.7	90.1	1.49	12.67	1.63	0.27	0.12	60.50
Spain, Almería [e]	Venlo with gas heating	Pepper	18.9	30.9	96.5	1.93	14.68	3.25	0.86	0.22	49.30
Spain, Almería [e]	Venlo with gas heating	Cherry	15.4	45.1	86.9	3.01	21.27	7.21	1.78	0.26	114.80
Spain, Almería [e]	Venlo with gas heating	Pepper	13.5	50.4	89.3	3.12	23.68	6.42	1.68	0.28	69.00
Spain, Almería [e]	Heated double PE cover multispan	Tomato	8.2	64.4	90.1	3.60	30.51	3.91	0.96	0.28	145.90
Spain, Barcelona [f]	Plastic multispan, closed hydroponics	Tomato	15.0	-	0	0.08	-	-	0.10	-	22.50
Spain, Barcelona [f]	Plastic multispan, soil cultivation	Tomato	12.0	-	0	0.11	-	-	0.27	-	32.60

Table 24. Values the potential environmental impacts of tomato production systems in different types of greenhouses and countries according to various authors: *P*, production; *GER*, *Global Energy Requirement*; *C*, percentage of heating requirements; GWP, *Global Warming Potential*; *ADP*, abiotic *depletion*; *AAP*, *Air acidification*; *EUP*, eutrophication; *POP*, photochemical oxidation; *W*, water requirements ([a] Heuts *et al*., 2012; [b] Boulard *et al*., 2011; [c] Ntinas *et al*., 2017; [d] Torrellas *et al*., 2012; [e] van Zundert, 2012; [f] Torrellas *et al*., 2013; [g] Naseer *et al*., 2022; [h] Carlsson-Kanyanma, 1998).

Country	Type of greenhouse	*Crop*	*P* [kg/m^2]	*GER* [MJ/kg]	*C* [%]	*GWP* [kg CO_2eq/kg]	*ADP* [kg Sb eq/t]	*AAP* [kg SO_2 eq/t]	*EUP* [kg PO_4^{-3} eq/t]	*POP* [kg C_2H_4 eq/t]	*W* [m^3/t]
Belgium [a]	Glass Venlo with gas heating	Tomato	50.2	39	82.8	2.20	19.00	2.00	0.40	-	-
Belgium [a]	Venlo with oil heating and CO_2 input	Tomato	53.5	80	37.9	3.36	37.10	30.00	5.00	-	-
Belgium [a]	Glass Venlo with cogeneration	Tomato	53.5	–3.7 (61.0)	90.2	2.12	17.80	–1.1	–1.4	-	-
France [b]	Tunnel with plastic cover	Tomato	14.6	5.2	0	0.50	-	1.40	-	0.85	34.20
France [b]	Glass Venlo heated	Tomato	44	31.3	85.3	2.00	-	3.40	-	0.45	28.40
France [b]	Heated plastic multispan	Tomato	44	31.6	-	2.00	-	3.40	-	0.46	28.40
Germnay [c]	Venlo, 2 F-clean and 2 thermal screens, wood heating	Tomato	17.9	22.2	77.3	0.40					25.60
Germnay [c]	Venlo, 2 PE cover and 2 thermal screens, wood heating	Tomato	12.1	36.5	78.8	0.70					37.00
Germnay [c]	Venlo, double PE cover, wood pellets heating	Tomato	14.7	46.1	79.4	0.70					28.10
Greece [c]	Multispan, natural gas heating, water solar sleaves	Tomato	6.5	111.1	65.3	7.20					33.50
Greece [c]	Multispan, natural gas heating	Tomato	5.8	160.5	96.3	10.10					34.50
Hungary [d]	Glass Venlo with geothermal heating	Tomato	48.0	6.9	0	0.44	2.80	1.70	1.20	0.09	14.60
Hungary [d]	Glass Venlo with gas heating	Tomato	48.0	87.0	95.8	5.00	42.00	5.00	1.70	0.40	14.60
Netherlands [e]	Glass Venlo with cogeneration	Tomato	56.5	5.0	-	0.80	-	1.30	1.85	0.24	-
Netherlands [e]	Glass Venlo with cogeneration and lighting	Tomato	76.5	11.9	39	1.20	-	1.60	1.97	0.09	-
Netherlands [d]	Glass Venlo with cogeneration	Tomato	56.5	12.0	-	0.78	5.60	1.20	–1.1	0.19	14.10
Netherlands [f]	Glass Venlo with heating	Tomato	56.5	30.9	31	1.90	14.70	3.20	0.85	0.22	14.10
Norway, Orre [g]	Venlo, night thermal screens	Tomato	41.4	25.6		2.20		2.06			
Norway, Orre [g]	Venlo, day-night thermal screens, fogging, heat pump	Tomato	40.2	16.1		1.31		1.54			
Norway, Orre [g]	Venlo, night thermal screens, lighting	Tomato	81.2	33.2		2.12		2.25			
Norway, Orre [g]	Venlo, day-night t. screens, fogging, heat pump, lighting	Tomato	81.4	24.0		1.17		1.73			
Norway, TromsØ [g]	Venlo, night thermal screens	Tomato	37.2	36.8		3.09		2.70			
Norway, TromsØ [g]	Venlo, day-night thermal screens, fogging, heat pump	Tomato	35.6	24.3		1.76		1.86			
Norway, TromsØ [g]	Venlo, night thermal screens, lighting	Tomato	76.3	40.6		2.62		2.66			
Norway, TromsØ [g]	Venlo, day-night t. screens, fogging, heat pump, lighting	Tomato	77.0	29.4		1.51		2.03			
Sweden [h]	Heated glass	Tomato	-	42.0	-	3.30	-	-	-	-	-

The contribution of the structure can be reduced with the improvement of the design and using recycled materials and it would be advisable to better adjust the doses of fertigation in Spain and Hungary (Torrellas *et al*., 2012b).

Van Zundert (2012) analysed three alternatives for tomato production in Venlo-type greenhouses in the Netherlands through a LCA analysis and using as a basis of comparison a greenhouse without lighting assimilation, with an average tomato production of 56.5 kg m^{-2}. As a result of the research developed, it was observed that increasing production (to 76.5 kg m^{-2}) with the help of conventional assimilation lighting (at an average intensity of 160 µmol m^{-2} s^{-1}), increased the environmental impact of the production process from 0.839 to 1.18 kg CO_2 equivalent per kg of tomatoes (Table 24).

Heuts *et al*. (2012) also assessed and compared by means of an LCA the environmental impact of three heating systems applied to glass greenhouses for tomato cultivation in Belgium: a traditional boiler with gas burner, boiler with oil burner and a cogeneration system. The system with the lowest environmental impact was cogeneration, but only because of the social credit by allowing to avoid the production of electricity in conventional power plants (Heuts *et al*., 2012). However, in relation to ozone depletion and photochemical oxidation, the gas boiler generates a minor impact, although the differences with the previous one are small. The system with the diesel burner is the one that produced a more unfavourable impact since the combustion of diesel has a greater potential for pollution than natural gas (Heuts *et al*., 2012).

In Italy, Cellura *et al*. (2012) also carried out an LCA to evaluate the environmental and energy impact of 5 different crops (pepper, melon, tomato, cherry tomato and zucchini) in different types of greenhouses (tunnel and multispan). The results they obtained showed that for all the products examined, the packaging and the structure of the greenhouse are the most relevant elements in the environmental impact. They also concluded that the two types of greenhouses analysed presented comparable eco-profiles and both were characterized by lower energy consumption than those of greenhouses in northern Europe, due to the non-use of heating systems (Cellura *et al*., 2012).

Greenhouses are a production system in which active climate control equipment can be used, such as heating or evaporative cooling systems, which imply significant energy consumption, in the first case, and energy and water in the second. In the Mediterranean region, other greenhouses coexist performing a passive control of the microclimate inside the greenhouses through natural ventilation and whitewashing of the cover, with a very low energy consumption (Valera *et al*., 2016).

These two techniques do not allow to maintain optimal climatic conditions for the crop neither in the cold winter nights, where the temperatures inside the greenhouse are lower than those necessary for a correct development of the plants, nor in summer, when the outside air has a very high temperature that does not allow cooling the greenhouse by exchange of ventilation air. However, the great advantage of these two techniques traditionally used in Mediterranean greenhouses is that they do not involve a significant economic, energy or water cost in their daily operation (Table 23).

In climatic zones more adverse to the cultivation of horticultural species, the climate control of greenhouses involves the use of active techniques that involve greater energy expenditure. Heating systems have to compensate for the deficit of solar energy compared to southern areas. Thus, if we look at the amount of global energy (*Global Energy Requirement*) needed to produce a kilogram of tomato in greenhouses in different geographical locations, it can be seen in countries with colder climates such as Sweden or Norway that up to 10 times more energy is needed than in Spain, Italy or France (Table 24). One way to mitigate the potential pollution differential of these greenhouses in northern areas with significant heating needs is the cogeneration of electricity, something very widespread in countries such as the Netherlands. In this way it is considered that the energy expenditure for heating is not associated with the tomato crop, but with the production of electricity.

4.4. Constraints of the greenhouse production in Europe

Globally, current food consumption and trade are placing unprecedented demand on agricultural systems and increasing pressure on natural resources, requiring compromises between food security and environmental impacts especially given the tension between market-driven agriculture and agro-ecological goals (Castro *et al*., 2019). Thus, the sustainability of Almeria's greenhouse production sector faces six fundamental challenges in next years, many of which are common to other productive areas of Europe. These challenges are a governance based on collective responsibility for sustainability, the sustainable and efficient use of water, the conservation of biodiversity, the application of a circular economy plan, the transfer of new technologies and scientific knowledge to growers and the creation of an image and identity face to consumers (Castro *et al*., 2019).

Besides the structural problems, the fruit and vegetable sector in Europe had four major problems in the last years: the modification of the weather, an unregulated Brexit, the coronavirus pandemic and the war in Ukraine (FL, 2021; FL, 2023).

4.4.1. Effect of the Climate Change in greenhouse production in Europe

Climate projections indicate significant warming and drying in the Mediterranean Basin, together with intensification of climate extremes such as drought and heat waves (Mrabet *et al*., 2020). For many regions, there were obvious signs of worsening agroclimatic condition in terms of increased drought stress and shortening of the active growing season, which in some areas become increasingly squeezed between a cold winter and a hot summer (Trnka *et al*., 2011). Negative impacts of Climate Change are expected to be more evident in the Southern Mediterranean countries where water scarcity is already limiting factor of agricultural production (Saadi *et al*., 2015).

Thus, severe impacts on the agriculture sector are to be expected if no adaptation and mitigation will take place. These impacts include changes on flowering date (Funes *et al*., 2016), combined with an increase in water demands due to higher evapotranspiration associated with anthropogenic warming (Austin *et al*., 2012; Saadi *et al*., 2015; Bloomfield *et al*., 2019) that can be moderated by plant physiological changes (Vahmani *et al*., 2021).

Additional constraints include an intensification and a longer duration of water scarcity in the EU under global warming, specifically in the Mediterranean countries (Bloomfield *et al*., 2019; Bisselink *et al*., 2020) and soil salinization due the increase of droughts and irrigation (Lagacherie *et al*. 2018). Rodriguez Diaz *et al*. (2007) predicted increase of between 15 and 20% in seasonal irrigation need by the 2050s, in Spain, as consequence of the impacts predicted of climate change in agroclimatic conditions. Any increase in water demand could further stress already constrained water resources (Vahmani *et al*., 2021), with an increasing deficit between available supplies and water demand (Rodriguez Diaz *et al*., 2007).

Hailstorms also cause damage to agricultural crops in most of Europe, but the most vulnerable regions to hail events are the Mediterranean region (EEA, 2019). Hailstorms can also significantly damage greenhouses, causing serious damage to greenhouse horticulture sector. Botzen *et al*. (2010) estimated show that by 2050 annual hailstorm damage to outdoor farming could increase by between 25% and 50%, with considerably larger impacts on greenhouse horticulture in summer of more than 200%.

Climate change also induced disruptions of ecosystems include development of pathogens, spread of invasive species, imbalance between pests and their natural enemies, phenological mismatches between the life cycles of crops and associated pollinators (De Ridder et al., 2020).

Future projections report an increase in drought frequency and intensity in the Mediterranean area, western Europe and northern Scandinavia by the end of the 21st century (Spinoni *et al*., 2018), as well as a greater increase in the length of meteorological dry spells, mainly in southern Europe (Kovats *et al*., 2014; IPCC, 2019).

4.4.2. Effect of the Brexit in greenhouse production in Europe

The UK was the third-largest importer of fruit and vegetables within the EU. Individual EU countries would have been affected to varying degrees by an unregulated Brexit. After all, the UK was the third-largest importer of fruit and vegetables within the EU. In 2019, around 15% of EU-27 vegetable exports went to the UK (FL, 2021).

4.4.3. Effect of the coronavirus pandemic in greenhouse production in Europe

The Covid-19 pandemic also has affected vegetable markets in Europe in several ways. Growers faced higher costs when meeting stricter accommodation and employment requirements. Due to travel restrictions, there were delays in the movement of goods (FL, 2021). The EU economy should recover to pre-COVID-19 levels by 2023. Following several years of low inflation, the strong resumption of economic activity has been accompanied by an increase in commodity prices – mostly in energy prices, leading to a 10-year high in euro area inflation of 4.9 % in November 2021 (EC, 2021).

4.4.4. Effect of the war in Ukraine in greenhouse production in Europe

For consumers in the EU, 2022 was characterized by a sharp rise in the cost of living. Energy sources in particular became significantly more expensive with the start of the war in Ukraine. This was felt both by private consumers and by producers and traders of fruit and vegetables. At the beginning of the year, the rates of change in the consumer price index compared with the previous year were still comparatively moderate. In January, food and non-alcoholic beverages were 4.8% more expensive for consumers in the EU than a year earlier. The rate of change was thus still below that of the overall cost of living index. This was increasingly influenced by high energy costs. With a year-on-year increase of 11.5%, the cost-of-living index in the EU reached its peak for the time being in October 2022 (FL, 2023).

The sharp rise in energy costs hit the cultivation of fruit and vegetables in greenhouses particularly hard. Cultivation during the winter months in particular was curtailed for cost reasons. However, fuel for tractors and fertilizers and crop protection products also became significantly more expensive over the course of 2022. The price index of agricultural inputs with the base year 2015 was close to the 100 per cent mark until the third quarter of 2020. From 2021 onward, the index rose noticeably from quarter to quarter, averaging 154% for the EU-27 in the third quarter of 2022. While seed and crop protection products have so far only increased moderately in price, the cost increase is largely attributable to fuels and fertilizers.

The price index for fertilizers was 229% in the third quarter of 2022. For fruit and vegetable producers, the high purchase prices for inputs and the associated high production costs were a challenge. This was because goods sometimes flowed slowly off the market due to subdued consumer demand in some cases, with the result that the market situation prevented producers from raising selling prices to the extent that would actually have been necessary given the cost structure. For example, the price index for agricultural products for vegetables was only 143% in the third quarter of 2022. For fruit, it reached 165%, although the increase was significantly weaker in quarters one and two (FL, 2023).

Russia is the world's biggest supplier of fertilisers, and second largest exporter of potash, a key ingredient in fertilisers. The recently adopted sanctions will oblige the EU to replace the import share of Russia and Belarus, respectively 60 % for potash and 35 % for phosphates. In the EU, some fertiliser producers have temporarily halted production, as energy costs were too high, and some companies have even ceased to accept further orders as prices and availability are very unclear for the rest of spring 2022 (Laaninen, 2022).

In the first days of the war, energy prices spiked and further impacted on the production costs of, for example, vegetables grown in heated greenhouses; in animal farming, electricity is needed for ventilation, lighting and other electric equipment, such as milking machines. High fuel prices have also increased transport costs. These simultaneous disruptions to harvests and global fertiliser production are likely to cause merging crises in global food markets, which were already strained by the Covid-19 pandemic (Laaninen, 2022).

Due to the high energy prices, the cultivation of these tomato and cucumber crops started later and ended earlier. However, high energy prices had less impact on aubergines and peppers because they can be grown more easily in an energy-efficient way in winter (CBS, 2023).

4.4.5. Effect of competition from external countries in greenhouse production in Europe

Another additional problem for horticultural production in greenhouses is competition from countries outside the EU. For vegetables, the amount coming from outside the EU is 14%, tomatoes, imports from Morocco and Türkiye. Imports from Morocco have increased a 62% in the last 7 years, from 344 094 t in 2016 to 557 605 t in 2022 (EC, 2023). In the same way, imports from Türkiye have augmented a 160%, from 71 166 t in 2016 to 185 718 t in 2022. Consequently, cultivated surface of greenhouse in Spain and Italy have decreased in these last 7 years a 19.9% and a 4.8%, respectively (JA, 2022a; ISTAT, 2023). The decline in tomato production is driven by the strong drop of winter production in Spain and a shift to small-sized tomatoes which have a lower volume but higher added value (EC, 2021).

5. Types of greenhouses in Spain

Crops cultivated inside greenhouses or accessible tunnels are those crops which, during the entire or most period of their growth, are covered by greenhouses or by fixed or mobile upper cover (glass or rigid or flexible plastic); plastic sheets placed on the ground are excluded, as well as crops under tunnels not accessible to man, or under portable frames covered with glass. Areas of crops grown temporarily in greenhouses and temporarily outdoors shall be considered exclusively as greenhouse crops, provided that the greenhouse period is not extremely short (MAAMA, 2023). Spanish greenhouses can be classified into three categories according to the type of structure and the level of technification (MAPA, 2020a).

5.1. Elementary greenhouses

Elemental greenhouses have the following characteristics (MAPA, 2020a):

- Simple structure, with flat roof (Fig. 28) or gabled, with wooden pillars (Fig. 29a) or metal tubes (Fig. 29b).
- Simple cover of plastic sheet or anti-insect mesh.
- Manual lateral ventilation without overhead ventilation (Fig. 28).
- Generally, the height of these structures does not exceed 2.8 m.

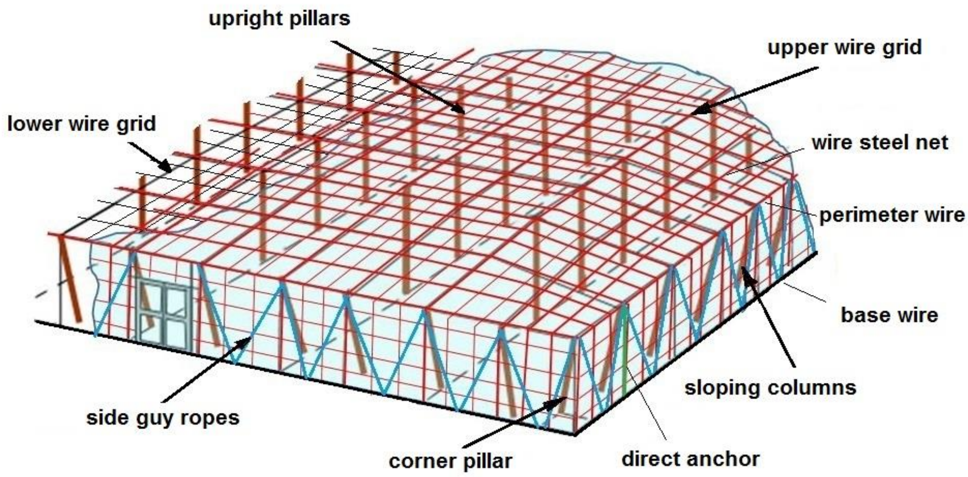


Figure 28. Elementary greenhouse with flat structure, called "*parral plano*".

Figure 29. Interior image of elementary greenhouses without roof ventilation, with flat structure and wooden pillars (a) and with gabled structure of metal tubes (b).

5.2. Simple greenhouses

Simple greenhouses (Fig. 30) are characterized by the following qualities (MAPA, 2020a):

- Metal structure with galvanized steel tubes (Fig. 31a-b).
- Cover of plastic sheet (Fig. 31a) or anti-insect mesh (Fig.e 31b).
- Roof and side ventilation (Fig. 31a).
- They may have a heating system.
- Height greater than 2.8 m, in some cases it can reach 6 m (banana trees for banana cultivation in the Canary Islands).

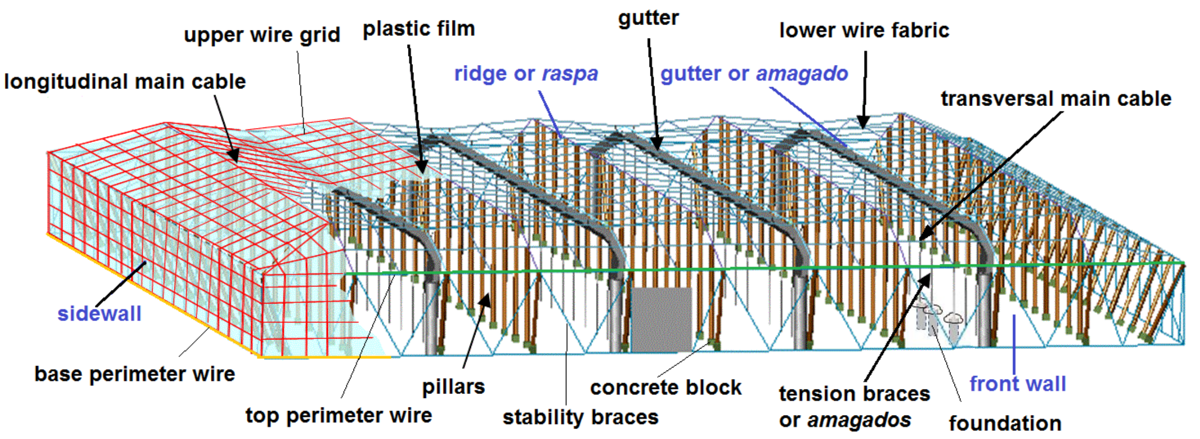


Figure 30. Simple greenhouse of *Almeria*-type with structure in "*raspa y amagado*".

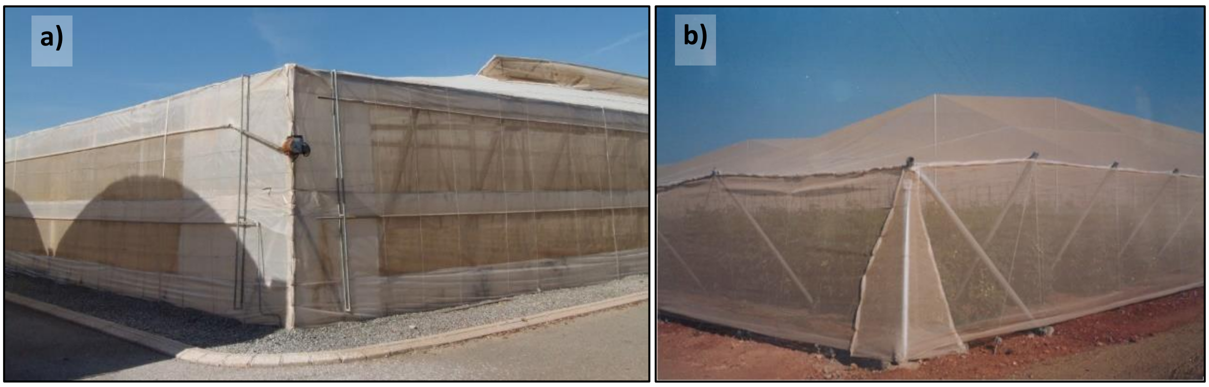


Figure 31. Image of simple greenhouses with metal pillars of *Almería*-type in "*raspa y amagado*" with side and roof ventilation (a) and with insect-proof screen cover (b).

5.3. High tech greenhouses

High-tech greenhouses are considered those that have the following characteristics (MAPA, 2020a):

- Rigid steel or concrete structure, often multispan (Fig. 32).
- Semi-rigid or rigid cover (Fig. 33) or even with double inner cover.
- Automatic side and roof ventilation even forced.
- Heating and humidity control systems.
- Fertigation systems in hydroponics or substrate.
- Height greater than 3 m.

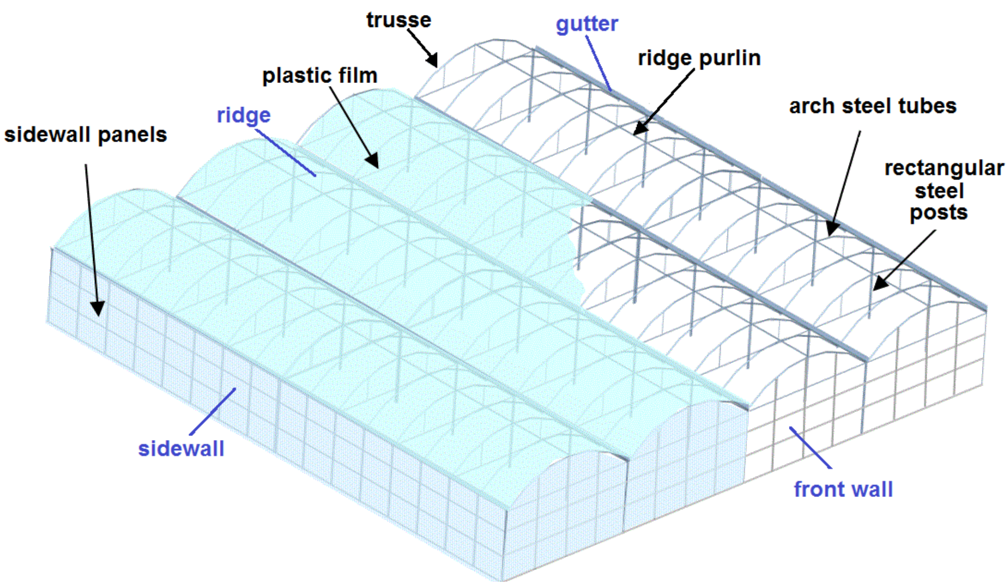


Figure 32. High-tech greenhouse with multispan structure.

The construction of greenhouses is regulated in Spain by the European standard UNE-EN 13031-1: 2001. "Greenhouses. Design and construction. Part 1: Commercial production greenhouses ". This standard regulates the construction of commercial production greenhouses used for the professional production of plants (crops) where human occupancy is restricted to authorized personnel, concerning low levels in number and duration.

Figure 33. Images of high-tech greenhouses with a multi-tunnel structure of the exterior with rigid polycarbonate front wall (a) and interior with flexible walls (b).

6. Cultivation in Spanish greenhouses

Most greenhouses in Almería grow in artificial soil with sand mulching (Table 25), called "*enarenado*" soil (Valera *et al*., 2016). The maximum height of the greenhouses ranged from 3.7 to 4.3 m and the minimum between 2.8 m and 3.5 m depending on the areas. Around 82% of greenhouses have double doors as a pest control measure. Most greenhouses have some form of fixed roof ventilation openings, but 4.7% (Valera *et al*., 2016) totally lack overhead ventilation and 90% of greenhouses have side ventilation, with manual control. Insect-proof screens are used in the ventilation openings of 96% of greenhouses, and only 3% of them have automated climate control systems (JA, 2022a).

Table 25. Characteristics of greenhouses in the Andalusian region in 2019 (JA, 2020a).

Characteristics	% greenhouses
Type of soil	
Sand mulched soil "*enarenado*"	82.8
Natural soil	9.4
Substrates	6.7
Structure of the greenhouse	
Flat vine greenhouse (Figure 11)	25.0
Almeria-type greenhouse in "*raspa y amagado*" (Figure 13)	72.2
Multispan greenhouse (Figure 15)	1.7
Others	1.1

The percentage of multispan greenhouses (1.7%) is similar to that of greenhouses with climate control (3%), and with those classified by the Ministry of Agriculture as highly technical (2.8%). The average size of Andalusian greenhouse farms is 2.3 ha (Table 26), and the average age of farmers is 45 years, 29% under 40 years and 8.8% over 60 years. Only 16.2% of farmers are women (JA, 2020A).

Table 26. Characteristics of greenhouse farms in the Andalusian region and its main production areas in 2019 (JA, 2020A).

Feature	Andalucía	Campo de Dalías	Campo de Nijar and Bajo Andarax	Coastal area	Other areas
Average area of holdings (m^2)	23 508	24 556	28 442	11 069	28 623
Number of greenhouses per farm	2.8	2.9	2.5	2.4	2.7
Average greenhouse area (m^2)	6 920	7 479	7 918	3 778	3 649

6.1. Area and production of greenhouses in Spain

Spain with 72 151 ha (Tables 27-28) is the country with the largest wintering area in the European Union, ahead of Italy (42 800 ha), France (11 500 ha), Poland (6 750 ha) and the Netherlands (4 836 ha) (RRFA, 2021; STATISTA, 2021).

6.1.1. Distribution of greenhouses in Spain

Most of the crops in Spanish greenhouses are concentrated in the regions of Andalucía (76.8%), Murcia (9.0%) and the Canary Islands (7.7%) (Fig. 34 & Table 27). In the last year recorded (2021) there was an increase of 1 497 ha of cultivated area (Table 27). Most of the greenhouses are simple (54.7%) or elemental (41.1%) with very few highly technical (2.7%). Most Spanish greenhouses work solely with the contribution of solar energy, so they are called solar greenhouses (CT, 2021; EUCOFEL, 2021).

Table 27. Area cultivated in the different types of greenhouses in the regions of Spain in the years 2019, 2020, 2021 and 2022 (MAPA, 2021, 2022, 2023 and 2024).

Regions	*ELE **	*SIM*	*TEC*	Total		*ELE*	*SIM*	*TEC*	Total		*ELE*	*SIM*	*TEC*	Total		*ELE*	*SIM*	*TEC*	Total	
	[ha]	[ha]	[ha]	[ha]	%	[ha]	[ha]	[ha]	[ha]	%	[ha]	[ha]	[ha]	[ha]	%	[ha]	[ha]	[ha]	[ha]	%
Year	***2019***					***2020***					***2021***					***2022***				
Galicia	202	244	35	481	0.7	172	275	35	482	0.7	187	255	35	477	0.7	166	259	35	460	0.6
Asturias	1	78	31	110	0.2	1	81	31	113	0.2	16	95	31	142	0.2	9	95	31	136	0.2
Cantabria	35	1	0	36	0.1	2	23		25	0.0	5	1	0	6	0.0	1	1	0	2	0.0
País Vasco	78	211	17	306	0.4	78	211	17	306	0.4	78	211	17	306	0.4	78	211	17	306	0.4
Navarra	313	95	129	537	0.8	147	238	129	514	0.7	139	203	129	471	0.7	111	245	153	509	0.7
La Rioja	40	0	0	40	0.1	40	0	0	40	0.1	41	0	0	41	0.1	50	0	0	50	0.1
Aragón	202	37	0	239	0.3	204	35	15	254	0.4	204	35	0	239	0.3	230	26	0	256	0.3
Cataluña	358	569	40	966	1.4	379	551	49	979	1.4	293	579	49	921	1.3	252	529	43	825	1.1
Baleares	51	77	0	128	0.2	51	75	0	126	0.2	23	103	0	126	0.2	60	82	0	142	0.2
Castilla y León	29	125	60	214	0.3	45	76	99	219	0.3	47	133	38	218	0.3	66	57	654	777	1.0
Madrid	49	31	84	163	0.2	63	31	84	177	0.2	101	31	84	216	0.3	60	20	52	132	0.2
Castilla La Mancha	18	51	0	69	0.1	18	51	0	69	0.1	14	51	0	65	0.1	13	76	12	101	0.1
C. Valenciana	344	643	86	1 073	1.5	377	719	86	1 183	1.6	464	660	89	1213	1.7	395	587	86	1 068	1.4
Murcia	3 520	2 542	314	6 376	9.0	3 573	2 601	316	6 491	9.0	3 607	2 579	305	6491	9.0	3 532	2 577	292	6 401	8.4
Extremadura	78	77	0	155	0.2	102	73	0	175	0.2	102	73	0	175	0.2	67	40	0	107	0.1
Andalucía	22 950	29 785	1 167	53 902	76.2	23 822	30 148	1 169	55 138	76.8	24 142	30 903	1 193	56238	77.9	26 452	31 913	1 048	59 413	77.6
Canarias	648	5 261	40	5 948	8.4	660	4 811	20	5 491	7.7	625	4 161	20	4806	6.7	711	5 181	22	5 914	7.7
Spain	**28 917**	**39 825**	**2 002**	**70 744**	**100**	**29 736**	**39 998**	**2 049**	**71 783**	**100.0**	**30 088**	**40 073**	**1 990**	**72 151**	**100**	**32 254**	**41 900**	**2 445**	**76 600**	**100**

* ELE – Elementary, SIM – Simple and TEC – High technology.

Table 28. Area cultivated (ha) in greenhouses of Spain of the different crops from 2004 to 2023 (MAPA, 2023b-2024c).

Crops	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Tomato	9 274	11 868	9 792	7 972	8 148	6 795	8 468	7 264	6 452	6 189	6 249	6 617	6 641	6 937	10 520	5 962	5 948	6 467	7 245	7 713
Pepper	4 059	5 841	3 390	5 488	4 827	3 904	4 698	3 314	3 864	3 138	3 820	4 361	4 373	5 563	8 866	5 958	4 983	4 622	4 175	4 230
Cucumber	947	2 814	1 310	1 933	1 784	1 068	2 299	1 474	1 654	1 001	1 104	1 729	1 196	1 473	2 420	2 015	1 653	2 483	1 431	1 526
Watermelon	774	593	1 439	312	360	1 259	1 284	932	912	1 288	896	1 588	807	1 653	662	981	825	1 412	650	746
Courgette	1 468	2 346	1 472	1 291	1 108	1 070	1 755	825	413	406	501	528	953	1 038	1 577	373	590	480	484	545
Melon	2 301	1 192	2 197	2 879	1 433	1 195	626	576	722	829	678	710	782	803	530	321	230	523	378	357
Eggplant	457	779	604	493	432	470	689	395	277	280	412	472	317	503	1 366	231	286	132	383	758
Green bean	380	1 217	955	498	357	429	827	732	511	643	340	292	426	214	332	224	141	134	152	134
Lettuce	129	151	155	123	311	51	148	162	90	114	170	160	152	130	251	90	156	39	91	118
Strawberry *	340	3 962	4 401	3 934	4 956	5 674	6 060	6 289	2 232	3 097	5 416	4 267	6 691	8 235	7 092	7 933	7 152	8 414	10 091	10 054
Raspberry *	0	0	0	22	936	836	809	340	522	776	273	1 347	1 129	1 799	1 783	1 885	2 072	2 055	2 869	2 724
Blueberry *	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3 590	4 512
Banana	2 130	3 084	2 683	2 907	2 915	3 122	3 110	3 121	3 124	3 201	3 073	2 967	3 016	3 195	3 104	3 085	3 106	3 081	3 095	2 788
Papaya	84	76	40	97	59	116	256	286	90	85	165	338	403	515	548	479	372	383	446	451
Mango	40	93	95	50	60	132	98	138	185	170	353	303	346	290	269	268	287	330	301	301
Pineapple	0	110	110	129	129	106	106	106	109	69	109	111	111	111	136	136	141	141	141	129
Avocado	0	8	0	0	0	22	64	81	76	71	72	18	35	31	10	12	91	115	174	200
Flower	3 892	3 651	3 263	2 357	1 523	1 680	1 446	1 668	1 387	1 275	1 334	1 184	1 091	1 198	1 203	1 124	1 054	821	620	682
Nurseries	461	1 378	770	1 020	1 321	1 071	931	829	1 259	1 279	1 429	1 460	1 377	1 262	1 093	1 093	1 186	1 195	1 462	1 475
Total	**58 231**	**65 218**	**64 668**	**66 097**	**65 989**	**63 335**	**62 505**	**62 283**	**60 842**	**62 085**	**65 055**	**65 644**	**65 674**	**69 705**	**70 545**	**70 744**	**71 783**	**72 151**	**76 600**	**77 923**

* Protected crops in non-permanent tunnels changing plastic cover every year.

Figure 34. Map of Spanish regions with different surfaces of greenhouses: >10 000 ha (■), 5 000-10 000 ha (■), **2 000-5 000 (■), 1 000-2 000 ha (■) and** <1 000 ha (■).

The Andalusian greenhouses (Fig. 35) are distributed on the coast of Granada and Malaga, and mainly in Almería, with three production areas (Campo de Dalías, Campo de Nijar and Bajo Andaráx), also located on the Mediterranean coast, in the part of the province with a flatter orography. In 2023, 82.5% of Andalusian greenhouses are concentrated in the province of Almería (33 634 ha), around the areas of Campo de Dalias (22 508 ha), Campo de Níjar and Bajo Andarax (9 478 ha) (JA, 2024c).

The area of horticultural greenhouses in Andalucía reached 37 897 ha in 2023 (JA, 2024c), excluding the area of the province of Huelva with 15 549 ha of protected crops (JA, 2024d), since it corresponds mostly to different tunnel structures, where various types of red fruits are grown (MAPA, 2023b). The area in the other three provinces was 3 505 ha in Granada, 945 ha in Cádiz, 758 ha in Málaga and 469 ha in Sevilla (JA, 2024c-e).

Figure 35. Distribution of the main greenhouse producing areas in Andalucía.

6.1.2. Evolution of the surface area of greenhouses in Spain

The total area and production of vegetables in the year 2022 has increased by 20.0% and 13.3% compared to the previous season from 2016 to 2020 (Table 29) as consequence of the falls in open air production in the last two years (with reduction of 6.5% and 17.2%, respectively), which represents the lowest levels since 2012/13 with 359 617 ha and 13 127 947 t (MAPA, 2023f). The impact of the drought has led to significant deficits in productivity at the national level, especially in the south and west, specifically in the Guadalquivir and Guadiana basins. The Mediterranean arc and the Ebro Valley have also been affected by winter flooding and spring rains, which has affected yields. Greenhouse crops were protected from this but whether conditions, and the reduction in the surface and production inside greenhouses was practically negligible, 0.7% and 0.6%, respectively (Table 29).

Table 29. Evolution of surface S_c, production P_c and productivity Y_c of fresh vegetables inside greenhouses in Spain (MAPA, 2023f-2024d).

Crop	Total			Open air			Greenhouses				
Season	S_c [ha]	P_c [t]	Y_c [kg/m^2]	S_c [ha]	P_c [t]	Y_c [kg/m^2]	S_c [ha]	%	P_c [t]	%	Y_c [kg/m^2]
2016	387 895	15 608 652	4.02	324 306	10 955 364	3.38	63 589	16.4	4 653 288	29.8	7.32
2017	378 294	15 052 077	3.98	318 134	10 338 821	3.25	60 160	15.9	4 713 256	31.3	7.83
2018	366 392	16 114 124	4.40	302 644	11 144 475	3.68	63 748	17.4	4 969 649	30.8	7.80
2019	386 084	15 072 708	3.90	322 681	10 210 799	3.16	63 403	16.4	4 861 909	32.3	7.67
2020	381 860	15 628 591	4.09	317 989	10 840 472	3.41	63 871	16.7	4 788 119	30.6	7.50
2021	360 047	13 127 947	3.65	296 657	8 370 479	2.82	63 390	17.6	4 757 468	36.2	7.51
2022	372 159	14 290 286	3.84	296 615	8 854 076	2.98	75 544	20.3	5 436 210	38.0	7.20

The greater productivity in greenhouse crops (7.20 kg/m^2) compared to outdoor crops (2.98 kg/m^2) allows to obtain a 38.0% of production of vegetables in Spain with the use of only 20.3% of the surface total cultivated with vegetables (Table 29). This difference in productivity is also increased when weather conditions are adverse, as occurred in the 2021.Thus, while outdoor productivity decreased by 17.2% compared to the previous season, in the greenhouse it remained at the same level as the previous year. In the overall number of years, a greater variability in outdoor productivity is also observed than that of greenhouse crops (Table 29).

The area of crops under greenhouse in Spain has increased by 15.8% in the last decade (Table 29, Fig. 36), from 62 283 ha in 2011 to 72 151 ha in 2021, mainly due to an increase of 28.0% in the Andalusian region, from 43 923 ha to 56 237 ha (Table 30 – Fig. 36).

Table 30. Evolution of surface of greenhouses and crop protected in different regions of Spain (MAPA, 2024a).

Year	Spain	Andalucía[a]	Murcia	Canary Islands
2009	63 335	44 887	6 567	7 476
2010	62 505	43 946	6 733	7 261
2011	62 283	43 923	6 961	6 997
2012	60 842	42 823	6 889	6 826
2013	62 085	44 280	6 624	6 925
2014	65 055	47 367	6 523	6 834
2015	65 644	48 428	6 230	6 692
2016	65 674	48 509	6 235	6 744
2017	69 705	52 737	6 330	6 293
2018	70 545	53 528	6 511	6 092
2019	70 744	53 902	6 376	5 948
2020	71 783	55 138	6 491	5 491
2021	73 280	56 237	6 491	5 776
2022	76 600	59 413	6 401	5 914
2023	77 923	61 099	6 449	5 495

[a] Area including low tunnels used for berry fruits.

In the Region of Murcia, the area of crops in greenhouses has also increased a 40.4% in the last ten year (being 6 449 ha in 2023), while it has been gradually decreasing in the Canary Islands (from 6 925 ha in 2013 to 5 495 ha in 2023).

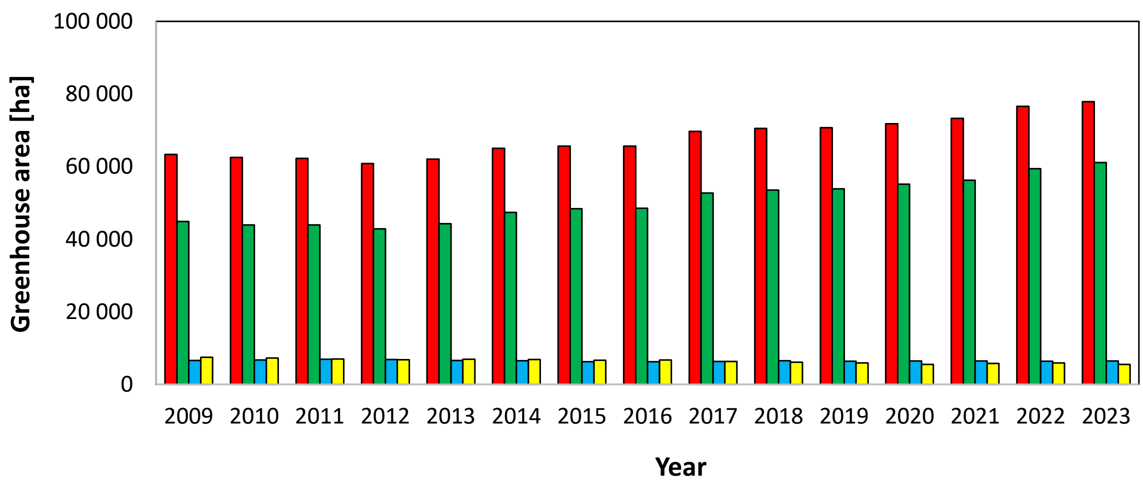


Figure 36. Evolution of the greenhouse area in Spain (■), Andalucía (■), Murcia (■) and the Canary Islands (■). (MAPA, 2024a).

6.2. Production of crops in Spanish greenhouses

The main crops in Spanish greenhouses (Table 31) are tomatoes (Figure 37a) and peppers (Figure 37b). In the Canary Islands, the main crop is bananas with half of its surface of greenhouses.

Table 31. Area [ha] of protected crops in Spain in 2019 and 2021 (MAPA, 2020a; [a]JA, 2020a; [b]CREM, 2020a; [e] CREM, 2022a; [f] JA, 2022a; [g] MAPA, 2021; [h] JA, 2021a).

Crops	Murcia	Andalucía	Canary Islands	Spain
		2019		
Tomato	2 316 [b]	12 762 [a]	951	16 029 [c]
Pepper	1 248 [b]	11 115 [a]	296	12 659 [c]
Cucumber	172 [b]	6 037 [a]	0	7 521 [c]
Watermelon	118 [b]	8 283 [a]	0	8 401 [c]
Courgette	236 [b]	7 349 [a]	141	7 726 [c]
Melon	62 [b]	2 012 [a]	0	2 074 [c]
Eggplant	12 [b]	2 164 [a]	5	2 181 [c]
Green bean	19 [b]	703 [a]	23	745 [c]
Lettuce	1	0	0	90
Strawberry	0	7 850 [d]	0	7 933
Raspberry	0	1 885 [d]	0	1 885
Banana	0	0	3 085	3 085
Papaya	30 [b]	70	409	509 [c]
Mango	0	145	123	268
Pineapple	0	0	136	136
Avocado	0	0	12	12
Flower	204	571	47	1 124
Nurseries	233	239	42	1 093
Total	**6 376 [b]**	**53 902 [h]**	**5 948 [g]**	**70 744 [g]**
		2021		
Tomato	2 029 [e]	8 187 [f]	927	11 143 [c]
Pepper	1 287 [e]	12 574 [f]	97	13 958 [c]
Cucumber	203 [e]	5 614 [f]	9	5 826 [c]
Watermelon	99 [e]	9 095 [f]	0	9 194 [c]
Courgette	243 [e]	7 927 [f]	0	8 170 [c]
Melon	89 [e]	1 908 [f]	0	1 997 [c]
Eggplant	12 [e]	2 387 [f]	10	2 409 [c]
Green bean	23 [e]	219 [f]	10	252 [c]
Lettuce	0	13	1	39
Strawberry	0	8 353	0	8 414
Raspberry	0	2 047	0	2 055
Banana	0	0	3 081	3 081
Papaya	32 [e]	5	378	383
Mango	16 [e]	204	126	330
Pineapple	0	0	141	141
Avocado	1 [e]	32	83	115
Flower	187 [e]	374	39	821
Nurseries	313	220	55	1 195
Total	**6 491 [e]**	**56 237 [h]**	**5 776 [g]**	**72 151 [g]**

[c] Calculated from data from the different sources consulted. [d] Cultivation in low tunnels.

Table 31. Continuation.

Crops	Murcia	Andalucía	Canary Islands	Spain
		2022 [k]		
Tomato	1 711	8 187 [i]	929	7 245
Pepper	1 671	12 574 [i]	114	4 175
Cucumber	98	5 614 [i]	14	1 431
Watermelon	5	9 095 [i]	0	650
Courgette	15	7 927 [i]	26	484
Melon	152	1 908 [i]	0	378
Eggplant	12	2 387 [i]	18	383
Green bean	0	219 [i]	20	152
Lettuce	0	0	31	91
Strawberry	0	9 364 [d]	0	10 091
Raspberry	0	2 869 [d]	0	2 869
Banana	0	0	3 095	3 095
Papaya	0	4	442	446
Mango	0	187	114	301
Pineapple	0	0	141	141
Avocado	6	16	158	174
Flower	0	298	42	620
Nurseries	313	342	55	1 462
Total	**6 401**	**59 413**	**5 914**	**76 600**
		2023 [L]		
Tomato	1 599	8 555 [j]	936	7 713
Pepper	1 504	12 452 [j]	1	4 230
Cucumber	6	5 750 [j]	0	1 526
Watermelon	0	8 695 [j]	0	746
Courgette	0	8 142 [j]	73	545
Melon	131	2 107 [j]	0	357
Eggplant	12	2 318 [j]	0	758
Green bean	0	261 [j]	0	134
Lettuce	0	0	31	118
Strawberry	0	9 264 [d]	0	10 054
Raspberry	0	2 693 [d]	0	2 724
Banana	0	0	2 788	2 788
Papaya	0	9	442	451
Mango	0	187	114	301
Pineapple	0	0	129	129
Avocado	0	16	184	200
Flower	111	333	22	682
Nurseries	310	366	81	1 475
Total	**6 449**	**61 099**	**5 495**	**77 923**

[c] Calculated from data from the different sources consulted. [d] Cultivation in low tunnels.

In recent years, new crops are being developed, such as papaya (Figure 37c) as an alternative to more traditional crops such as tomatoes (Honoré *et al*., 2019a-2020b), which have reduced their production (Tables 28 & 31).

Figure 37. Tomato (a), pepper (b) and papaya (c) crops in greenhouses in Almería.

6.3. Greenhouse production in Andalucía

6.3.1. Greenhouse surface

The area cultivated within greenhouses in Andalucía in 2023 (61 099 ha, Table 30) was greater than the current area of soil they occupy in 2023, 37 897 ha (JA, 2024c) because some farmers produced two different crops in the same season, a first autumn-winter crop and a second spring-summer crop (Valera *et al.,* 2016).

In recent seasons, greenhouse tomato production was reduced by 32% in surface area and 38% in quantity produced, as for green beans (Table 32 – Fig. 38). The reduction in the area under tomato and bean cultivation has been partially offset by increases in the other six main crops (Table 32), with an increase in the area under pepper of 26% (Fig. 38).

Table 32. Area (S_G) and production (P_G), value of production (V_P) productivity (Y_C) and average price (A_P) of crops cultivated in the Andalusian greenhouses (Almería and Granada) in the last 7 seasons (JA, 2021b; JA, 2022a). Surface of greenhouses measured from the satellite image analysis (S_S) in Almería and Granada (JA, 2016; JA, 2020b; 2021c; 2022b: 2024c-d).

Crops	Parameters	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23
Tomato	S_G [ha]	14 126	13 425	13 795	12 762	11 814	11 536	11 316	8 555*
	P_G [t]	1 436 907	1 337 903	1 337 696	1 174 338	1 129 651	1 051 786	1 043 353	688 472*
	V_P [Thousands €]	1 123 404	882 762	882 600	841 600	751 000	756 100	1 031 300	702 241*
	Y_C [kg/m²]	10.2	10.0	9.7	9.2	9.6	9.1	9.2	8.0*
Pepper *	S_G [ha]	9 439	10 260	10 143	11 115	11 936	12 294	12 574	12 452*
	P_G [t]	664 340	693 215	732 118	845 595	942 207	957 782	979 604	893 134*
	V_P [Thousands €]	604 549	506 047	563 731	659 564	734 921	802 800	818 000	1 098 600*
	Y_C [kg/m²]	7.0	6.8	7.2	7.6	7.9	7.8	7.8	7.2*
Cucumber	S_G [ha]	5 989	5 949	6 066	6 037	6 358	6 324	6 657	5 750*
	P_G [t]	540 903	524 544	545 221	632 575	688 117	658 721	693 370	525 328*
	V_P [Thousands €]	380 844	288 686	286 872	366 893	317 517	375 471	554 696	499 061*
	Y_C [kg/m²]	9.0	8.8	9.0	10.5	10.8	10.5	10.4	9.1*
Watermelon *	S_G [ha]	6 833	7 129	7 797	8 283	8 515	9 569	9 095	8 695
	P_G [t]	423 359	441 831	397 832	464 581	489 083	549 986	438 103	492 286
	V_P [Thousands €]	146 202	208 930	117 391	227 645	239 651	170 100	280 400	196 900
	Y_C [kg/m²]	6.2	6.2	5.1	5.6	5.7	5.7	4.8	5.7
Courgette *	S_G [ha]	7 490	7 863	7 755	7 349	7 611	8 074	7 927	8 142
	P_G [t]	428 425	445 057	452 035	455 846	478 869	486 216	476 715	420 852
	V_P [Thousands €]	291 329	231 430	244 099	237 040	249 012	243 300	367 400	282 000
	Y_C [kg/m²]	5.7	5.7	5.8	6.2	6.3	6.0	6.0	5.2
Melon *	S_G [ha]	1 954	1 752	1 808	2 012	2 237	2 511	1 908	2 107
	P_G [t]	78 048	76 324	73 394	99 120	101 642	114 161	72 470	89 258
	V_P [Thousands €]	36 682	31 293	41 101	47 578	56 919	45 664	60 875	46 700
	Y_C [kg/m²]	4.0	4.4	4.1	4.9	4.5	4.5	3.8	4.2
Eggplant *	S_G [ha]	2 300	2 150	2 209	2 164	2 391	2 277	2 387	2 318
	P_G [t]	184 161	168 046	181 130	190 614	227 910	212 575	222 843	207 602
	V_P [Thousands €]	66 815	123 256	92 822	114 741	102 560	117 900	133 400	153 600
	Y_C [kg/m²]	8.0	7.8	8.2	8.8	9.5	9.3	9.3	9.0
Green bean	S_G [ha]	2 014	1 711	1 014	703	671	719	760	261*
	P_G [t]	43 632	38 471	22 741	16 719	16 031	16 810	17 608	4 905*
	V_P [Thousands €]	73 613	57 477	41 720	28 590	27 300	27 400	34 159	11 085*
	Y_C [kg/m²]	2.2	2.3	2.3	2.4	2.4	2.4	2.3	1.9*
All crops	S_G [ha]	50 145	50 239	50 587	50 425	51 533	53 304	52 624	48 280*
	P_G [t]	3 799 775	3 725 391	3 742 167	3 879 388	4 073 510	4 048 037	3 944 066	3 321 837*
	V_P [Thousands €]	2 723 438	2 329 881	2 270 336	2 523 651	2 478 880	2 538 735	3 156 647	2 990 187*
	Y_C [kg/m²]	7.6	7.4	7.4	7.7	7.9	7.6	7.5	6.9*
	A_P [€/kg]	0.72	0.63	0.61	0.65	0.61	0.63	0.80	0.98*
Greenhouses	S_S [ha]	**32 855**	**34 121**	**34 714**	**35 170**	**35 935**	**36 218**	**36 935**	**21 523***

* Production corresponding only to greenhouses in Almería.

We can observe and increase from 2015/16 to 2021/22 of 9.4% (4 080 ha) in the surface of greenhouses measured from the satellite image analysis, whereas the rise in the surface of crops cultivated inside these greenhouses was 2.8% (2 479 ha) (Table 32 – Fig. 38). This difference show that some growers have changed the cultivation option, from two short crops to one long cycle crops.

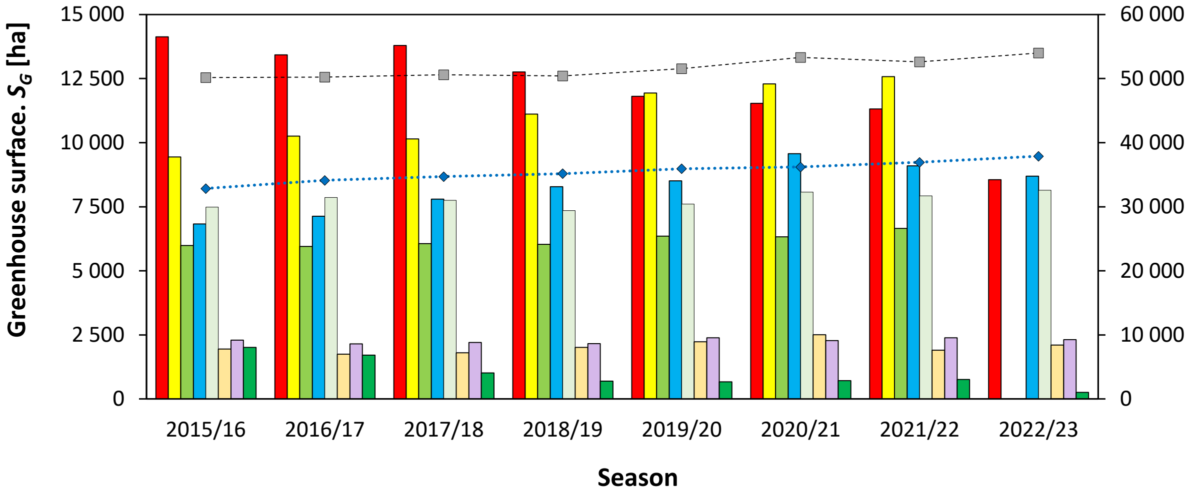


Figure 38. Evolution of the surface area of greenhouses in Andalucía: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■) and green bean (■) (Data from Table 32).

In the 2022/23 season, a historical maximum of greenhouse area was reached in the province of Almería, with 33 634 ha (JA, 2024c), 0.51% higher than the previous season). Considering the double cycle system used in some crops, the cultivated area in Almería was 50 874 ha, which represents a decrease in the cultivated area of 5.4% compared to the previous season.

The main reason for this reduction has been a lower planting in the spring season due to the reliable performance in the market of autumn plantations at the end of the cycle (CAJAMAR, 2022). This resulted in some farmers deciding to extend this crop cycle to the detriment of spring plantations, especially melon and watermelon. In fact, these are the crops that have decreased their hectares the most in this period (CAJAMAR, 2022).

By products, pepper has become the main crop in the greenhouses of Almeria and since 2016 its surface has been increasing to the detriment of that of the tomato (Fig. 38). Thus, in the 2022/23 season, the pepper area of 12 452 ha, like the previous season when rose by 2.3%, while that of tomatoes has maintained the downward trend of recent seasons, with a decline of 2.6%, reaching 8 555 ha in Almería (Table 32).

However, the effect of the increase in energy prices in the plantations of Central Europe, mainly in the Netherlands, could change this negative curve of the tomato, since to avoid the high energy cost of its production, these origins have had to modify their production calendar, favouring the commercialization of the tomato of Almería (CAJAMAR, 2022).

The rest of the crops remained stable, highlighting, in the case of spring, watermelon with an area of 8 695 ha in 2022/23, with a fall of -4.4% compared to the previous season 2021/22 when their surface also decreased 5.0% (JA, 2022c-2024c).

6.3.2. Greenhouse production

We can observe as the crop productivity in greenhouses has been maintained stable from 2015/16 to 2021/22, but the reduction of tomato surface has produced a reduction of 52.1% in the production of this crop and a overall reduction of 12.6% of vegetable and fruits greenhouse production in Andalucía (Table 32 – Fig. 39). The decrease of tomato production has been compensated partially by the increase of 34.4% of pepper, 16.3% for watermelon, 14.4% for melon and 12.7% for aubergine.

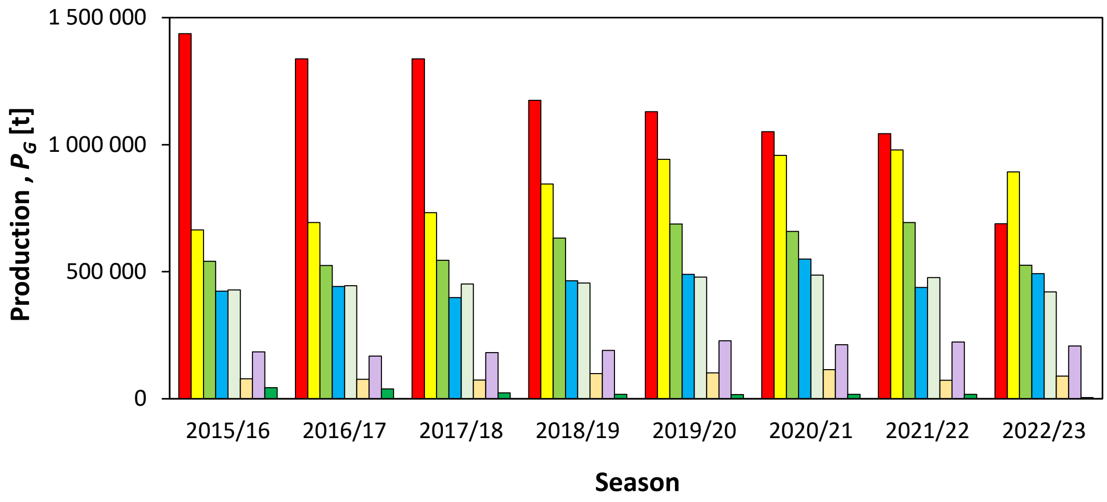


Figure 39. Evolution of the production of the main crops in Andalucía: tomato (■), **pepper** (■), **cucumber** (■), **watermelon** (■), **zucchini** (■), **melon (■), eggplant** (■) **and green bean** (■) **(Data from Table 32).**

Almeria's solar greenhouses produced 3,561 million kg of vegetables in the 2021/22 season. Although production fell by 6.7% compared to the previous season, its value of 2,940.3 million euros was 13.9% higher than that obtained in the previous season (CAJAMAR, 2022), thanks to the increase in sales prices (Table 33). Of this production, a total of 2 864.2 million kilos were exported, 4.4% less than the 2020/21 season, which reached a value of 3 701.5 million euros, revenues that exceeded by 17.4% those of the previous season (CAJAMAR, 2022).

The production of the 2021/22 season was affected by adverse climatic phenomena with a direct impact on the final production. Thus, although it was a generally warm season, the arrival of winter temperatures in November helped regulate production. January and February saw the lowest temperatures of the production period, avoiding situations of oversupply in the market (CAJAMAR, 2022).

To these circumstances we must add the unusual episodes of haze that took place in the month of March, the spring rains and, consequently, a greater number of cloudy days, which also contracted the supply of vegetables in the province. The products most affected by these circumstances were: melon, watermelon, and lettuce (CAJAMAR, 2022).

The pepper produced in Almeria reached 979 604 tons, an increase of 2.3%, also registering increases in green beans, eggplant and cucumber; Meanwhile, tomato production stood at 716 739 tonnes, 1.2% lower than the previous season, with the falls in watermelon and melon also noteworthy, with productions 40% and 50% respectively lower (JA, 2022c).

6.3.3. Greenhouse productivity

Although the average productivity of greenhouses has remained around 7.7 kg/m^2, the value of agricultural production in Andalusian greenhouses fell to 2 190 million euros in 2019/20, 19.4% lower than the value of 2015/16 (Table 32). This reduction in production value is mainly due to the decrease in the area of tomato cultivation (Fig. 38) and its productivity (Fig. 40). The reduction in productivity is a direct consequence of the increasing incidence of the *Tuta absoluta* (Meyrick) pest and increase of mean temperature in spring-summer period (Fig. 3). This pest, native to South America, was first detected in eastern Spain in late 2006, becoming a serious threat to tomato production (Cabello *et al.*, 2012). The reduction in cultivated area is affected by this decrease in crop productivity, as well as by increasing competition from tomatoes from Morocco. Tomato cultivation has been replaced by other crops with a lower selling price such as watermelon or zucchini (Fig. 40).

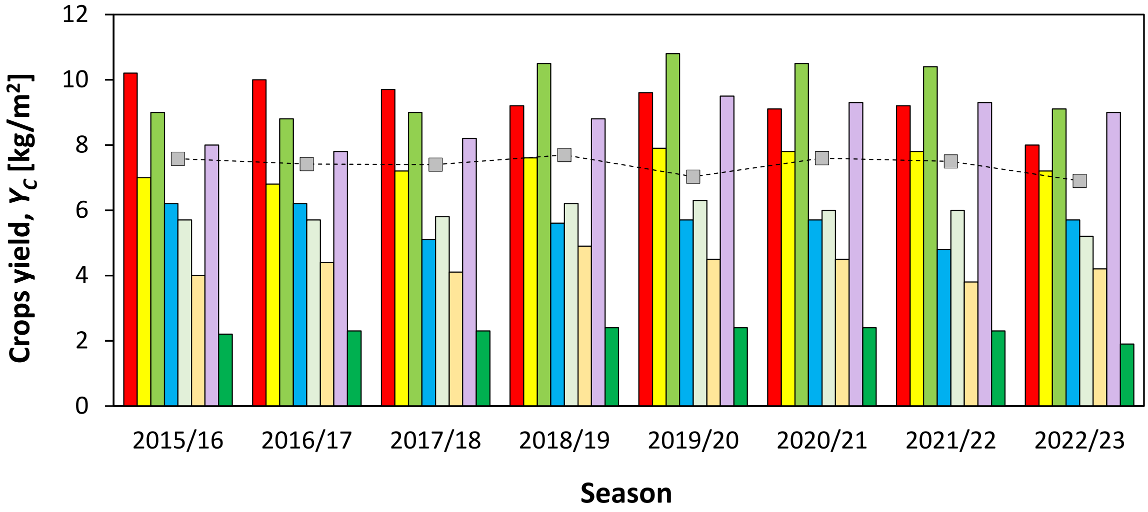


Figure 40. Evolution of greenhouse crop productivity in Andalucía: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■) and average of all products (-■-) (Data from Table 32).

6.4. Commercialisation of greenhouse production

6.4.1. Evolution of production value in greenhouse of Andalucía

Horticulture in greenhouses is the most dynamic sector of Andalusian agriculture due to its economic productivity and export vocation. Spanish greenhouses are pioneers in the application of biological control techniques consisting of the use of beneficial insects to naturally combat pests, while bumblebees are increasingly used for natural pollination of flowers (EUCOFEL, 2021). The fruit and vegetable production in solar greenhouses is certified with the highest level of quality standards such as IFS (*International Featured Standards*) or GRASP (*GLOBAL G.A.P Risk Assessment on Social Practices*).

The increase in the quality of fruit production and marketing has made it possible to maintain the average price of greenhouse crops, with significant variations from year to year, depending on climatic conditions and market demand (Table 33). The average price reached by all the main vegetables grown under greenhouse in Andalucía was 0.80 €/kg in 2021/22, the higher registered (Fig. 41), and 11.7% greater than that of the 2015/16 season (JA, 2020A).

Table 33. Average price [€/kg] obtained by farmers for greenhouse production in Andalucía (Almería and Granada) in the last seasons (JA, 2021b; JA, 2022c-2024c-d).

Crops	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23
Tomato	0.45	0.66	0.52	0.61	0.57	0.60	0.87	0.94
Cherry tomato	0.93	1.28	1.21	1.12	1.12	1.23	1.40	1.56
Pepper	0.86	0.91	0.73	0.77	0.78	0.84	0.84	1.23
Cucumber	0.44	0.70	0.55	0.53	0.57	0.57	0.80	0.95
Watermelon	0.34	0.35	0.47	0.30	0.49	0.31	0.64	0.40
Zucchini	0.47	0.68	0.52	0.54	0.52	0.50	0.77	0.67
Melon	0.47	0.41	0.56	0.48	0.56	0.40	0.84	0.49
Eggplant	0.36	0.73	0.51	0.60	0.45	0.55	0.60	0.74
Bean	1.37	1.69	1.49	1.83	1.71	1.63	1.94	2.26
Average	0.72	0.63	0.61	0.65	0.61	0.63	0.80	0.90

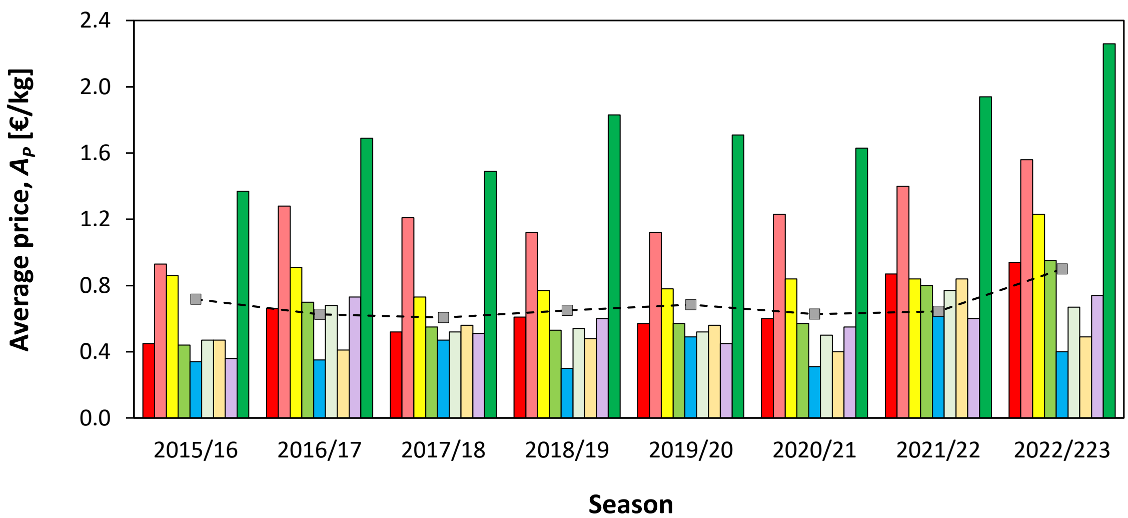


Figure 41. Evolution of the price of the main crops in Andalucía: tomato (■), tomato cherry (■) pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■) and average of all products (-■-) (Data from Table 33).

Horticultural exports have managed to improve results in recent years both in volume and economic value, thanks to an improvement in production quality standards. The highest degree of quality certification in the sector is GLOBAL G.A.P, present in 81% of farms (JA, 2022A). This standard has been required for the last fifteen years by the exporting clients of the marketers, mainly Dutch and German (JA, 2020a).

Value of the total production in greenhouses of Andalucía was 3 156.6 million of euros in the season 2021/22 (Table 32) as consequence of the increase of prices (Table 33). However, this increase was accompanied by a similar rise of the production cost, maintaining the final revenue for the growers. Although, the value of tomato crops suffered a gradual reduction from 2015/16 to 2020/21, in the season 2021/22 the rise in sales prices also allowed its final value to rise, as for the rest of the crops (Fig. 42). In the last season 2022/23 the value of production of pepper reached values similar to those of tomato in the 2015/16 season (Fig. 42).

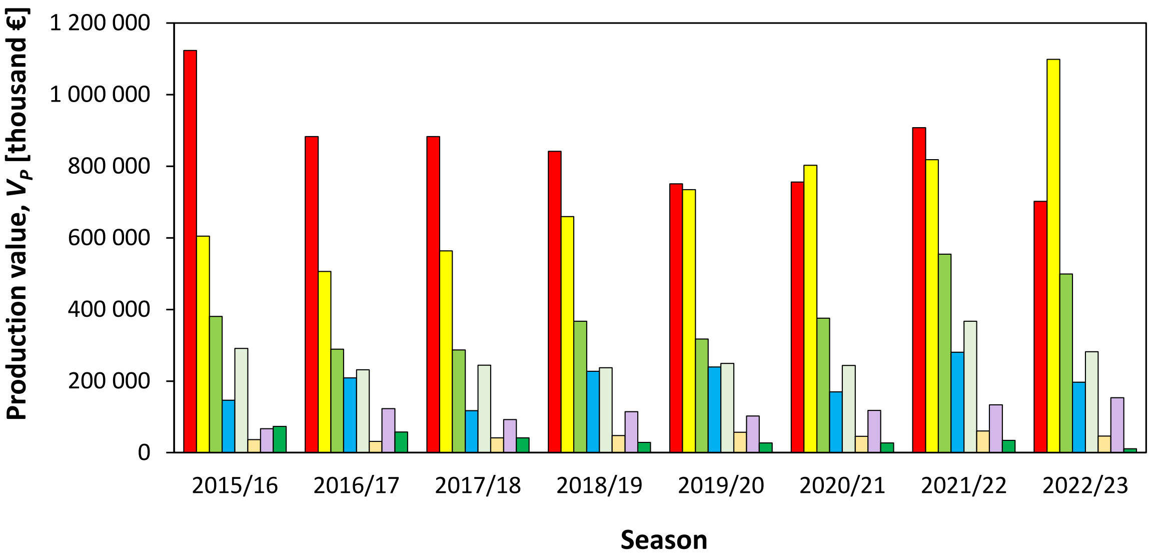


Figure 42. Evolution of the value of the production of the main crops in Andalucía: tomato (■), **pepper** (■), **cucumber** (■), **watermelon** (■), **zucchini** (■), **melon** (■**), eggplant** (■) **and green bean** (■) **(Data from Table 5).**

6.4.2. Evolution of production value in greenhouse of Almería

Almería generated in 2018 the 20% of Andalusian agricultural production and 22% of the value of agricultural production (JA, 2020A). The pepper has led in the season 2021/22 all records, both in surface area and volume produced or by the value of production. In this season the cultivation of pepper has occupied 12 574 ha in Almeria greenhouses, 2% more than in the previous season. Production has also increased by the same percentage to reach 979.6 million kg of pepper, with an average yield of 7.79 kg/m^2. This production has obtained a value of 814.5 million €, 7% more than in the previous season, with an average price at origin of 0.83 €/kg (JA, 2022a; JA, 2022c).

The area occupied by tomato cultivation has been 8 187 ha (-3%), with a production of 716.74 million kg (-1%), a yield of 8.75 kg/m^2 and a value of 680.8 million € (+41%), obtaining farmers an average price of 0.95 €/kg. Cucumber cultivation occupied in Almería in the season 2021/22 5 614 ha (+6%) that produced 584.1 million kg (+6%) and an average yield of 10.4 kg/m^2, with a value of 463.8 million €, 56% more than the previous season. The average price of cucumber grown in the season was 0.79 €/kg (JA, 2022a; JA, 2022c).

Zucchini cultivation occupied an area of 7 927 ha (-2%) that produced 476.71 million kg (-2%), giving a yield of 6.01 kg/m^2. The value of zucchini production was 352.2 million € (+53%), with an average price of 0.74 €/kg (JA, 2022a; JA, 2022c).

Almeria farmers used 2,387 ha of greenhouse (+5%) to grow eggplant, in which they obtained 222.8 million kilos of this vegetable (+5%), with an average yield of 9.33 kg/m^2, reaching a production value of 131.8 million € and an average price of 0.59 €/kg (JA, 2022a; JA, 2022c).

In green beans**,** the area was 219 hectares (+23%) that produced 4.22 million kilos (+23%) giving an average yield of 1.93 kg/m^2 and a total value of 8.29 million euros (+ 54%) with an average price of 4.29 €/kg (JA, 2022a; JA, 2022c).

The area under watermelon cultivation was 9 095 ha (-5%) with a production of 438.1 million kg (-20%) and a yield of 4.82 kg/m^2. Watermelon production reached a value at origin of 278.2 million euros, when paid at an average price of 0.63 €/kg (JA, 2022a; JA, 2022c).

A total of 1 908 ha has been allocated to cultivate melon in the 2021/22 season, producing 72.47 million kg with an average yield of 3.8 kg/m^2. The melon produced in the greenhouses of Almeria reached a value at origin of 57.4 million euros with an average price of 0.79 €/kg (JA, 2022a; JA, 2022c).

7. Technical-productive characterization of Almería greenhouses

The technical-productive characterization of the greenhouses of Almería has been carried out through the statistical processing of an extensive internal survey carried out during the year 2022 by the Andalusian Cooperative Society AFE to 222 members, through an agreement with the University of Almería. This survey covers 610 greenhouses, with a total of 463 ha, representing 1.4% of the total greenhouse area (33 464 ha) in the province of Almería in the year 2022 (JA, 2022c).

AFE Sociedad Cooperativa Andaluza was recognized as an Organization of Fruit and Vegetable Producers (OPFH) in 2017 and represents the first entity of a group of farmers at the national level that sells its products through "*alhóndiga*" (public house intended for the purchase and sale of horticultural products).

The survey carried out (Annex A) includes most of the aspects included in the characterization carried out at the provincial level in the 2012/13 season by the University of Almería to 212 farmers from 18 producing companies, with a total area of greenhouses of 685 ha, corresponding to 2.4% of the total (Valera *et al*., 2016). Previously, a first characterization work of the greenhouses of Almería was carried out in the 1996/97 season (Molina-Aiz, 1997). In this first study, farmers from 526 greenhouses throughout the province, with a total area of 340 ha, were directly interviewed, representing a sampling percentage of 1.4% of the greenhouse area in the province of Almería (Valera *et al*., 1999).

7.1. Characteristics of growers

7.1.1. Demographics characteristics

The first part of the surveys, referring to the members of the Producer Organization, focuses on the analysis of the demographic characteristics of the members. Most of the members of the Producer Organization are in intermediate age ranges, with the 41-46- and 46-50-years age brackets as the most prevalent (Fig. 43). It should be noted that 73% of the Organization's members are male (Fig. 44).

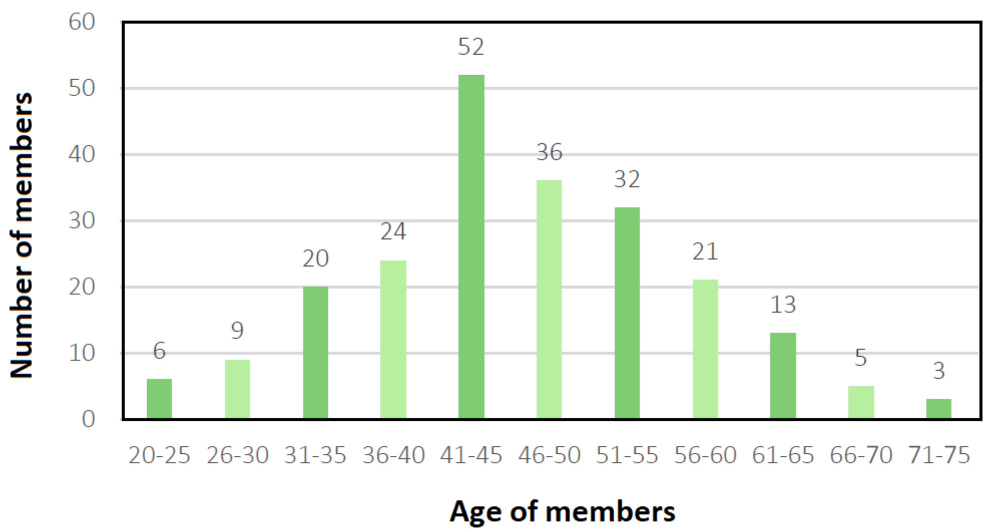


Figure 43. Absolute frequencies of the age of the members in years.

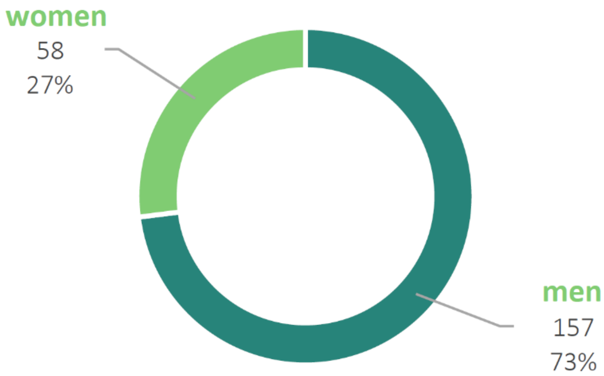


Figure 44. Percentage of the sex of the partners.

7.1.2. Formation and experience of growers

The average years of experience of the partners is between 16-20 years (Fig. 45). These data are consistent with the values obtained in the survey carried out at the provincial level in the 2012/13 season, with an average age of 46 years, although then they had somewhat more experience, 25 years (Valera *et al*., 2016).

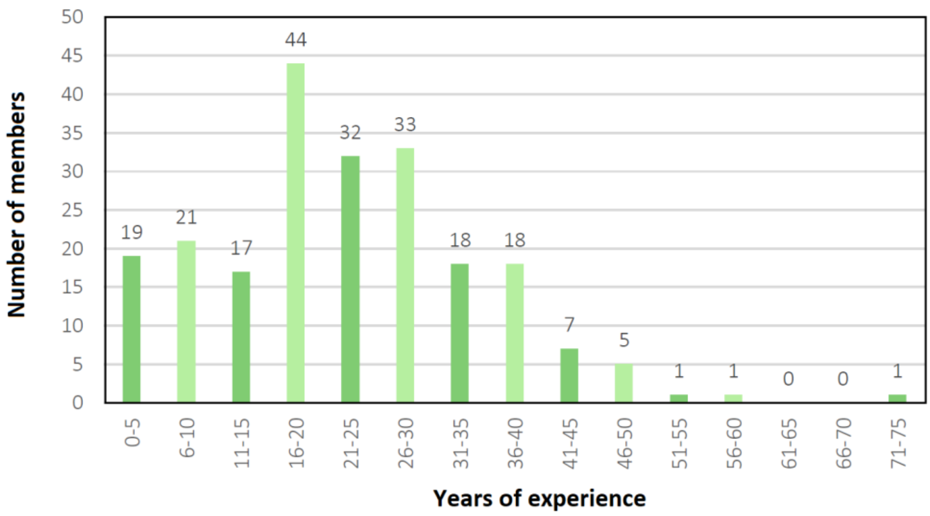


Figure 45. Absolute frequencies of years of experience.

Around 69% of farmers have EGB (basic education) and ESO (secondary education) studies, 14% have university studies, while only 6% have no academic training (Fig. 46). In the 2012/13 survey, 10% had a university education and 5% had no education. This is a significant improvement from the 33% of farmers with no education and 3% of producers with university degrees in the 1996/97 survey (Valera *et al*., 2016).

About 40% of respondents have completed a training course in the last two seasons (Fig. 47). The main source of information for farmers is field technicians (94%), although 75% also use the internet as a source of information.

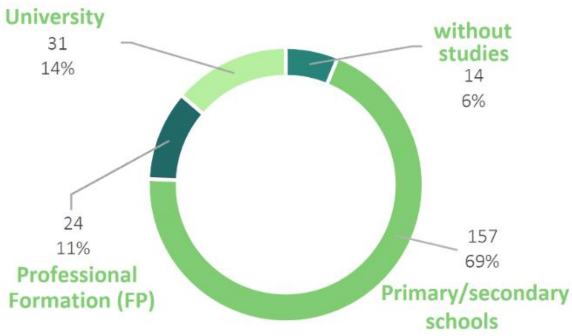


Figure 46. Percentage of members according to their training.

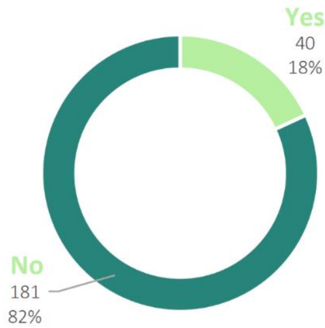


Figure 47. Percentage of members who have completed training courses in the last two seasons.

7.2. Crop management

7.2.1. Crop protection

The 77.4% of the farmers surveyed perform the tasks related to the application of phytosanitary treatments themselves, 18% of the partners prefer to hire an employee and only 2.7% opt for hiring a specialized treatment company (Fig. 48).

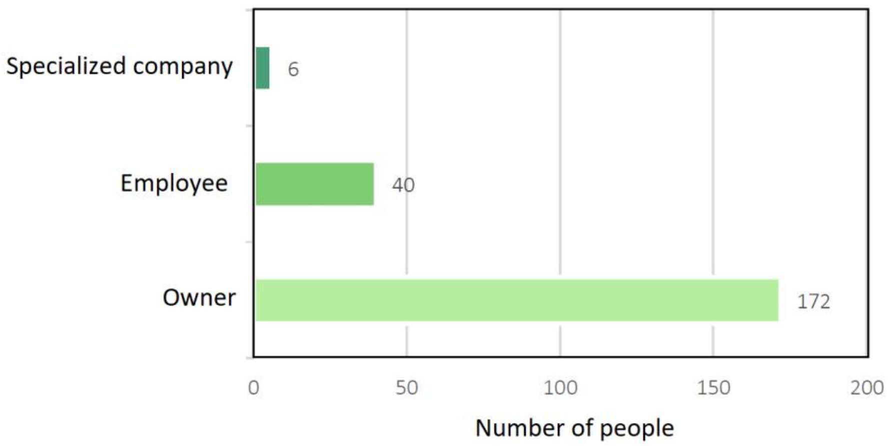


Figure 48. Absolute frequencies of people who perform phytosanitary treatments.

For the application of phytosanitary treatments, hydraulic sprayers (94.1%), dusts (27.0%) or the irrigation network (71.2%) are used, 1 to 4 times for the same crop (Fig. 49).

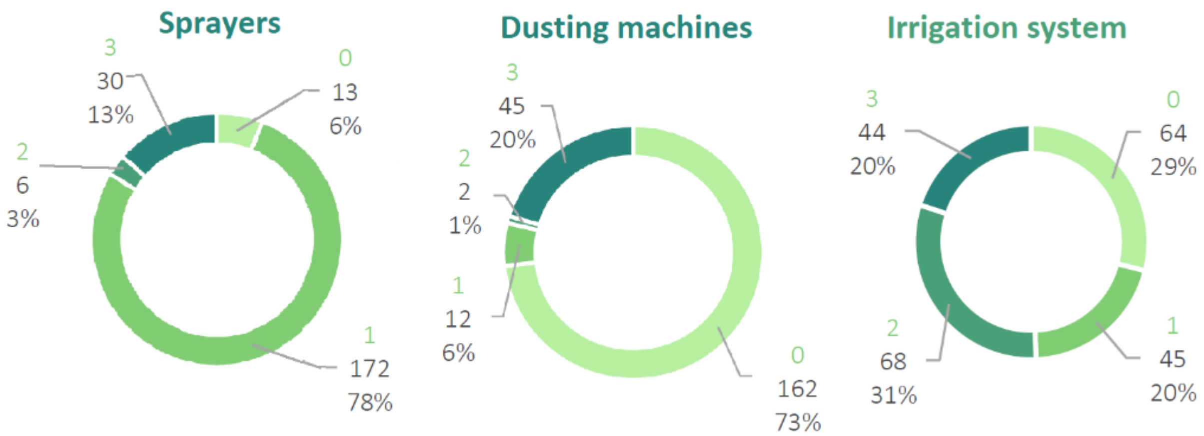


Figure 49. Percentage (number of partners) of the level of use of the different systems for treatments (0-3).

7.2.2. Agricultural residues

The 78% of the growers do not have waste containers in the farms to put the crop residues (Fig. 50).

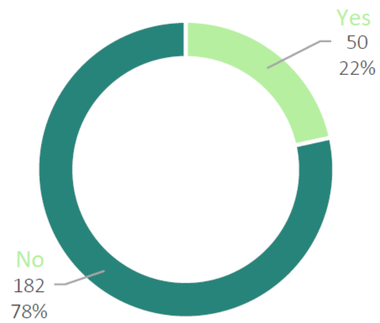


Figure 50. Relative frequencies of possession of waste containers.

The 67.7% of farmers take their waste to an authorized landfill, 40.1% shred vegetable waste for composting – green fertilizer and 16.2% use plant remains for livestock feed (Fig. 51).

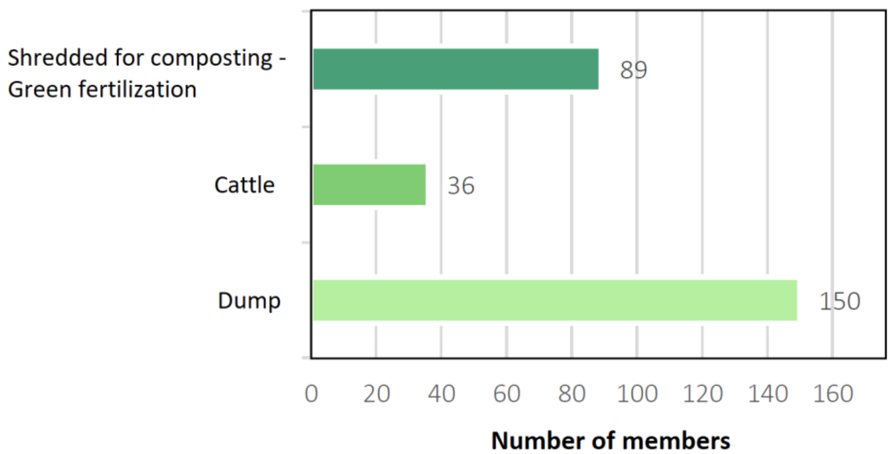


Figure 51. Absolute frequencies of plant waste management.

The 94% of the growers surveyed manage the packaging of fertilizer and phytosanitary products, 79% of the irrigation material and 69% the chromatic plates for capturing insects. 78% of farmers manage cover plastics and 76% of respondents manage some form of plastic waste management for soil mulching or solarization. 65% manage the plastics used as a double roof and 63% the plastics used in the trellising of the plants (Fig. 52).

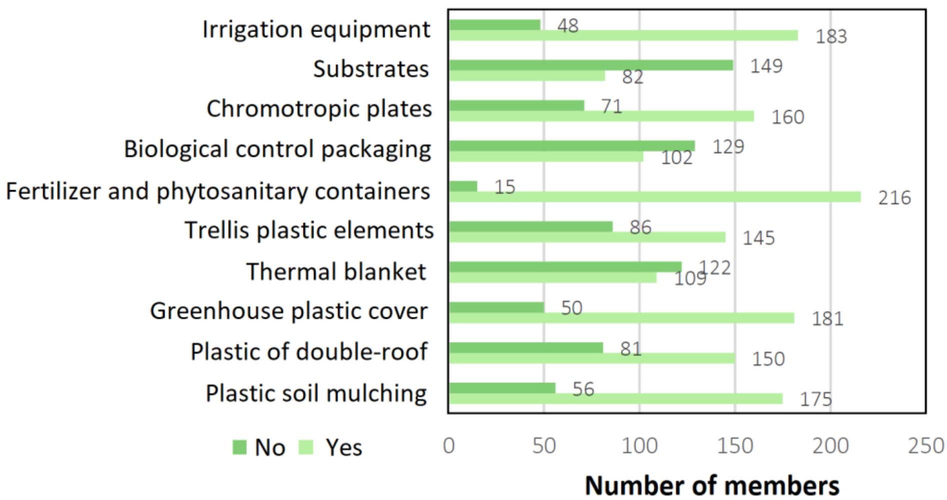


Figure 52. Absolute frequencies of waste treatment.

The 69% of growers say they are willing to use innovative solutions for the treatment of waste from their farm.

7.3. Capacity of work

7.3.1. Machinery

The members of the Producers' Organization use different machinery options for the development of their activity such as crop carts, backpack, treatment tank, tractor or truck. 92.8% of farmers use crushers of the vegetable remains of the crop, 87-88% use tools for soil work, manual hydro-pneumatic sprayers with barrel, hydraulic spray trucks and stapler machines for trellising. 59% of farmers have a van or truck to transport their products (Fig. 53).

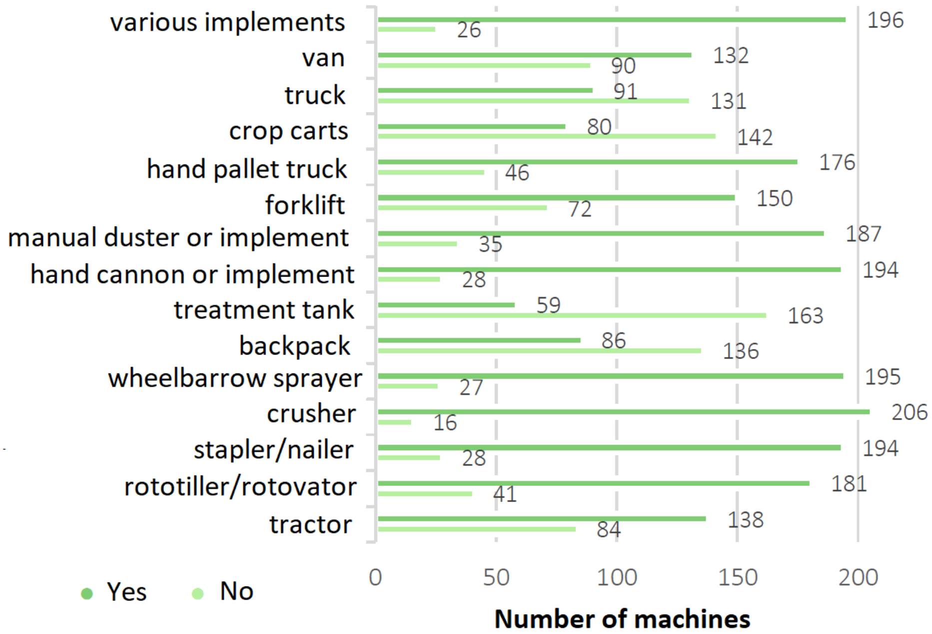


Figure 53. Absolute frequencies of the different machinery used.

Grow carts are used by more than half of users (64% members), 38% of farmers use tractors inside their greenhouses, 32% forklifts and 21% hand pallet trucks (Fig. 53), 73% of farmers use phytosanitary treatment tanks and 61% use hydraulic spray backpacks to carry out localized phytosanitary treatments.

The 59% of the growers decide to hire some service such as transport, labour or cover whitewashing, compared to 41% of respondents who opt for the alternative of not hiring any service (Fig. 54).

Figure 54. Percentage of contracting services.

7.3.2. Labor

This section details the types of employees hired by the members of the Producer Organization to develop their activities. Most farmers employ 1 to 3 workers, 14.0% of farmers hire permanent family employees, 5.8% temporary family employees, 34.2% non-family permanent employees and 50% temporary non-family employees (Fig. 55).

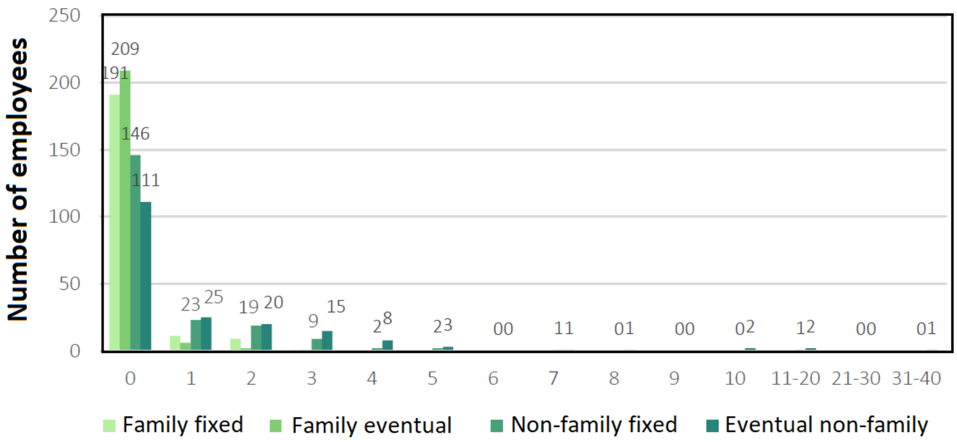


Figure 55. Absolute frequencies of the number of employees.

7.4. Soil

The 90% of the greenhouses surveyed use the "*sanding*" system by sand-mulching (Fig. 29). This type of soil is the traditional system used in Almería (Valera *et al*., 2016). The value obtained is slightly higher than the 82.8% corresponding to all greenhouses in Andalucía in 2019 (Table 25). 5% grow in substrate (Fig. 56), a figure very close to 6.7% of all greenhouses in Andalucía (Table 25).

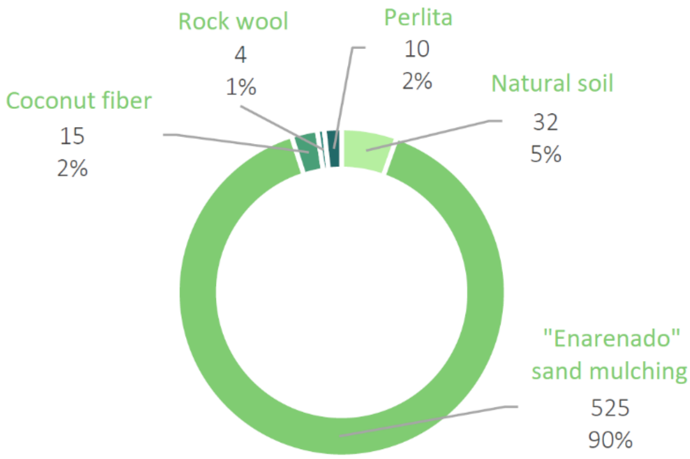


Figure 56. Percentage of soil type in greenhouse.

In 78% of the greenhouses organic matter is supplied and in 69% of them it is carried out with the contribution of manure, followed by 17% in which compost is provided (Fig. 57).

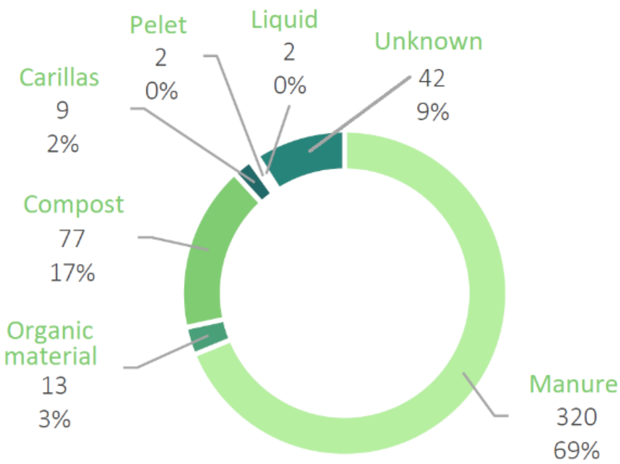


Figure 57. Percentage of the different sources of organic matter for the soil.

The frequency with which the contribution of organic matter is carried out is usually carried out mostly every 3 years, in 32.2% of greenhouses (Fig. 58).

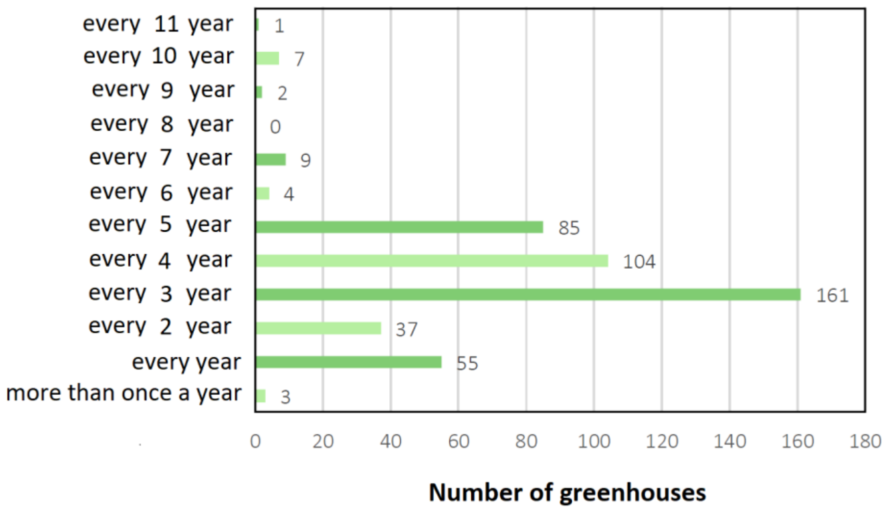


Figure 58. Frequency of organic matter inputs.

7.5. Fertigation systems

7.5.1. Irrigation system

The 74.6% of the greenhouses in which the irrigation system was analysed, had installed equipment for water filtering and 75.9% of them have automated irrigation heads (Fig. 59). 42% of this irrigation control equipment is between 0 and 10 years old, while 37% of the installations of the general pipe network are between 21 and 30 years old, and 28% of cases between 11 and 20 years old.

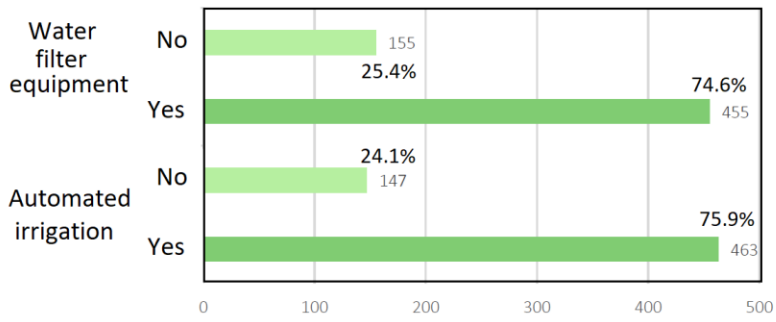


Figure 59. Absolute frequencies (number of greenhouses) of irrigation machinery

The most used type of drip irrigation in the greenhouses studied is the turbulent drip 64.1% (Fig. 60), the second most used is the self-compensating drip (30.6%).

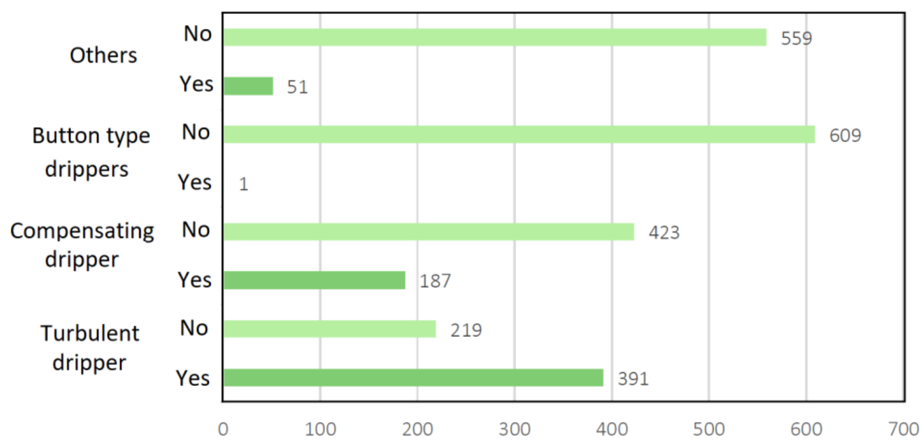


Figure 60. Absolute frequencies (number of greenhouses) of the drip irrigation type.

Only 365 greenhouses of the 610 studied (60%) have a water meter on the farm and only 6% of the partners know the total water consumption that occurs in their properties.

7.5.2. Fertilizer application

The most used fertilizer application system in the irrigation network (Fig. 61) is direct suction (59.8%), followed by Venturis (47.4%) and injection pumps (45.6%). The elements of the fertigation system are mostly old between 0 and 10 years.

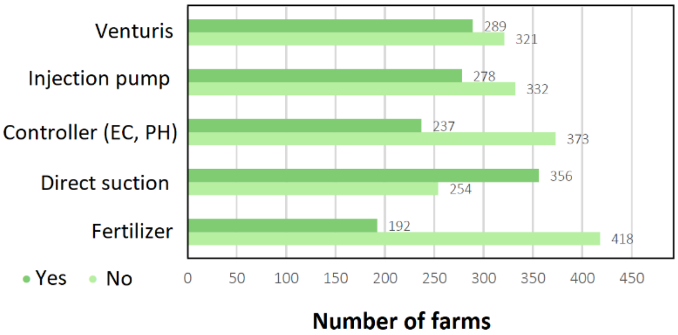


Figure 61 Absolute frequencies of fertigation elements.

7.6. Auxiliary buildings

7.6.1. Elements of the farm

The elements that most farms have (Fig. 62) are concrete ponds for storage of irrigation water (74.4%) and a warehouse (72.9%). Only 53% of concrete ponds have a cover to prevent water evaporation.

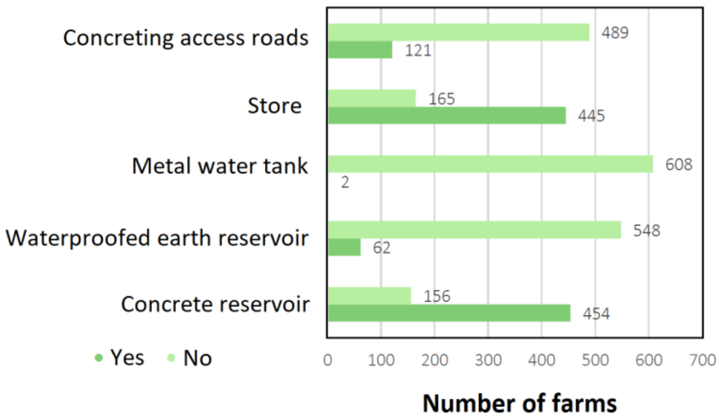


Figure 62. Absolute frequencies of the elements of the farms.

A large majority of farms, 79% have an electricity connection (Fig. 63a) but only 13% of the partners surveyed know the electricity consumption that occurs on their farms (Fig. 63b).

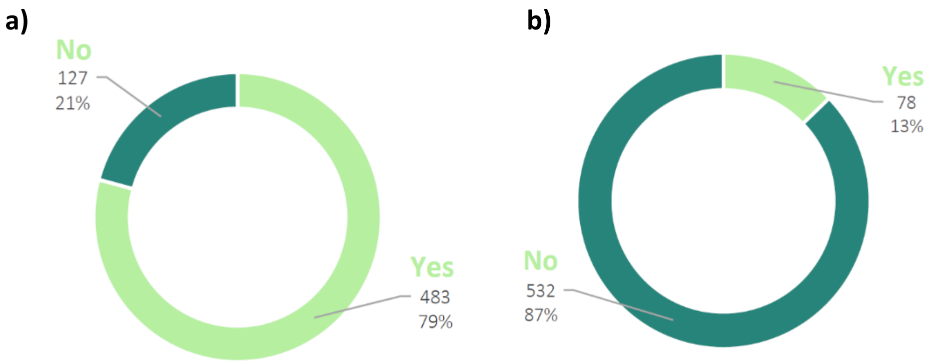


Figure 63. Percentage of farms with electricity connection (a) and percentage of partners who know the total consumption of electricity (b).

Regarding solar energy and the installation of solar panels, although only 1% of the farms have the installation of these (Fig. 64a), 37% of the partners are interested in the future installation of solar panels on their land (Fig. 64b).

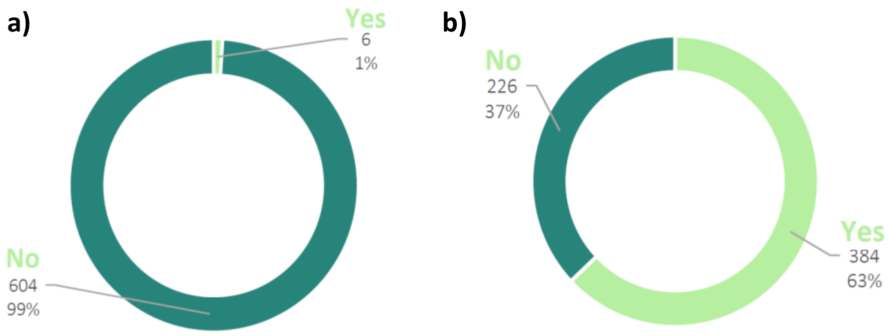


Figure 64. Percentage of farms that have solar panels (a) and percentage of growers interested in solar energy.

7.7. Management of the farm

7.7.1. Certification of the quality

The GlOBAL GAP certification is the one with the highest absolute frequency (100% of the partners) of the different quality certifications analysed (Fig. 65). In the 2012/13 season, only 28% of respondents had this certification. Currently 52.8% of partners are certified in integrated production, while in 2012/13 only 30% were.

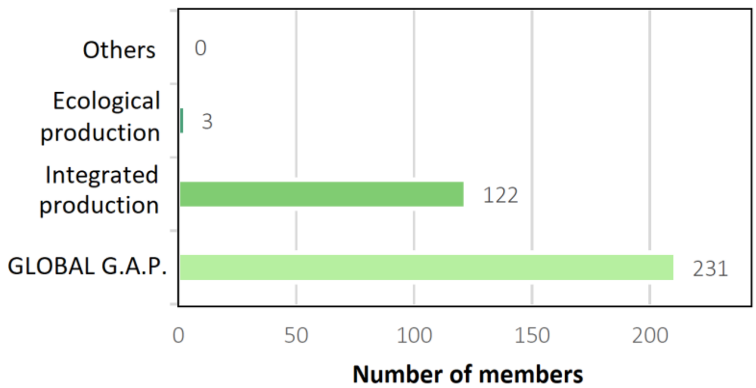


Figure 65. Absolute frequencies of quality certificates.

7.7.2. Insurance

The 60% of farmers subscribe some type of insurance (Fig. 67), mainly for the structure of the greenhouse in 57.6%, and only 16.2% insure the crop (Fig. 68).

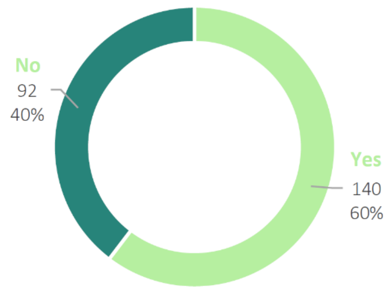


Figure 66. Percentage of members who take out insurance.

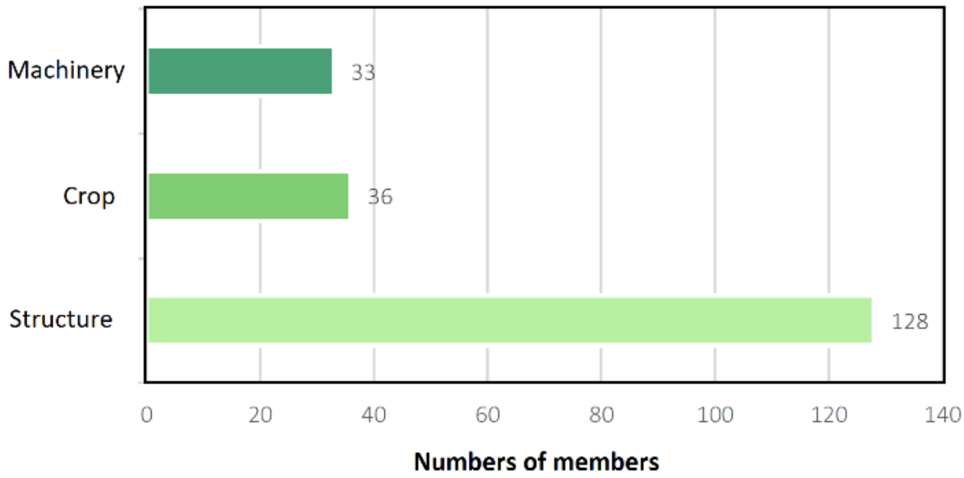


Figure 67. Absolute frequencies of the insured elements.

7.8. Greenhouse structure

The second part of the surveys deals with the farms owned by the members of the Producers' Organisation.

7.8.1. General data

The farmers surveyed have an average of 2.7 greenhouses, which agrees with the average data for the province of Almería (Table 26). The years 2000 and 2002 are the years in which more greenhouses were built, 17.1% in each year (Fig. 68). 23% of the greenhouses analysed are between 21 and 30 years old, while the percentage of newly built greenhouses (between 0 and 10 years old) is only 12% (Fig. 69).

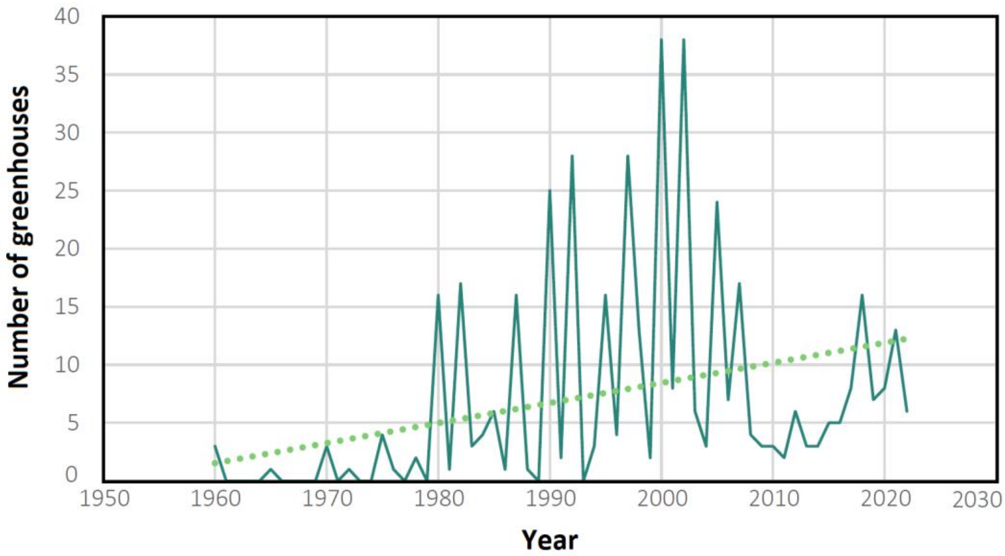


Figure 68. Age of construction of greenhouses

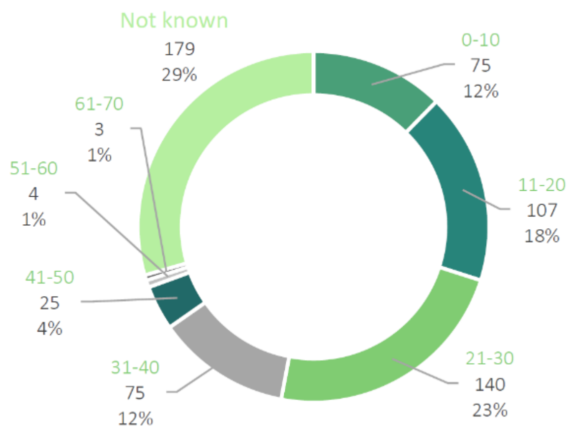


Figure 69. Percentage of the age in years of greenhouses.

The 64% of greenhouses are owned by farmers, while 35% are leased (Fig. 70).

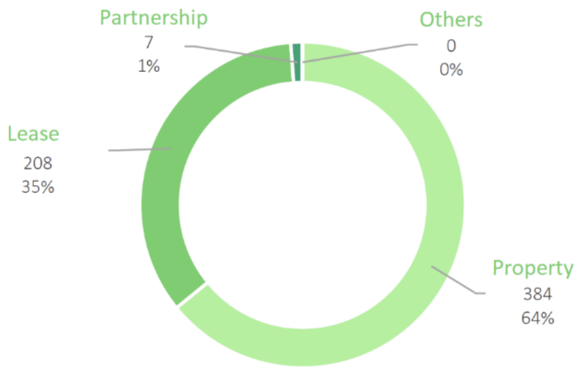


Figure 70. Percentage of different tenure regimes.

7.8.2. Type of greenhouses

The 82% of the greenhouses are of type-Almería with structure in “*raspa y amagado*” and 17% with flat structure "*parral-plano*" (usually the oldest). Only 1% of the farmers surveyed had multispan greenhouses (Fig. 71). These data are similar to the average values corresponding to the greenhouses of Almería and Granada in 2021, but with a higher percentage of the structure in "*raspa and amagado*" (Table 26).

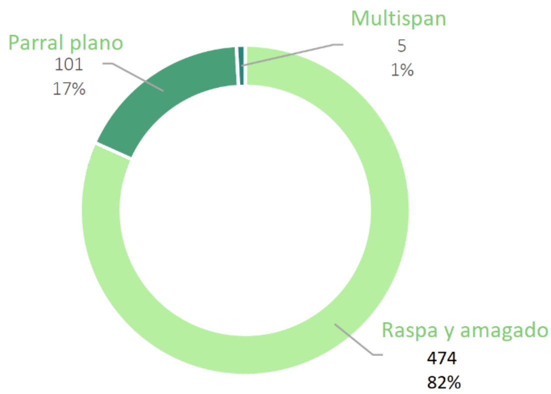


Figure 71. Percentage of different types of greenhouses.

7.9. Greenhouse climate control systems

7.9.1 Climate control systems

The 84.6% of greenhouses have manually operated side vent opening and only 2.6% with motorized drive. The 61.1% have manually operated roof vents and 3.3% are powered by motors. Insect-proof screens are placed on the vent openings of 94.4% of greenhouses (Fig. 72). The 8.0% of greenhouses have automated climate control systems. Only 3.9% of greenhouses have some heating system and 9.0% have humidification-cooling systems by water evaporation.

The 73.8% of the greenhouses have anterooms to prevent the entry of insects and 67.5% have fixed facilities for the application of phytosanitary treatments. Only 1 of the 610 greenhouses have a CO_2 injection system (Fig. 72).

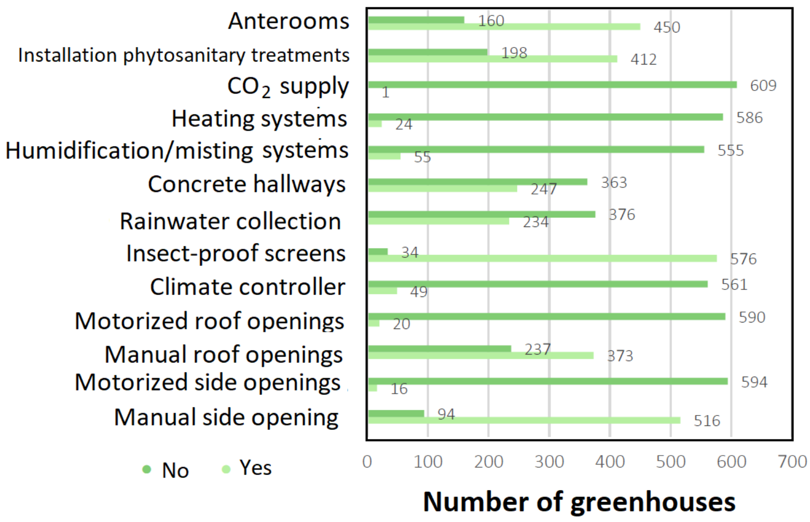


Figure 72. Absolute frequencies of the different elements of the greenhouse.

The 38.4% of the greenhouses perform rainwater recovery and 40.5% have concreted corridors. Most of the climate control systems installed, 82.7%, are recent (0-10 years). Similarly, most heating and cooling-humidification installations are less than 10 years old, while the only CO_2 injection installation is more than 20 years old (Fig. 73).

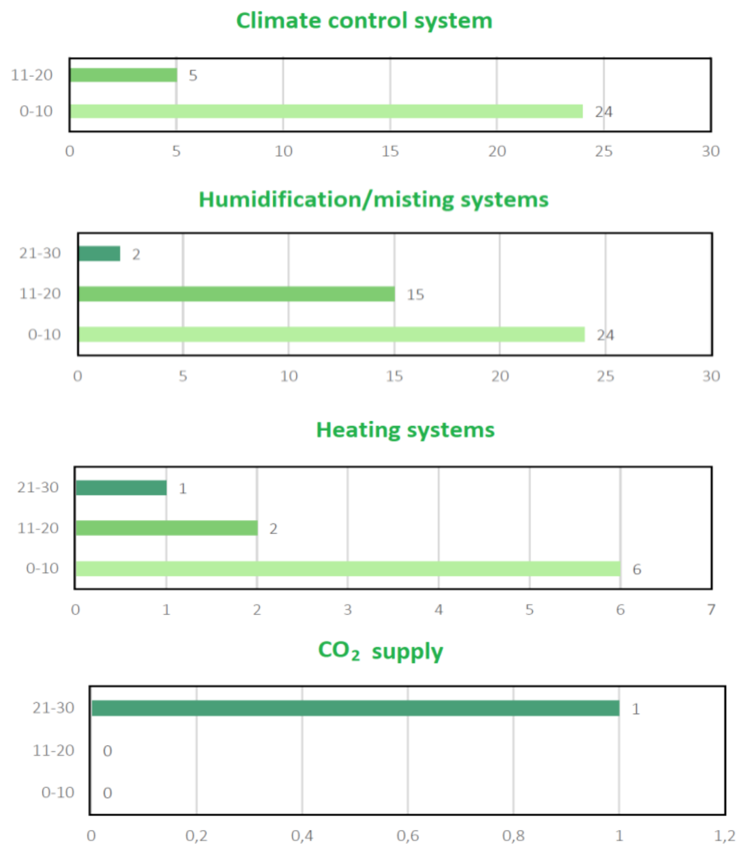


Figure 73. Absolute frequencies of the age in years of the different climate control systems in greenhouses.

7.9.2. Ventilation systems

It should be noted that most manually operated side and roof vent openings are 0-10 years old, while most motorized windows are 11-20 years old (Fig. 74).

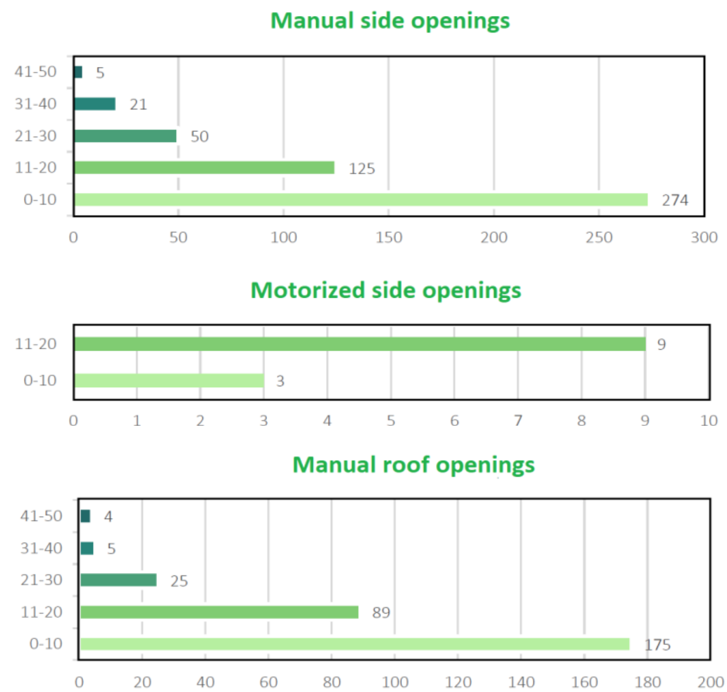


Figure 74. Absolute frequencies of antiquity in years of the different ventilation openings of the greenhouse.

5.10. Planned investments

The vast majority of the investments planned by the 866 partners surveyed on this aspect correspond to the structure of the greenhouse itself (90%). 5% foresees an investment in irrigation facilities, reservoirs, wells and ponds. Only 1-2% of respondents foresee investments in machinery, auxiliary buildings or plot or crop management systems (Fig. 75).

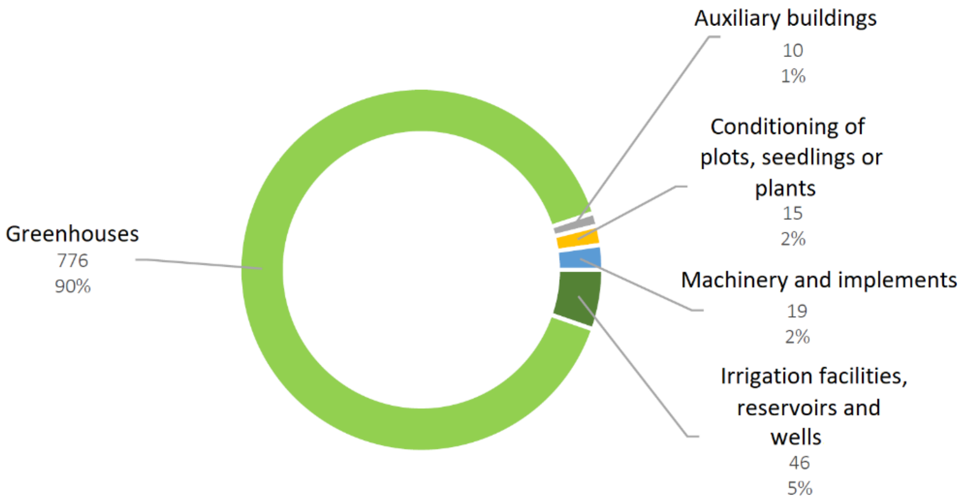


Figure 75. Relative frequency of investments planned by partners.

8. Production cost in Spanish greenhouses

8.1. Methodology for the monitoring of production costs in Andalusian greenhouses

8.1.1. Greenhouses analysed in the season 2022/23

The costs of the horticultural crops were elaborated by the Junta de Andalucía from personal interviews with growers of farms of horticultural greenhouses located in the *Poniente* and *Levante* areas of the province of Almería and in the coastal area *La Costa* of Granada (Fig. 35) that were carried out between the months of October 2020 and June 2021, being the data collected relative to the 2019/20 season (JA, 2023a). The data has been updated to the 2022/23 season using the indicators of prices paid by farmers (MAPA, 2024b).

The production costs correspond to average data of representative farms. They depend on multiple factors, such as the date of transplantation, duration of the cycle, size and location of the farm, phytosanitary incidents, etc. The results are adjusted, therefore, to the parameters described for each crop in question, as well as to the conditions described, and must be taken as an approximation and never as a fixed and unquestionable value (JA, 2023a).

8.1.2. Price indices paid in the season 2022/23

The price calculated is the market price paid by the farmer for the means of production (goods and services) of medium quality, located on the agricultural farm and without VAT (MAP, 2023e). The price index measures the changes that occur in prices over space and specifically in a period of time (month or year). The 2021/22 season was marked by the increase in the prices of fuels and materials in a period of recovery of productive activity after the COVID-19 health crisis and an energy crisis in Europe caused by the war in Ukraine. The confluence of these factors caused an inflationary spiral in Europe that significantly influenced the production costs of agricultural activity. In the 2021/22 season, there is a general increase in all the inputs that make up production costs, especially highlighting the increases in electricity (102%), fertilizers (73%) and fuel (53%). However, in this particular season, the prices received by greenhouse vegetable farmers also increased, cushioning the rise in production costs. In the year 2023 the prices of fertilizers were reduced a -31.8% respt to 2022. In the same way, the price of electricity payed by the growers in 2023 was -33.7% lower than in 2022 (MAPA, 2024b). However, this reduction was only of -2.6% for the phytosanitary products (Fig. 76).

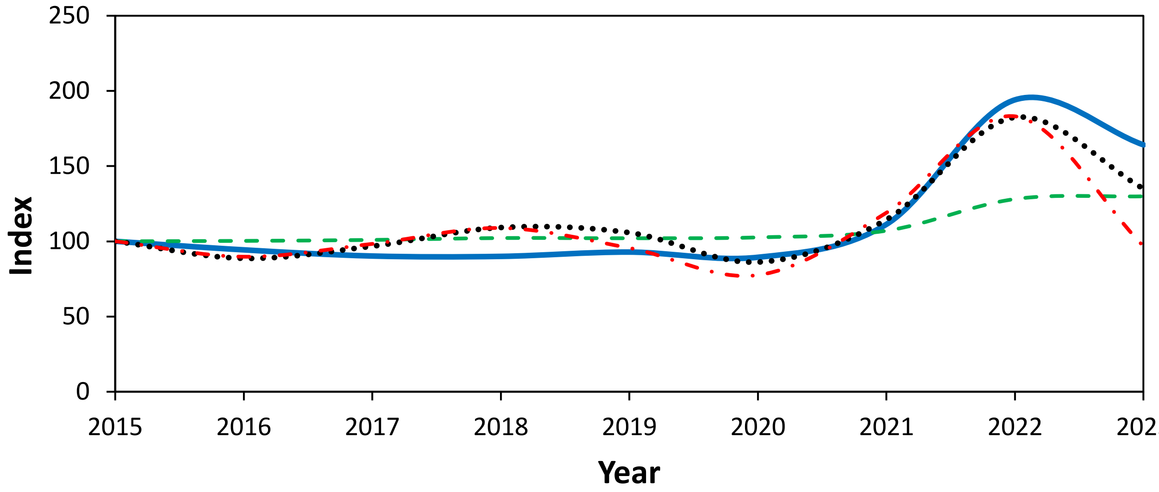


Figure 76. Evolution of the price indices of the main agricultural supplies in the years 2015-2023 (Obtained from data of MAPA, 2024b): Fertilizers (—), phytosanitary protection (– –), energy (·····) and electricity (–·–).

8.2. Production cost of tomato inside greenhouses in Almería

8.2.1. Production costs of tomato branch

The unitary cost of production of tomato in branch in the greenhouses of Almería in the season 2022/23 was 0.59 €/kg for a crop yield of 13.0 kg/m^2 (Table 34).

Table 34. Production costs of tomato branch cultivated in Almería greenhouses in season 2021/22 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	28 152 m²	**Average covered area**	24 546 m²
Greenhouses per farm	2	**Greenhouse area**	12 273 m²
Location	Almería West and East: Níjar, Almería, Roquetas de Mar and El Ejido		
Crop specifications			
Commercial type	on vine or branch	**Crop type**	Ungrafted
Varieties	Alcazaba, Valkyries and Athenaeum		
Transplant / final time	August / second half of April until mid-June		
Cycle	Long	**Cycle length**	274 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**13.0**
Input costs			**31 346**
Seedlings	Seeds		*6 299*
	Nursery (without grafting)		*858*
Fertilizers	Fertilisers and manure		*8 247*
Phytosanitary	Phytosanitary products		*3 334*
	Auxiliary insects		*1 744*
	Auxiliary biological control material		*1 387*
Water and Energy	Water		*2 816*
	Electricity		*2 295*
	Fuel		*1091*
Others	Pollination hives		*985*
	Materials (plastics solarization, padding, ...		*1 945*
	Tools and utensils		*345*
Labor			30 442
Contracted external services			2 903
Total direct costs			**66 879**
Amortizations			6 699
Repairs and maintenance			1 199
General and financial expenses			2 383
Total indirect costs			**10 281**
Total cost [€/ha]			**77 160**
Unitary cost [€/kg]			**0.59**

The different inputs necessary for the cultivation of vine tomato represent between 20-26% each of them (Fig. 77). The pronounced increase in production costs of 12.4% that occurred in the 2021/22 season has been partially cushioned in the following 2022/23 season where the annual increase was approximately half, 6.7% (Fig. 78). The cost of inputs and labour are very balanced in the cultivation of vine tomatoes, since each of them represents 41-42% of the total (Fig. 79).

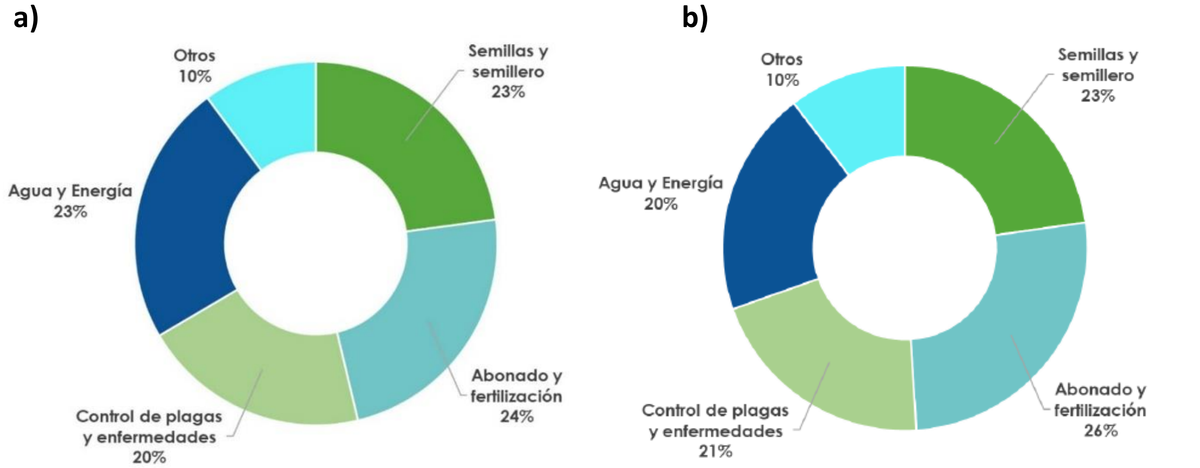


Figure 77. Distribution of expenditure on branch tomato inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

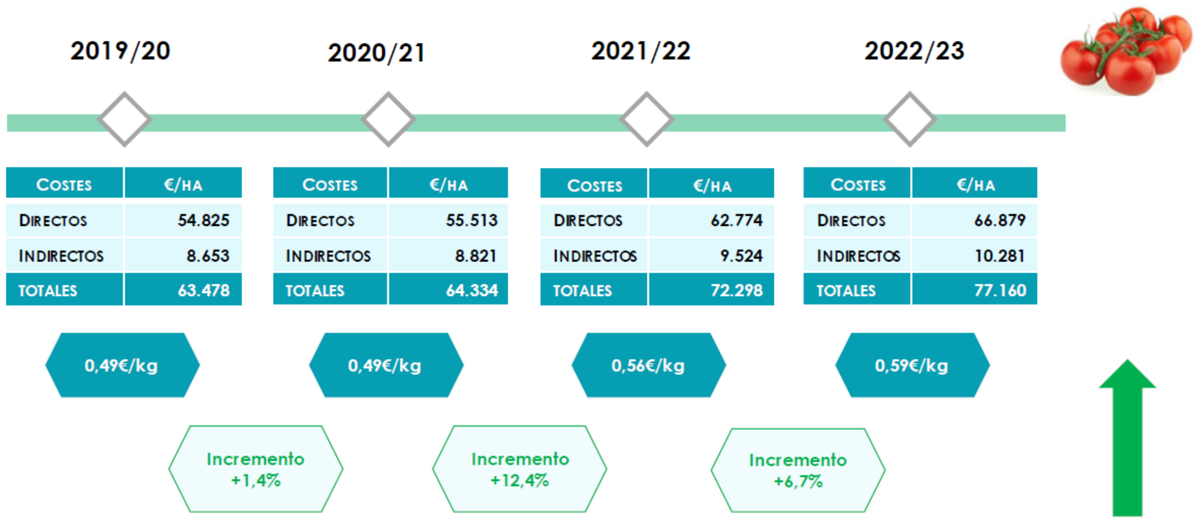


Figure 78. Evolution of the average production costs of branch tomato in Almería greenhouses in the last four seasons (JA, 2024b).

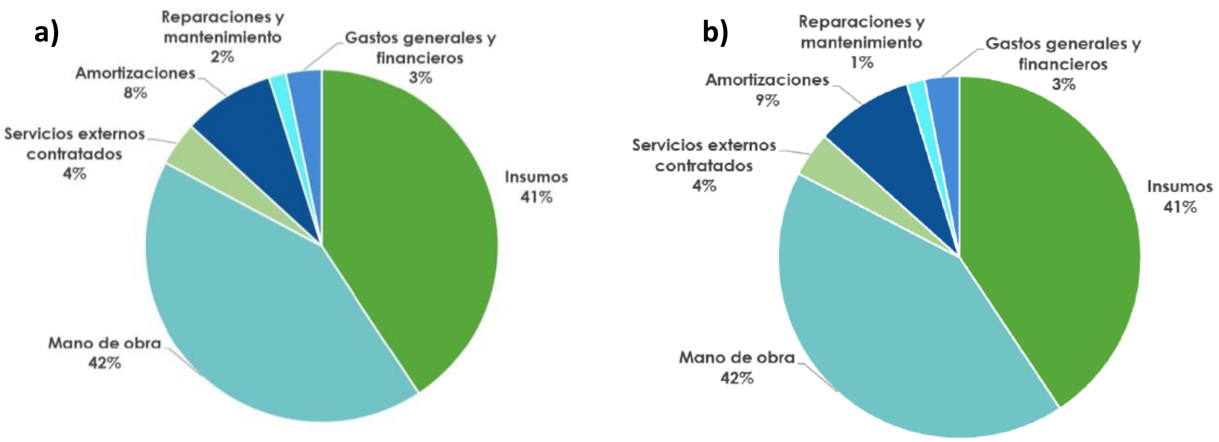


Figure 79. Distribution of production costs on branch tomato cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.2.2. Production costs of cherry tomato

Tomato cherry needs a greater total cost that the other types of tomato (Table 34), as consequence of the increase in the cost associated to the nursery and the labour cost (Table 35).

Table 35. Production costs of cherry tomato cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	40 303 m²	**Average covered area**	35 140 m²
Greenhouses per farm	2.4	**Greenhouse area**	14 642 m²
Location	Municipalities of Motril, Níjar, El Ejido and La Mojonera		
Crop specifications			
Commercial type	pear cherry	**Crop type**	Grafted
Varieties	Dolcetini and Sukita		
Transplant / final time	middle August / May-June		
Cycle	Long cycle	**Cycle length**	294 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**11.1**
Input costs			**34 242**
Seedlings	Seeds		*5 542*
	Nursery (with grafting)		*5 628*
Fertilizers	Fertilisers and manure		*7 169*
Phytosanitary	Phytosanitary products		*5 183*
	Auxiliary insects		*974*
	Auxiliary biological control material		*774*
Water and Energy	Water		*2 065*
	Electricity		*1 642*
	Fuel		*1 827*
Others	Pollination hives		*936*
	Materials (plastics solarization, padding, ...)		*2 186*
	Tools		*316*
Labor			**41 473**
Contracted external services			**1 281**
Total direct costs			**76 996**
Amortizations			6 699
Repairs and maintenance			1 199
General and financial expenses			2 383
Total indirect costs			**10 281**
Total cost [€/ha]			**87 277**
Unitary cost [€/kg]			**0.79**

Seed cost is the most important of input cost for cherry tomato (Fig. 80), corresponding to 33%. We can observe an increase of 9.9% in production cost of cherry tomato in the 2021/22 season compared to the previous 2020/21 (Fig. 81). Cherry tomato require more labour cost than for others tomato varieties, increasing its weight in total costs up to 48%.

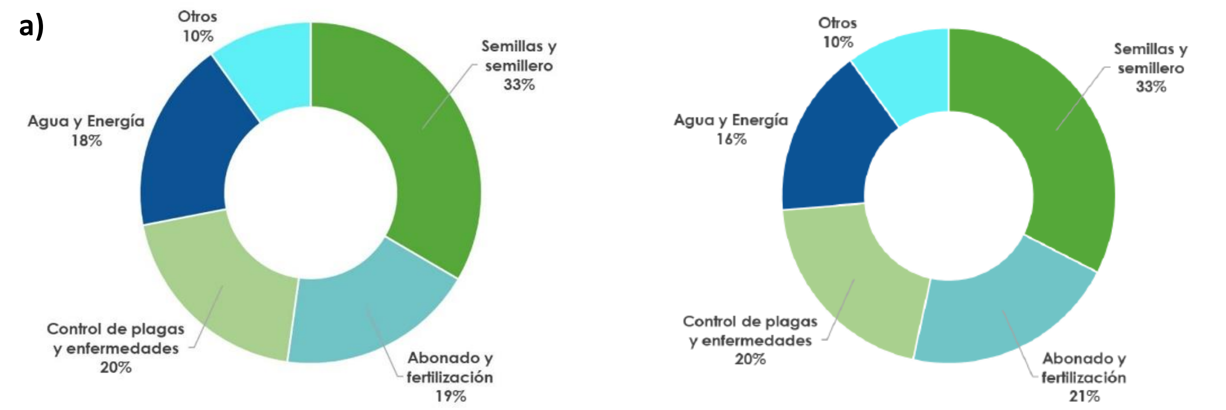


Figure 80. Distribution of expenditure on cherry tomato inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

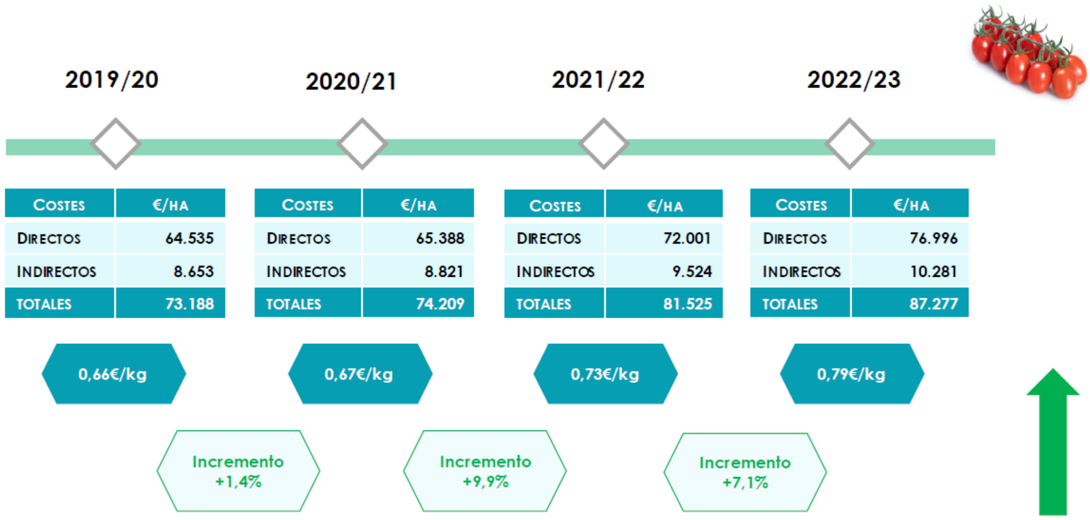


Figure 81. Evolution of the average production costs of cherry tomato in Almería greenhouses greenhouses in the last four seasons (JA, 2024b).

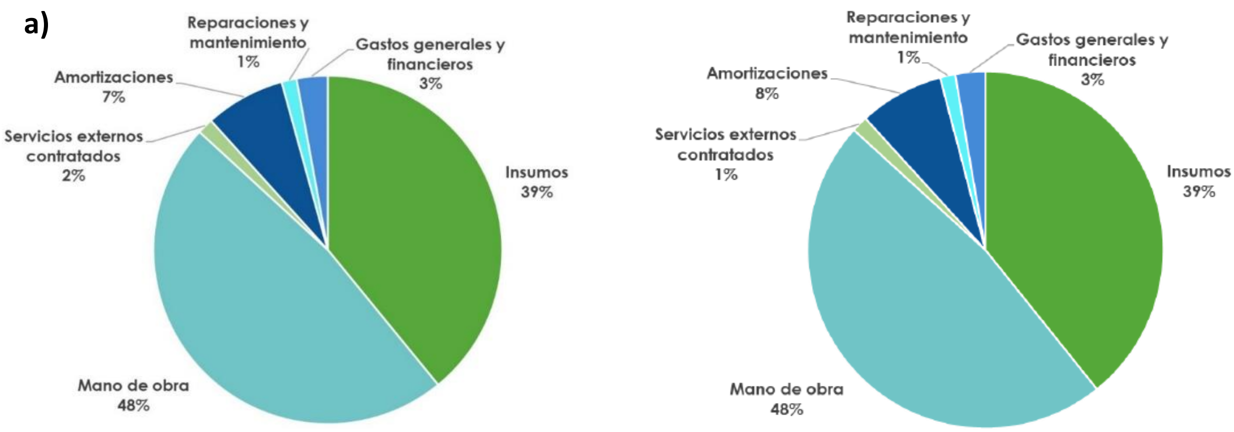


Figure 82. Distribution of production costs on cherry tomato cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.2.3. Production costs of pear tomato

The total cost of pear tomato (Table 36) has lower total cost that the branch and cherry tomatoes (Tables 34-35) as consequence of the lower labour cost. The cost of most of the inputs is similar to the branch tomatoes.

Table 36. Production costs of pear tomato cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	21 060 m²	**Average covered area**	20 440 m²
Greenhouses per farm	2	**Greenhouse area**	10 220 m²
Location	Almería west and east: West "Poniente" and East "Levante" of Almeria. Municipalities of Vicar, Níjar and El Ejido.		
Crop specifications			
Commercial type	Pear	**Crop type**	Ungrafted
Varieties	Caniles, Deseo and Marcus		
Transplant / final time	August-first fortnight of September / second fortnight of May/June		
Cycle	Long cycle	**Cycle length**	291 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**13.1**
Input costs			**33 646**
Seedlings	Seeds		*6 452*
	Nursery (without grafting)		*858*
Fertilizers	Fertilisers and manure		*8 148*
Phytosanitary	Phytosanitary products		*5 772*
	Auxiliary insects		*743*
	Auxiliary biological control material		*1 417*
Water and Energy	Water		*2 257*
	Electricity		*903*
	Fuel		*2 115*
Others	Pollination hives		*1 731*
	Materials (plastics solarization, padding, ...)		*2 916*
	Tools		*334*
Labor			**21 109**
Contracted external services			**2 580**
Total direct costs			**57 335**
Amortizations			6 699
Repairs and maintenance			1 199
General and financial expenses			2 383
Total indirect costs			**10 281**
Total cost [€/ha]			**67 616**
Unitary cost [€/kg]			**0.52**

The cost of fertilizers, phytosanitary products and seeds and nurseries represents a 22-23% of total input costs (Fig. 83), that correspond with a half of the total production costs (Fig. 85). The cost of inputs increased a 13.1% for pear tomato in the 2021/22 season compared to the previous 2020/21 (Fig. 84).

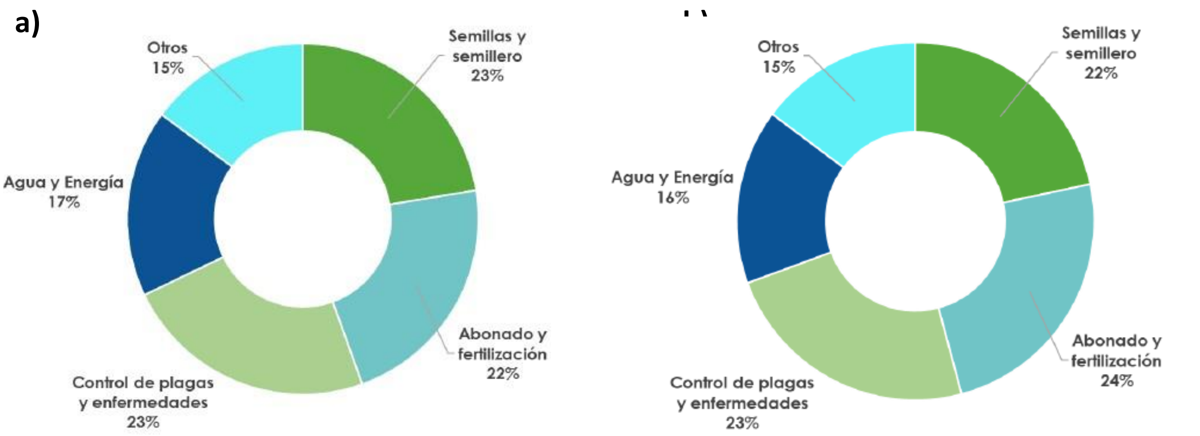


Figure 83. Distribution of expenditure on pear tomato inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

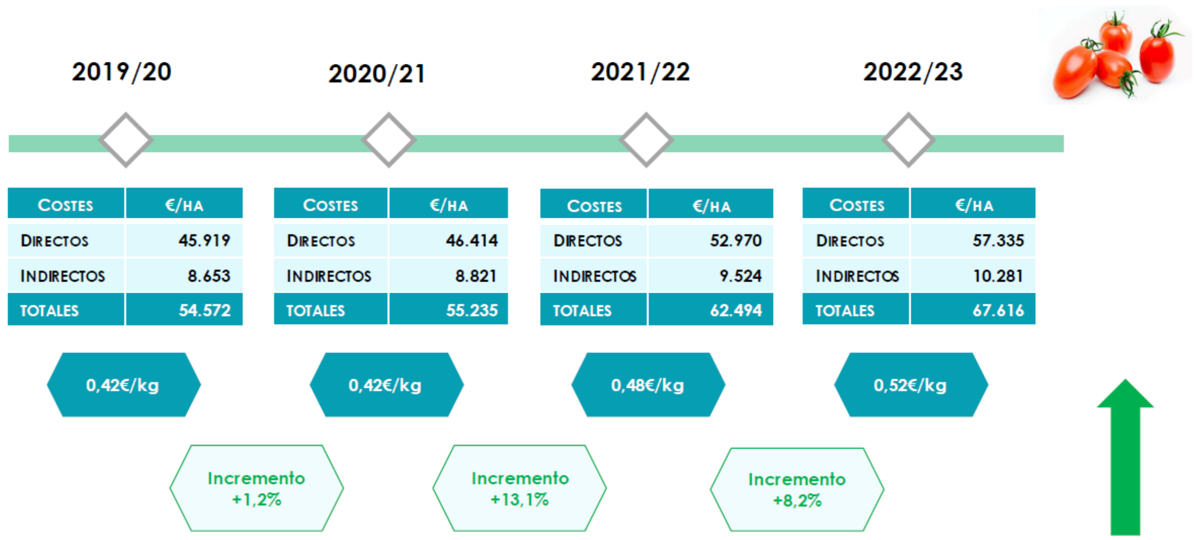


Figure 84. Evolution of the average production costs of pear tomato in Almería greenhouses greenhouses in the last four seasons (JA, 2024b).

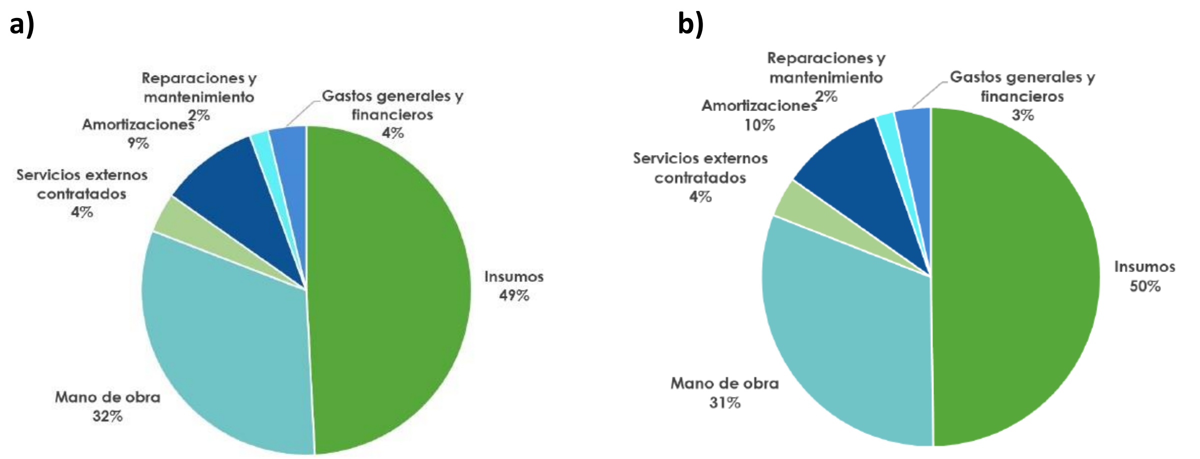


Figure 85. Distribution of production costs on pear tomato cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.3. Production cost of pepper inside greenhouses in Almería

Pepper is one of the different options of Almería growers to cultivate in the autumn-winter crop when they combine two short cycles instead of a long cycle. Instead, the total cost (Table 37) is lower than for the tomato (Tables 34-35), the cost of production per day is very similar.

Table 37. Production costs of pepper cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	28 327 m²	**Average covered area**	25 760 m²
Greenhouses per farm	**3**	**Greenhouse area**	8 578 m²
Location	West of Almeria "*Poniente*". Municipalities of El Ejido, Adra and Balanegra.		
Crop specifications			
Commercial type	California Red		
Varieties	Melchor, Abraham and Amon		
Transplant / final time	August / February until April		
Cycle	Short cycle	**Cycle length**	234 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**8.63**
Input costs			**30 297**
Seedlings	Seeds		*7 695*
	Nursery (with grafting)		*1103*
Fertilizers	Fertilisers and manure		*7 654*
Phytosanitary	Phytosanitary products		*4 129*
	Auxiliary insects		*2 546*
	Auxiliary biological control material		*777*
Water and Energy	Water		*1 818*
	Electricity		*851*
	Fuel		*2 382*
Others	Pollination hives		*0*
	Materials (plastics solarization, padding, ...)		*1 056*
	Tools		*286*
Labor			**23 054**
Contracted external services			**1 275**
Total direct costs			**54 626**
Amortizations			4 746
Repairs and maintenance			850
General and financial expenses			1 689
Total indirect costs			**7 285**
Total cost [€/ha]			**61 911**
Unitary cost [€/kg]			**0.72**

The cost of water and energy is only 17-18% of the input cost for pepper crops (Fig. 86), similar that values registered for the different types of tomato (17-23%). As for tomato crops, the input costs for pepper correspond to the half of the total cost (Fig. 88), increasing 12.7% in the 2021/22 season compared to the previous 2020/21 (Fig. 87).

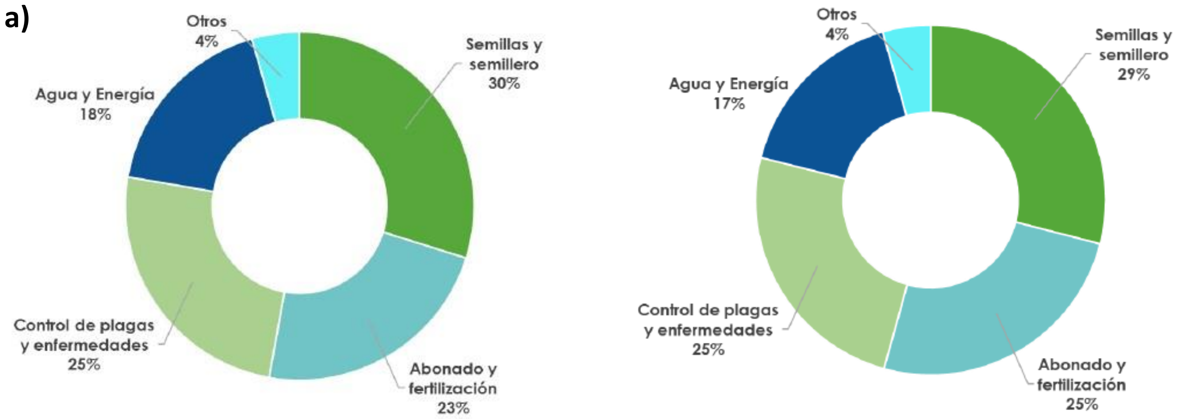


Figure 86. Distribution of expenditure on pepper inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

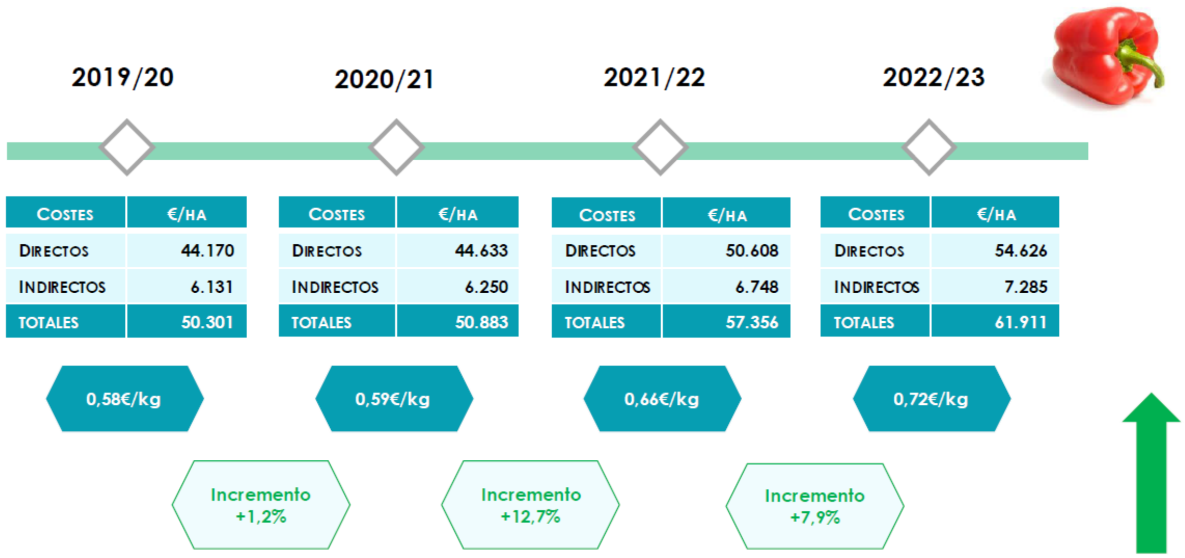


Figure 87. Evolution of the average production costs of pepper in Almería greenhouses in the last four seasons (JA, 2024b).

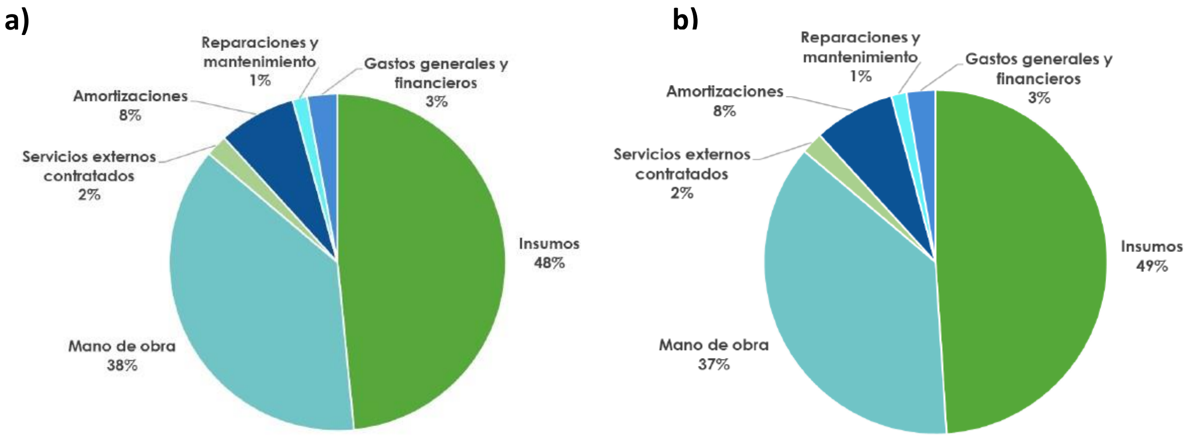


Figure 88. Distribution of production costs on pepper cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.4. Production cost of cucumber inside greenhouses in Almería

A second option of crop for cycle of autumn-winter is the cucumber, with a shorter period of growth of around 162 days (Table 38) instead of the 234 days necessaries for the pepper (Table 37). This crop can be sown directly in the greenhouse in August to finish in January, thus allowing a second harvest in the spring-summer cycle. Because of the shorter duration of the crop, the associated costs, both for inputs and labour (Table 38), are lower than those of long-cycle crops such as tomatoes or even short-cycle but longer-duration pepper crops.

Table 38. Production costs of cucumber cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	28 667 m²	**Average covered area**	25 883 m²
Greenhouses per farm	2.5	**Greenhouse area**	10 333 m²
Location	West of Almeria "*Poniente*". Municipality of El Ejido.		
Crop specifications			
Commercial type	Almería-type	**Crop type**	
Varieties	Manglar, Litoral and Squisito		
Transplant / final time	August-October / January until March		
Cycle	Short cycle	**Cycle length**	162 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**10.0**
Input costs			**24 399**
Seedlings	Seeds		*5 208*
	Nursery (with grafting)		*697*
Fertilizers	Fertilisers and manure		*7 463*
Phytosanitary	Phytosanitary products		*2 748*
	Auxiliary insects		*2 028*
	Auxiliary biological control material		*422*
Water and Energy	Water		*1 641*
	Electricity		*982*
	Fuel		*1 201*
Others	Pollination hives		*0*
	Materials (plastics solarization, padding, ...)		*1 773*
	Tools		*236*
Labor			**18 263**
Contracted external services			**1 257**
Total direct costs			**43 919**
Amortizations			4 037
Repairs and maintenance			723
General and financial expenses			1 436
Total indirect costs			**6 196**
Total cost [€/ha]			**50 115**
Unitary cost [€/kg]			**0.50**

In this crop, the fertilization weight is slightly increased, amounting to up to 28-31% (Fig. 89). Because of the general increase in prices that occurred in the 2021/22 season, the production costs rose by 14.0% on cucumber compared to the previous 2020/21 (Fig. 90). The different proportions of cost are very similar to the others crops, with labour cost representing 36-37% and inputs 48-49% (Fig. 91).

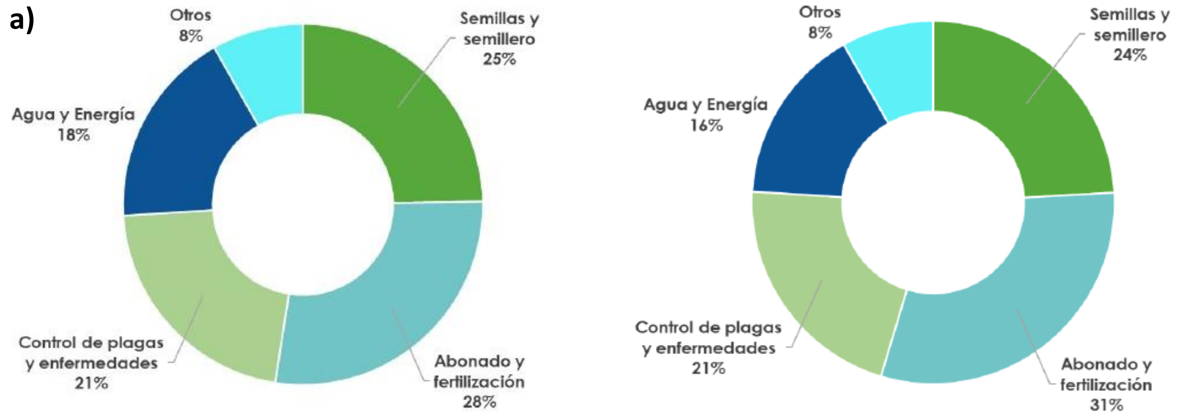


Figure 89. Distribution of expenditure on cucumber inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

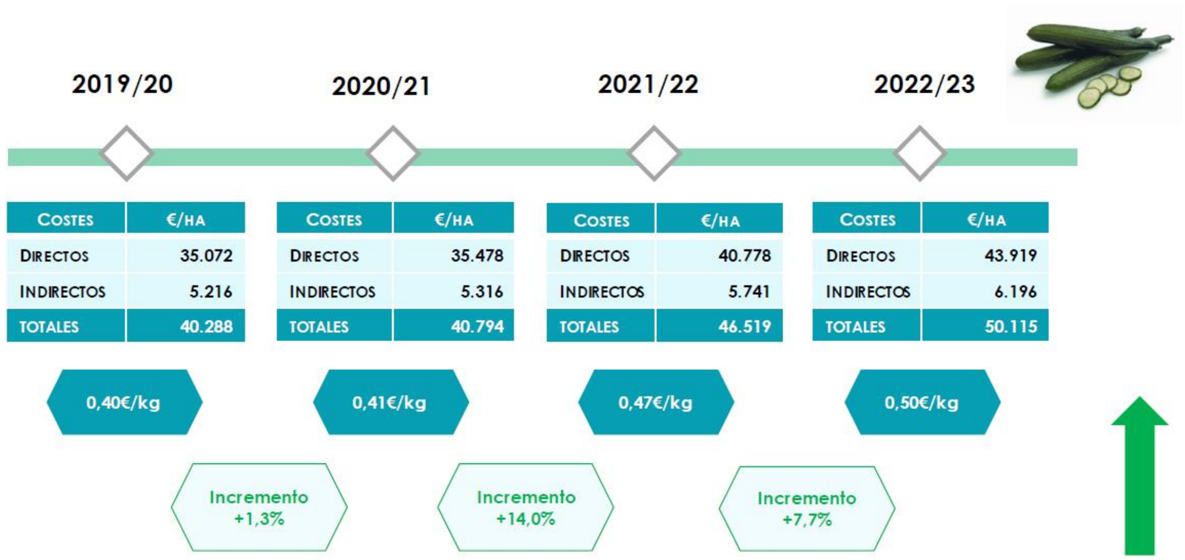


Figure 90. Evolution of the average production costs of cucumber in Almería greenhouses in the last four seasons (JA, 2024b).

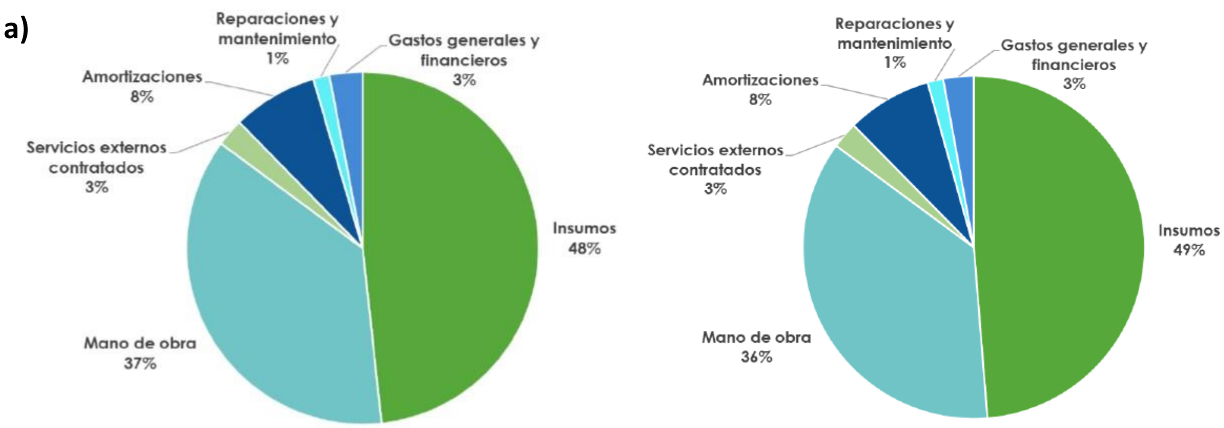


Figure 91. Distribution of production costs on cucumber cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.5. Production cost of watermelon inside greenhouses in Almería

8.5.1. Black watermelon without seeds

The production cost of watermelon 0.29 €/m^2 (Table 39) is the lowest of all greenhouse crops in Almería, but so are the marketing prices. It must be considered that at the end of summer, outdoor watermelon crops come into production, whose production costs are much lower, so sales prices drop considerably.

Table 39. Production costs of black watermelon in Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	21 230 m²	**Average covered area**	18 060 m²
Greenhouses per farm	2.2	**Greenhouse area**	8 209 m²
Location	West "*Poniente*" and East "*Levante*" of Almeria. El Ejido and Nijar.		
Crop specifications			
Commercial type	Black without seeds		
Varieties	Fashion and Fengway		
Transplant / final time	January-middle of February / second fortnight of May		
Cycle	Short cycle	**Cycle length**	100 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**7.65**
Input costs			**14 317**
Seedlings	Seeds and nursery		*2 542*
Fertilizers	Fertilisers and manure		*4 180*
Phytosanitary	Phytosanitary products		*2 120*
	Auxiliary insects		*409*
	Auxiliary biological control material		*362*
Water and Energy	Water		*1 442*
	Electricity		*806*
	Fuel		*1 264*
Others	Pollination hives		*528*
	Materials (plastics solarization, padding, ...)		*458*
	Tools		*206*
Labor			**3 016**
Contracted external services			**1 102**
Total direct costs			**18 435**
Amortizations			2 410
Repairs and maintenance			431
General and financial expenses			854
Total indirect costs			**3 695**
Total cost [€/ha]			**22 130**
Unitary cost [€/kg]			**0.29**

In the case of black watermelon, the cost of water and electricity and fertilization account for more than half of all inputs, with a slight increase in the percentage corresponding to fertilizers observed in the last 2022/23 season (Fig. 92). In the season 2021/22 the increase in the production cost of black watermelon was of 21.8% compared to the previous 2020/21, reducing to 8.0% for the following season 2022/23 (Fig. 93). Because of the number of fruits to yield and the maintenance tasks in this crop are lower than for tomato and pepper, the labour cost only represent 13-14% of the total cost (Fig. 94). The importance of the inputs in the total cost (around 64-65%) explain the greater increase of total cost in the season 2021/22 in comparison with other crops as tomato or pepper.

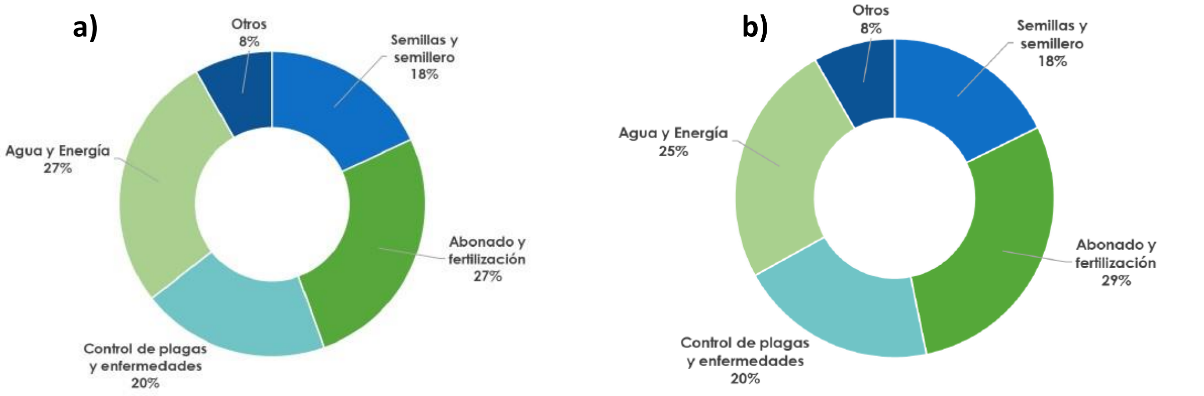


Figure 92. Distribution of input costs on black watermelon in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

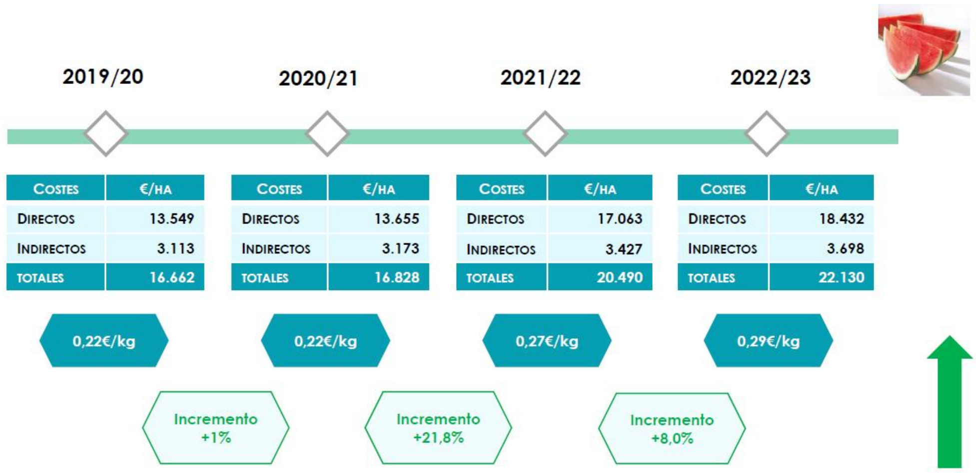


Figure 93. Evolution of the average production costs of black watermelon in Almería greenhouses in the last four seasons (JA, 2024b).

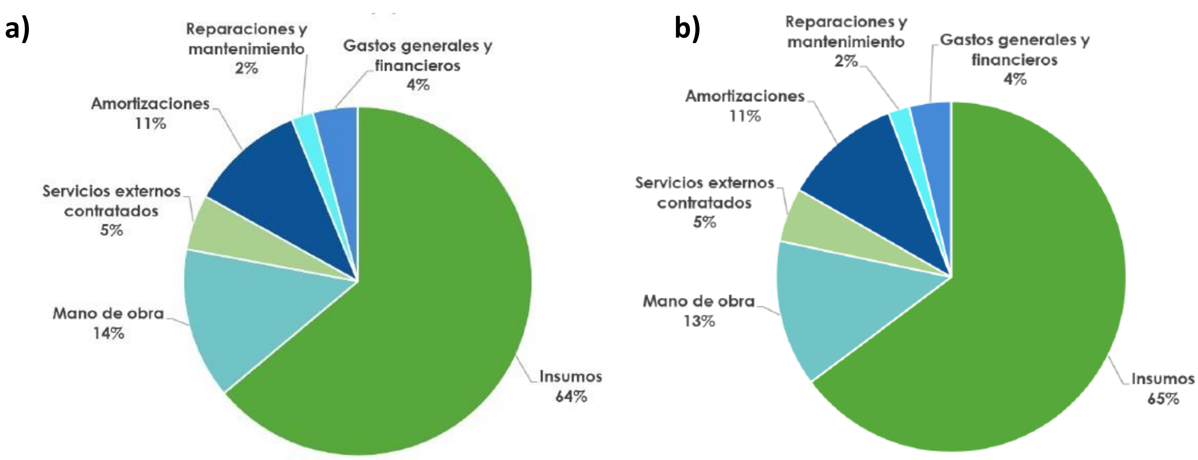


Figure 94. Distribution of production costs on black watermelon cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.5.2. Striped watermelon

The production costs of 0.27 €/m^2 of this type of watermelon (Table 40) are similar to this of black type with the same duration of the growing cycle.

Table 40. Production costs of striped watermelon cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	11 083 m²	**Average covered area**	10 033 m²
Greenhouses per farm	1.7	**Greenhouse area**	6 020 m²
Location	West "*Poniente*" and East "*Levante*" of Almeria. Municipalities of Adra, Balanegra and Nijar.		
Crop specifications			
Commercial type	Striped with seeds		
Varieties	Red Jasper		
Transplant / final time	February / May-beginning of June		
Cycle	Short cycle	**Cycle length**	100 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**8.15**
Input costs			**14 227**
Seedlings	Seeds and nursery		*2 461*
Fertilizers	Fertilisers and manure		*5 031*
Phytosanitary	Phytosanitary products		*2 624*
	Auxiliary insects		*347*
	Auxiliary biological control material		*270*
Water and Energy	Water		*1 119*
	Electricity		*406*
	Fuel		*1 064*
Others	Pollination hives		*383*
	Materials (plastics solarization, padding, ...)		*424*
	Tools		*98*
Labor			**2 746**
Contracted external services			**1 102**
Total direct costs			**18 075**
Amortizations			2 410
Repairs and maintenance			431
General and financial expenses			857
Total indirect costs			**3 698**
Total cost [€/ha]			**21 773**
Unitary cost [€/kg]			**0.27**

The inputs with the highest costs for this type of sand are fertilization, which involves 33-36%, and products and insects for pest and disease control, with a weight in the total of input cost of 23% (Fig. 95). As for the rest of the crops, the 2021/22 season produced a large increase in production costs of 21.6%, which in the last season 2022/23 has moderated to reach 9.4% (Fig. 96). For the same reasons discussed in the previous case of black watermelon, labour costs in watermelon are the lowest, with a weight of only 13% in the total (Fig. 97%).

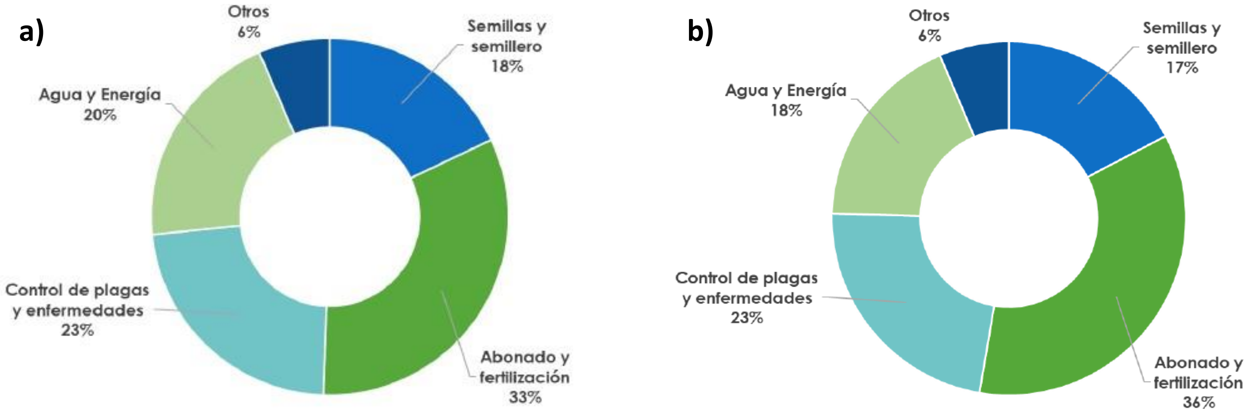


Figure 95. Distribution of expenditure on striped watermelon inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

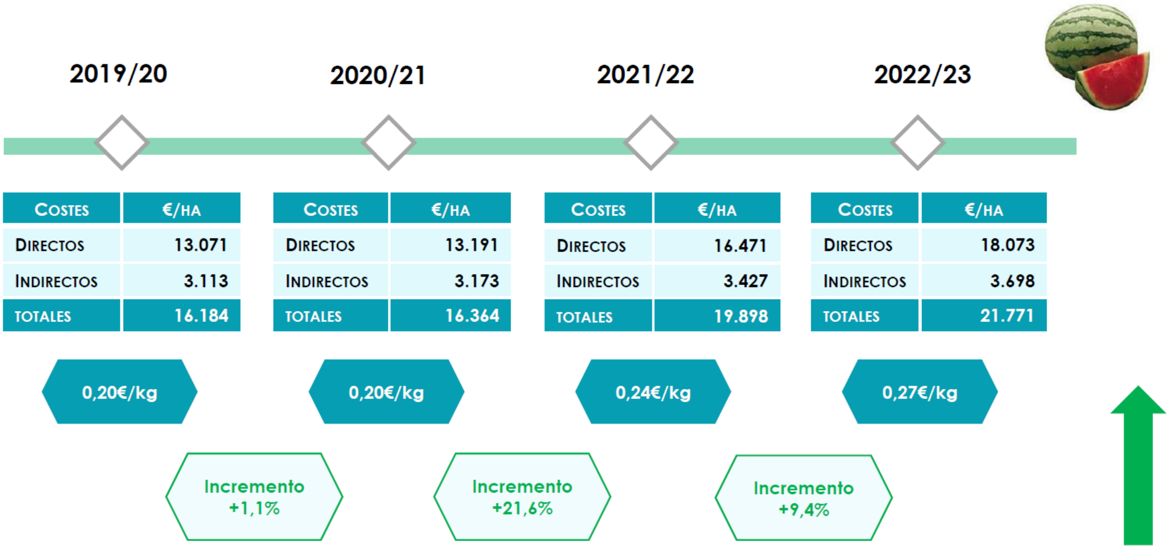


Figure 96. Evolution of the average production costs of striped watermelon in Almería greenhouses in the last four seasons (JA, 2024b).

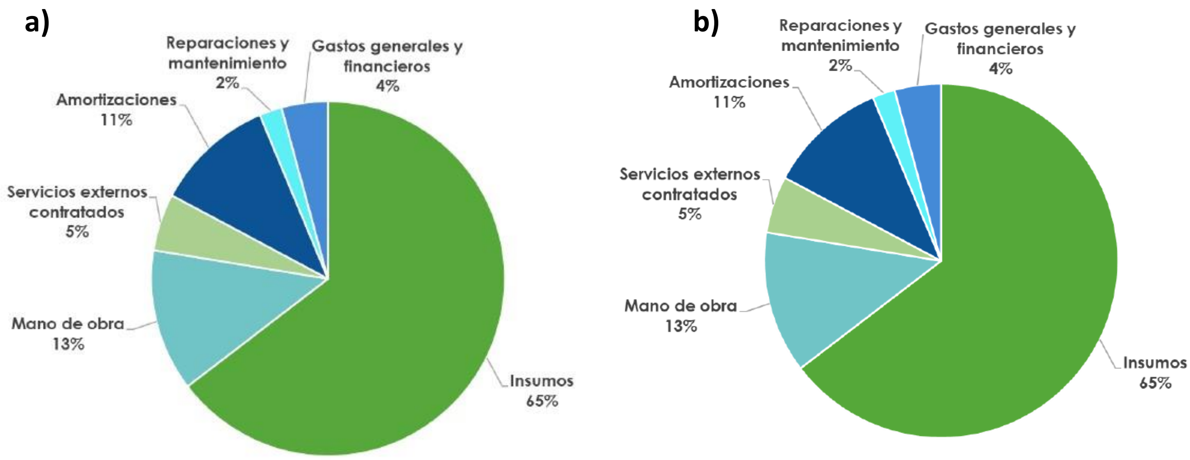


Figure 97. Distribution of production costs on striped watermelon cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.6. Production cost of zucchini inside greenhouses in Almería

8.6.1. Green zucchini of autumn-winter

In the 2022/23 season there was a general increase in all the costs of production (Table 41), except for electricity, which is reduced by 18.2%. This reduction was a consequence of the end of the crisis of energy registered in Europe in the 2021/22 season.

Table 41. Production costs of green zucchini of autumn cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	23 667 m²	**Average covered area**	21 383 m²
Greenhouses per farm	2.3	**Greenhouse area**	9 164 m²
Location	West of Almeria "*Poniente*". Municipalities of El Ejido and Vicar.		
Crop specifications			
Commercial type	Green		
Varieties	Prometeo, Logos and Victoria		
Transplant / final time	End of Jully - beginning of August / second fortnight of November -beginning of December		
Cycle	Short cycle	**Cycle length**	123 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**7.5**
Input costs			**11 901**
Seedlings	Seeds		*1 199*
	Nursery		*476*
Fertilizers	Fertilisers and manure		*3 313*
Phytosanitary	Phytosanitary products		*1 962*
	Auxiliary insects		*341*
	Auxiliary biological control material		*496*
Water and Energy	Water		*782*
	Electricity		*838*
	Fuel		*943*
Others	Materials (plastics solarization, padding, ...)		*0*
	Tools		*1 270*
Labor			**16 076**
Contracted external services			**947**
Total direct costs			**28 924**
Amortizations			2 756
Repairs and maintenance			493
General and financial expenses			980
Total indirect costs			**4 229**
Total cost [€/ha]			**33 153**
Unitary cost [€/kg]			**0.44**

In the case of green zucchini in autumn cultivation, the cost of seeds only represents 14-15% of the total inputs (Fig. 98). The 11.6% increase in 2021/22 in total costs in zucchini cultivation (Fig. 99) was lower than that of watermelon because half of the costs correspond to labour (Fig. 100), where the increase was much lower than that of the rest of the inputs.

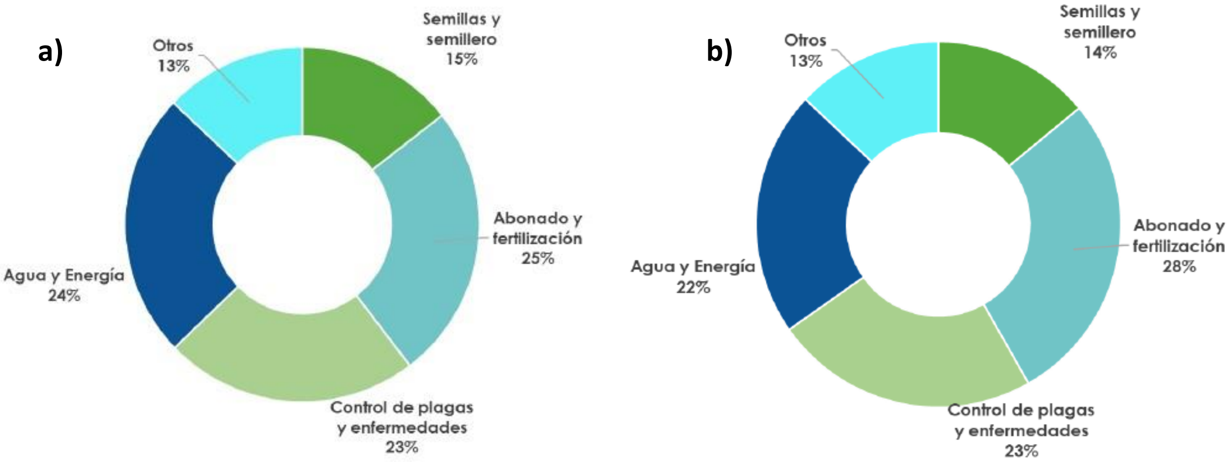


Figure 98. Distribution of expenditure on green zucchini of autumn inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

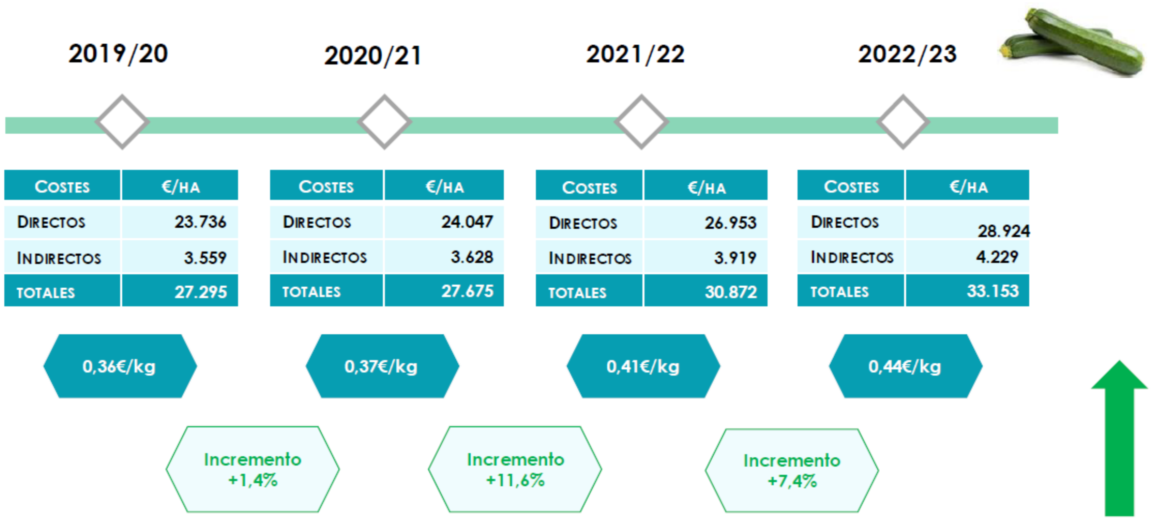


Figure 99. Evolution of the average production costs of green zucchini of autumn in Almería greenhouses in the last four seasons (JA, 2024b).

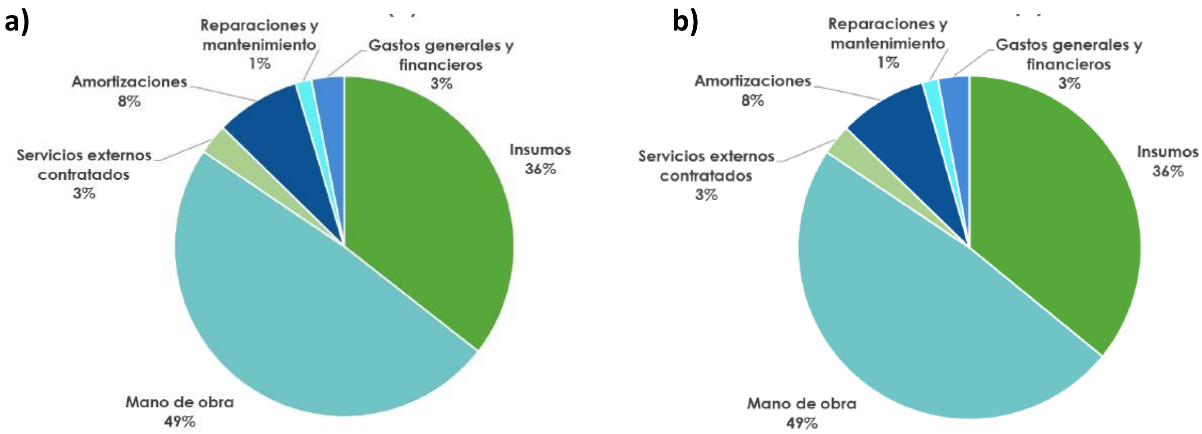


Figure 100. Distribution of production costs on green zucchini of autumn cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.6.2. Green zucchini of spring-summer

In the case of growing zucchini in the spring-summer cycle, production costs are 50% higher (Table 42) than those of the same crop in the autumn-winter cycle (Table 41), due to the longer duration of the cycle (43% longer).

Table 42. Production costs of green zucchini of spring cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	23 667 m²	**Average covered area**	21 383 m²
Greenhouses per farm	2.3	**Greenhouse area**	9 164 m²
Location	West of Almeria "*Poniente*". Municipalities of El Ejido and Vicar.		
Crop specifications			
Commercial type	Green		
Varieties	Logos, Victoria and Musa.		
Transplant / final time	End of November – December / May - June		
Cycle	Short cycle	**Cycle length**	176 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**11.13**
Input costs			**16 110**
Seedlings	Seeds		*1 199*
	Nursery		*476*
Fertilizers	Fertilisers and manure		*4 784*
Phytosanitary	Phytosanitary products		*2 679*
	Auxiliary insects		*223*
	Auxiliary biological control material		*634*
Water and Energy	Water		*1 240*
	Electricity		*1 408*
	Fuel		*1 242*
Others	Materials (plastics solarization, padding, ...)		*0*
	Tools		*1 768*
Labor			**26 092**
Contracted external services			**1 611**
Total direct costs			**43 813**
Amortizations			3 943
Repairs and maintenance			706
General and financial expenses			1 403
Total indirect costs			**6 052**
Total cost [€/ha]			**49 865**
Unitary cost [€/kg]			**0.45**

The distribution of the costs of the different inputs hardly varies with respect to cultivation in autumn (Fig. 101). The smaller increase in total costs is also observed again in the 2021/22 season (Fig. 102) due to the already mentioned effect of the heavy weight of labour in total costs (Fig. 103).

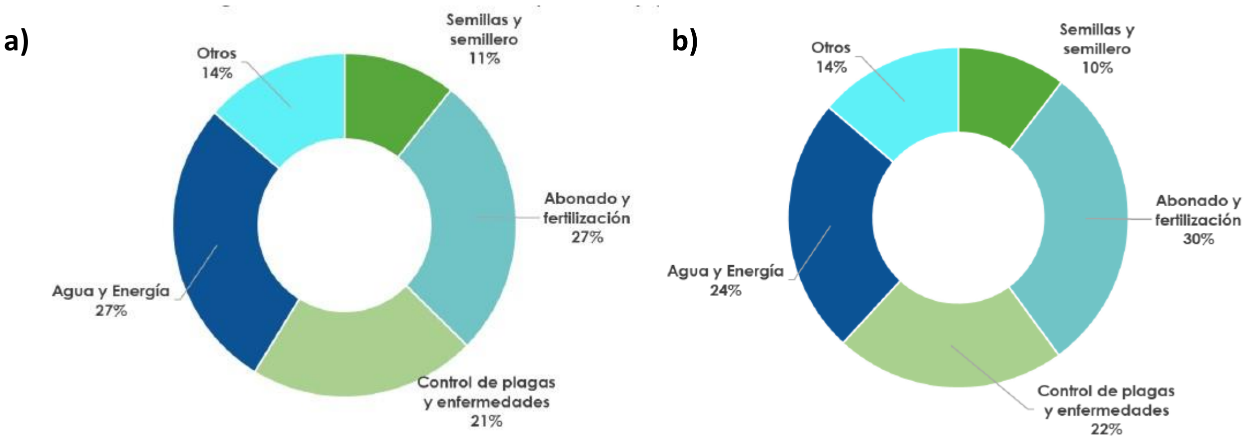


Figure 101. Distribution of expenditure on green zucchini of spring inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

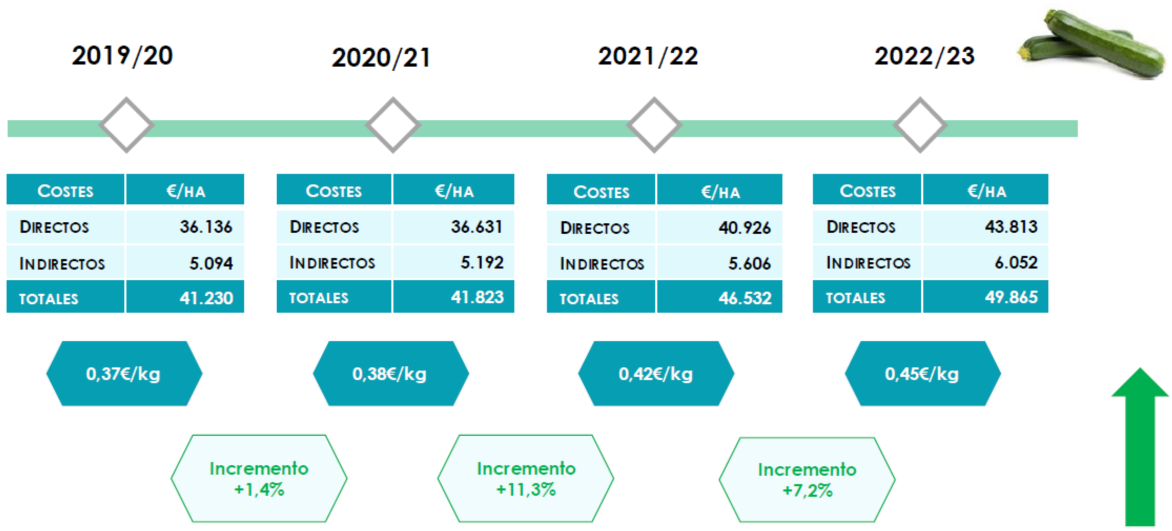


Figure 102. Evolution of the average production costs of green zucchini of spring in Almería greenhouses in the last four seasons (JA, 2024b).

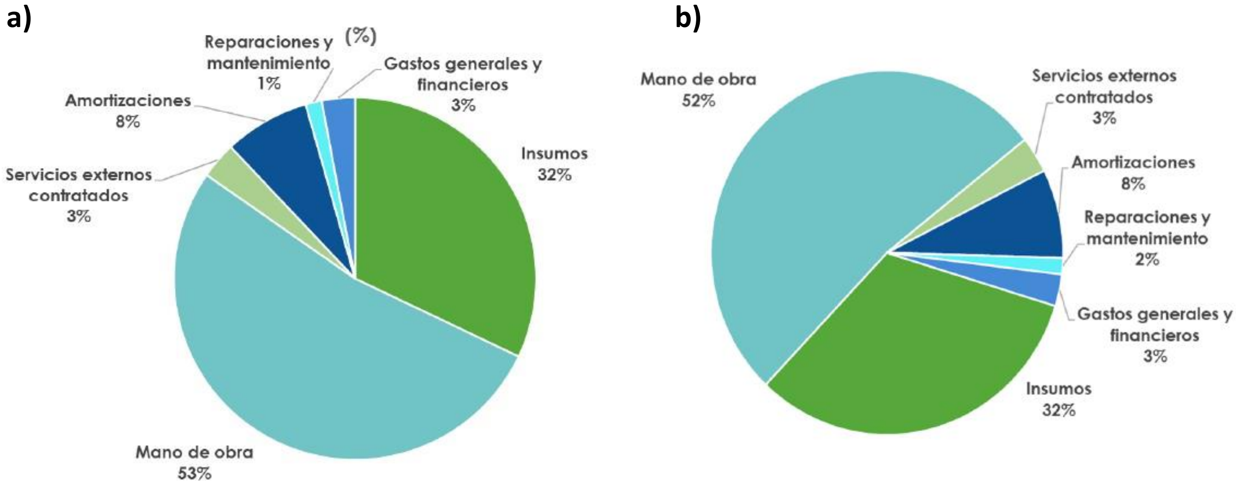


Figure 103. Distribution of production costs on green zucchini of spring cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.7. Production cost of melon inside greenhouses in Almería

The melon crop, together with watermelon, has the lowest production costs due to the short duration of its cycle, 85 days (Table 43), and the lower labour force necessary for cultural work and harvesting.

Table 43. Production costs of melon cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in “*Raspa y amagado*”		
Farm area	19 828 m²	**Average covered area**	17 480 m²
Greenhouses per farm	2.2	**Greenhouse area**	7 945 m²
Location	West of Almeria “*Poniente*”. Municipalities of El Ejido and Adra.		
Crop specifications			
Commercial type	Toad Skin of “*piel de sapo*”		
Varieties	Valverde and Valu		
Transplant / final time	February - March / middle of May - first fortnight of June		
Cycle	Short cycle	**Cycle length**	85 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**5.30**
Input costs			**12 249**
Seedlings	Seeds		*1 473*
	Nursery		*298*
Fertilizers	Fertilisers and manure		*4 201*
Phytosanitary	Phytosanitary products		*1 656*
	Auxiliary insects		*581*
	Auxiliary biological control material		*189*
Water and Energy	Water		*1 063*
	Electricity		*449*
	Fuel		*996*
Others	Pollination hives		*560*
	Materials (plastics solarization, padding, ...)		*573*
	Tools		*210*
Labor			**7 368**
Contracted external services			**522**
Total direct costs			**20 139**
Amortizations			2 162
Repairs and maintenance			387
General and financial expenses			769
Total indirect costs			**3 318**
Total cost [€/ha]			**23 457**
Unitary cost [€/kg]			**0.44**

The input with the highest cost for melon cultivation is fertilization, which represents 31-34% (Fig. 104). The increase in production costs of 17.3% in the 2021/22 season was reduced slightly in 2022/23 where the increase was 8.4%. Comparing this last season with 2019/20, the global increase has been 29.4% (Fig. 105), that is, almost a third. As for watermelon cultivation, more than half of the melon production costs are due to the purchase of inputs (Fig. 106).

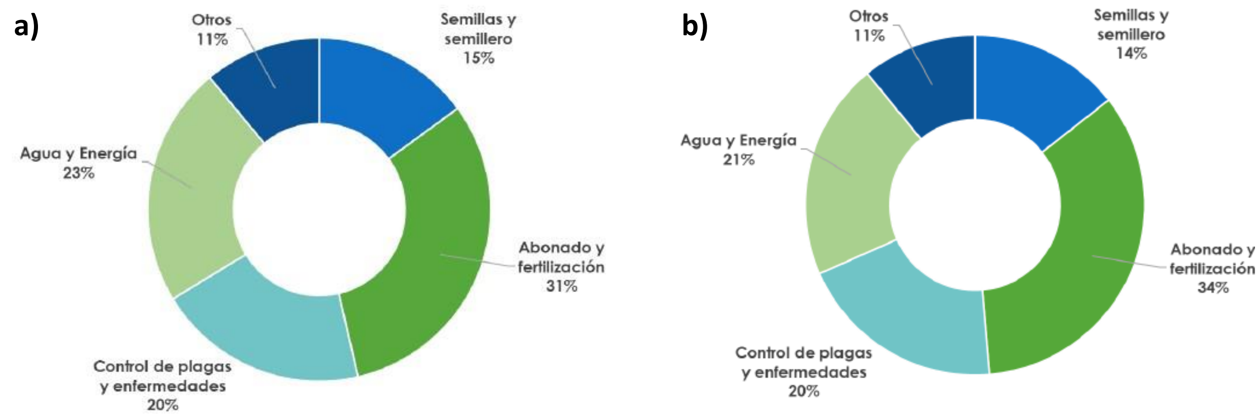


Figure 104. Distribution of expenditure on melon inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

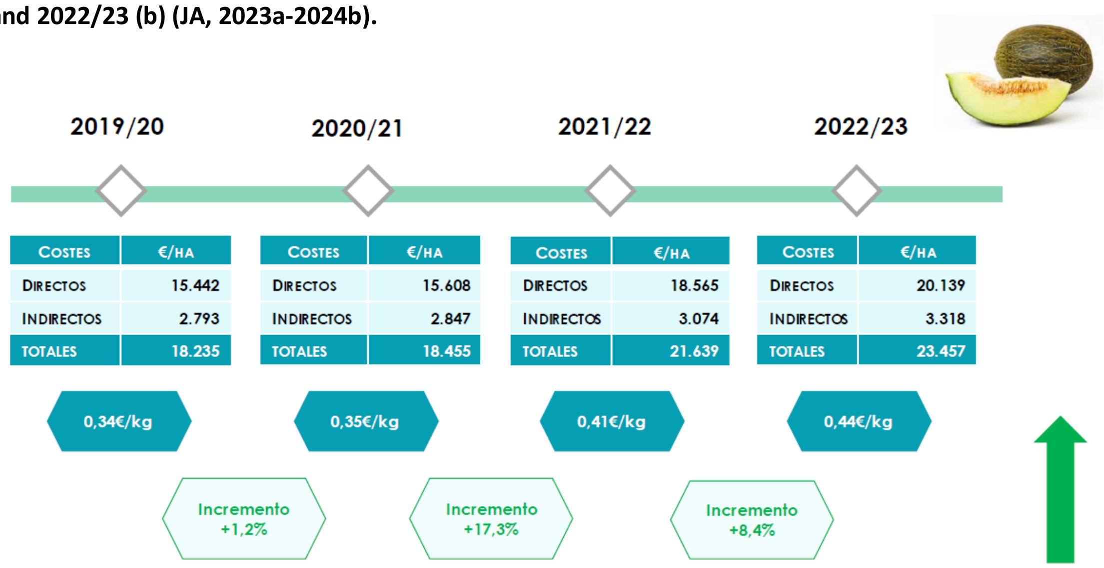


Figure 105. Evolution of the average production costs of melon in Almería greenhouses in the last four seasons (JA, 2024b).

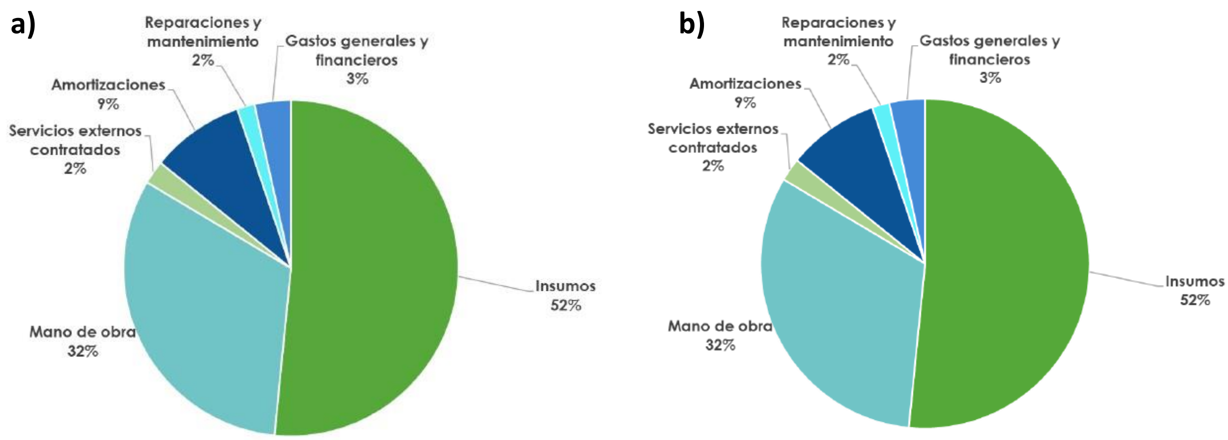


Figure 106. Distribution of production costs on melon cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.8. Production cost of eggplant inside greenhouses in Almería

The cultivation of eggplant in the greenhouses of Almería is one of those that allows the highest yields to be obtained along with tomatoes. It is grown in a long cycle, requiring the highest production costs along with tomatoes and peppers (Table 44).

Table 44. Production costs of eggplant cultivated inside Almería greenhouses in the season 2022/23 (JA, 2024b).

Characteristic of surveyed greenhouses			
Greenhouse type	Almería-type in "*Raspa y amagado*"		
Farm area	21 450 m²	**Average covered area**	20 213 m²
Greenhouses per farm	2.5	**Greenhouse area**	8 085 m²
Location	West of Almeria "*Poniente*". Municipalities of El Ejido, La Mojonera and Roquetas de Mar		
Crop specifications			
Commercial type	Black		
Varieties	Telma and Leticia		
Transplant / final time	Middle of August / June		
Cycle	Long cycle	**Cycle length**	306 days
Type of cost	**Subtype of cost**		**€/ha**
Average yield [kg/m²]			**15.0**
Input costs			**23 138**
Seedlings	Seeds		*2 132*
	Nursery (with grafting)		*298*
Fertilizers	Fertilisers and manure		*7 120*
Phytosanitary	Phytosanitary products		*3 480*
	Auxiliary insects		*2 361*
	Auxiliary biological control material		*602*
Water and Energy	Water		*2 313*
	Electricity		*1 231*
	Fuel		*1 973*
Others	Pollination hives		*0*
	Materials (plastics solarization, padding, ...)		*1 308*
	Tools		*320*
Labor			**27 362**
Contracted external services			**2 555**
Total direct costs			**53 055**
Amortizations			6 699
Repairs and maintenance			1199
General and financial expenses			2 383
Total indirect costs			**10 281**
Total cost [€/ha]			**63 336**
Unitary cost [€/kg]			**0.42**

The main inputs in eggplant cultivation are fertilization and pest control, with values of 28-31% (Fig. 107). As in the case of zucchini, eggplant is a crop that requires a lot of labour and this contributed to the increase in costs in the 2021/22 season being only 12.7% (Fig. 108), like crops such as tomato or pepper requiring similar inputs. The weight of labour represents 43-44% of the total production cost of eggplant (Fig. 109).

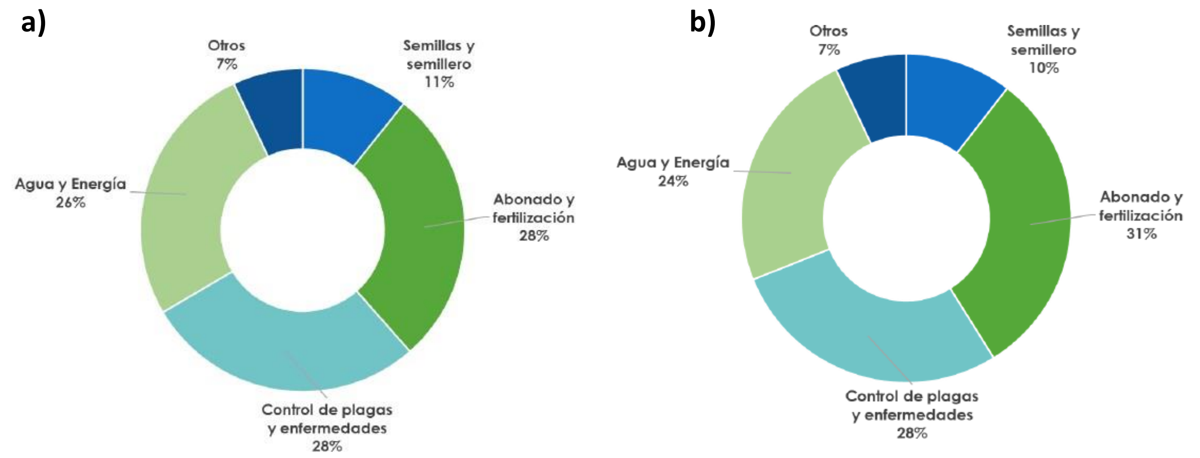


Figure 107. Distribution of expenditure on eggplant inputs in the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

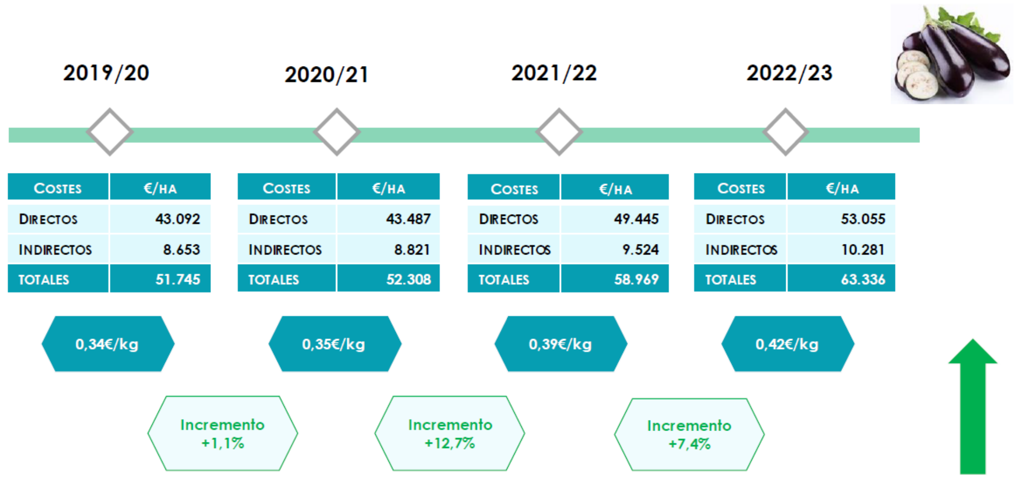


Figure 108. Evolution of the average production costs of eggplant in Almería greenhouses in the last four seasons (JA, 2024b).

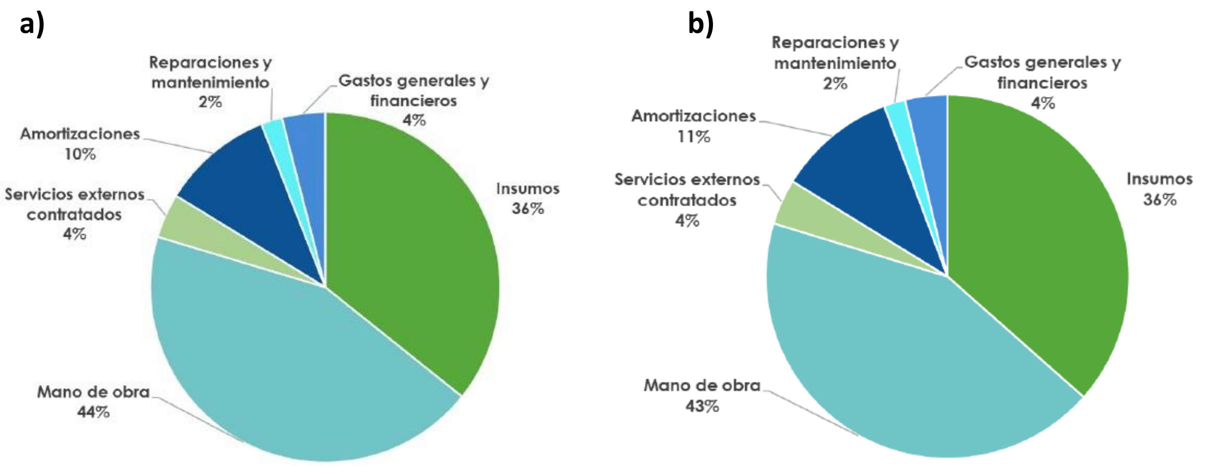


Figure 109. Distribution of production costs on eggplant cultivated inside the greenhouses of Almería in the seasons 2021/22 (a) and 2022/23 (b) (JA, 2023a-2024b).

8.9. Analysis of production cost inside greenhouses in Almería

The production costs for the different cultivation alternatives analysed in the 2022/23 seasons are quite similar (Fig. 110), varying between 63 336 € for eggplant in the long cycle and 87 277 € needed for the cultivation of cherry tomatoes also in the long cycle (Table 46). All the alternatives of double crops, with a first crop in the autumn-winter cycle and a second in spring-summer, are between these two values (Table 46).

Unit costs vary between 0.73 €/kg for cherry tomatoes and 0.40 €/kg required for the combination of cucumber in autumn-winter cycle and watermelon in spring-summer (Table 46). Taking into account the yield reported in the estimation of the production costs (JA, 2024b) and the average price of each crops (JA, 2024a), the benefits of the different cultivation alternatives in the season ranged between the 33 721 €/ha obtained for the cultivation of zucchini in autumn and in spring, and the 102 533 €/ha that were achieved with the cultivation of cherry tomato in the long cycle (Table 46). The increase of prices of products and the lower increase in production cost allowed in the season 2022/23 to improve the profits obtained in the 2021/22 season. For this previous season, the profit ranged between the 31 031 €/ha obtained for the cultivation of eggplant in the long cycle, and the 73 875 €/ha that were achieved with the cherry tomato in the long cycle (Table 45).

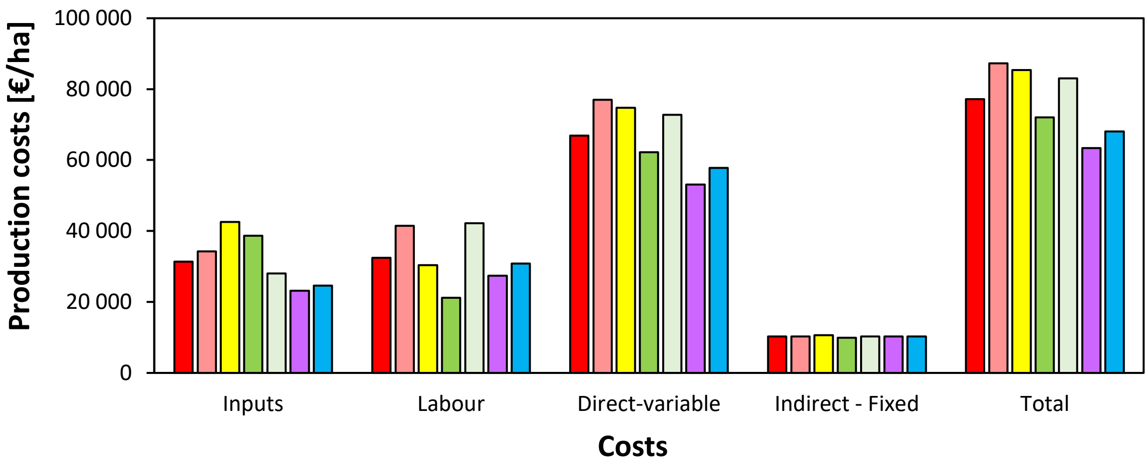


Figure 110. Comparison of production cost for different cultivation alternatives: tomato branch in long cycle (■), tomato cherry in long cycle (■), short cycles of pepper + melon (■), short cycles of cucumber + watermelon (■), short cycles of zucchini of autumn + spring (■), long cycle of eggplant (■) and average of all crops (■) cultivated inside the greenhouses of Almería in the 2022/23 season (Data from Table 46).

Table 45. Production costs (€/ha) of different crops cultivated inside greenhouses in Almería in the season 2021/22 (JA, 2023a).

Crops	Tomato	Cherry	Pear tomato	Pepper + melon	Cucumber + watermelon	Zucchini	Eggplant	Mixed [a]
Cycle	*Long*	*Long*	*Long*	*Autumn + Spring*	*Autumn + Spring*	*Autumn + Spring*	*Long*	*Long or 2 shorts*
Average yield [kg/m²]	**13.00**	**11.10**	**13.10**	**13.93**	**17.90**	**18.63**	**15.00**	**14.75**
Input costs	**29 429**	**31 879**	**30 738**	**38 938**	**36 989**	**25 906**	**21 369**	**33 518**
Seeds	5 905	5 196	6 048	8 595	7 227	2 248	1 999	6 357
Nursery	833	5 463	833	1359	676	924	290	1432
Fertilisers	6 880	5 981	6 797	9 890	10 068	6 755	5 940	8 306
Phytosanitary	2 979	4 630	5 156	5 159	4 574	4 145	3 109	4 535
Auxiliary insects	1 717	959	732	3078	2368.5	555	2 324	2 035
Biological control	1 271	709	1 299	885	677	1036	551	906
Water	3 097	2 270	2 486	3 170	3 213	2 223	2 543	2 866
Electricity	2 871	2 055	1 130	1627	1987	2810	1 541	1 934
Fuel	874	1 464	1 693	2705	1894.5	1750	1 580	1 966
Pollination hives	903	858	1 586	514	417.5	0	0	593
Materials	1 783	2 004	2 672	1493	2029.5	2784	1 199	1 912
Tools and utensils	316	290	306	424	356.5	676	293	394
Labour	30 442	38 920	19 810	28 549	19 843	39 573	25 677	28 337
External services	2 903	1 202	2 422	1686	2 214	2400	2 399	2 054
Total direct costs	**62 774**	**72 001**	**52 970**	**69 173**	**57 545**	**67 879**	**49 445**	**63 638**
Amortizations	6 042	6 042	6 042	6 231	5 816	6 042	6 042	6 066
Maintenance	1 137	1 137	1 137	1172	1094	1137	1 137	1 141
Financial expenses	2 345	2 345	2 345	2419	2258	2346	2 345	2 355
Total indirect costs	**9 524**	**9 524**	**9 524**	**9 822**	**9 168**	**9 525**	**9 524**	**9 561**
Total cost T_C [€/ha]	**72 298**	**81 525**	**62 494**	**78 995**	**66 713**	**77 404**	**58 969**	**73 200**
Unitary cost U_C [€/kg] [c]	**0.56**	**0.73**	**0.48**	**0.57**	**0.37**	**0.42**	**0.39**	**0.50**
Average price A_P [€/kg] [b]	**0.87**	**1.40**	**0.76**	**0.84 + 0.84**	**0.80 + 0.64**	**0.77**	**0.60**	**0.82**
Prod. value P_V [€/ha] [c]	**113 100**	**155 400**	**99 560**	**117 012**	**135 770**	**143 451**	**90 000**	**121 423**
Revenue R_V [€/ha] [c]	**40 802**	**73 875**	**37 066**	**38 017**	**63 866**	**66 047**	**31 031**	**48 223**

[a] Calculated from the cost of different crops (Tables 34-44) and their proportion of the total surface of crops (Table 32). For the calculation, the following cultivation options have been considered: tomato in single long cycle; pepper-melon; cucumber-watermelon; zucchini-zucchini and eggplant in single long cycle. For these combination the cost of the two crop developed are additioned.

[b] Values of A_P obtained from Table 32 (JA, 2021b; JA, 2022a).

[c] Calculated: U_C [€/kg]=T_C [€/ha]/(Y_C [kg/m²]·10 000); P_V [€/ha]= (Y_C [kg/m²]·10 000)·A_P [€/kg].

Table 46. Production costs (€/ha) of different crops cultivated inside greenhouses in Almería in the season 2022/23 (JA, 2024a-b).

Crops	Tomato	*Cherry* T.	*Pear* T.	Pepper + melon	Cucumber + watermelon	Zucchini + Zucchini	Eggplant	Mixed [a]
Cycle	AUG – JUNE	AUG – JUNE	AUG – JUNE	JULY-APR + MAR-JUNE	AUG-FEB + JAN-MAY	AUG-FEB + JAN-MAY	AUG – JUNE	***Long or 2 shorts***
Days of crop	274	294	291	234 + 85	162 + 100	123 - 176	306	292
Greenhouse surface [m²]	**12 273**	**14 642**	**10 220**	**8 266**	**7 662**	**9 164**	**8 085**	**10 045**
Average yield [kg/m²]	**13.00**	**11.10**	**13.10**	**8.63 + 5.30**	**10.00 + 7.83**	**7.50 + 11.13**	**15.00**	**13.05**
Input costs	**31 346**	**34 242**	**33 646**	**42 546**	**38 671**	**28 011**	**23 138**	**24 625**
Seeds	*6 299*	*5 542*	*6 452*	*9 168*	*7 710*	*2 398*	*2 132*	*5 672*
Nursery	*858*	*5 628*	*858*	*1 401*	*697*	*952*	*298*	*1 527*
Fertilisers	*8 247*	*7 169*	*8 148*	*11 855*	*12 069*	*8 097*	*7 120*	*8 958*
Phytosanitary	*3 334*	*5 183*	*5 772*	*5 785*	*5 120*	*4 641*	*3 480*	*4 759*
Auxiliary insects	*1 744*	*974*	*743*	*3 127*	*2 406*	*564*	*2 361*	*1 703*
Biological control	*1 387*	*774*	*1 417*	*966*	*738*	*1 130*	*602*	*1 002*
Water	*2 816*	*2 065*	*2 257*	*2 881*	*2 922*	*2 022*	*2 313*	*2 468*
Electricity	*2 295*	*1 642*	*903*	*1 300*	*1 588*	*2 246*	*1 231*	*1 601*
Fuel	*1091*	*1 827*	*2 115*	*3 378*	*2 365*	*2 185*	*1 973*	*2 133*
Pollination hives	*985*	*936*	*1 731*	*560*	*456*	*0*	*0*	*667*
Materials	*1 945*	*2 186*	*2 916*	*1 629*	*2 214*	*3 038*	*1 308*	*2 177*
Tools and utensils	*345*	*316*	*334*	*496*	*388*	*738*	*320*	*420*
Labour	**32 439**	**41 473**	**21 109**	**30 422**	**21 144**	**42 168**	**27 362**	**30 874**
External services	**3 094**	**1 281**	**2 580**	**1 797**	**2 359**	**2 558**	**2 555**	**2 318**
Total direct costs	**66 879**	**76 996**	**57 335**	**74 765**	**62 174**	**72 737**	**53 055**	**57 816**
Amortizations	6 699	6 699	6 699	6 908	6 447	6 699	6 699	6 693
Maintenance	1 199	1 199	1 199	1237	1 154	1199	1199	1198
Financial expenses	2 383	2 383	2 383	2 458	2 292	2 383	2 383	2 381
Total indirect costs	**10 281**	**10 281**	**10 281**	**10 603**	**9 893**	**10 281**	**10 281**	**10 272**
Total cost T_C [€/ha]	**77 160**	**87 277**	**67 616**	**85 368**	**72 067**	**83 018**	**63 336**	**68 088**
Unitary cost U_C [€/kg] [c]	**0.56**	**0.73**	**0.52**	**0.61**	**0.40**	**0.45**	**0.42**	**0.52**
Average price A_P [€/kg] [b]	**0.88**	**1.71**	**0.91**	**1.01**	**0.91**	**0.63**	**0.73**	**1.06**
Prod. value P_V [€/ha] [c]	**130 000**	**189 810**	**119 210**	**141 068**	**163 660**	**116 739**	**109 500**	**138 570**
Revenue R_V [€/ha] [c]	**52 840**	**102 533**	**51 594**	**55 700**	**91 594**	**33 721**	**46 164**	**62 021**

[a] Calculated from the cost of different crops (JA, 2024a) and their proportion of the total surface of crops (Table 32). For the calculation, the following cultivation options have been considered: tomato in single long cycle; pepper-melon; cucumber-watermelon; zucchini-zucchini and eggplant in single long cycle. For these combination the cost of the two crop developed are additioned. [b] Values of A_P obtained from JA (2024b). [c] Calculated: U_C [€/kg]=T_C [€/ha]/(Y_C [kg/m²]·10 000); P_V [€/ha]= (Y_C [kg/m²]·10 000)·A_P [€/kg].

8.10. Evolution of the production cost of greenhouses in Almería

8.10.1. Summary of the cost structure

Investment cost considers the variations that occur in the prices of the investment goods (farm building, infrastructures and equipment) that are acquired each year (CAJAMAR, 2016). The calculation of the amortization of depreciation cost considers the average value and the useful life of the infrastructures and equipment and its price at the end of its service life or salvage value (SIAP, 2016).

Thus, the estimation of production costs is based in the following assumptions (CAJAMAR, 2017):

- It has been considered a medium farm with a medium-high productive capacity.
- It is considered as reference a modern Almería-type greenhouse with structure "*raspa y amagado*" (Figs. 30-31) with roof vents, metal structure with incorporation of artificial soil and sand mulching "*enarenado*" (Fig. 24). The auxiliary infrastructures considered are an irrigation pond of 500 m^3 and a warehouse of 100 m^2.
- The age structure of the greenhouses has been estimated based on the data provided by the publication "*The greenhouses of Almería, analysis of their technology and profitability*" (Valera *et al*., 2016).
- The historical investment costs have been obtained through the database of the Technical Reports department of the Agri-Food Innovation Area of Cajamar - Caja Rural.
- The depreciation periods for each asset item have been as follows: sand mulching, 3 years; manure/substrate, 3 years; greenhouse structure, 15 years; plastic cover, 3 years; irrigation system, 15 years; irrigation pond 30 years.
- 70% of the total cost of the initial investment is financed in the long term, with a 15-year variable-rate mortgage loan.
- The cost of acquiring land is not taken into account, since it is understood that the evolution of its residual value does not necessarily have to evolve from more to less.
- For the calculation, the following cultivation options have been considered: tomato in single cycle; pepper-melon; cucumber-watermelon; zucchini-zucchini and green bean-green bean.
- The cost of acquiring land is not taken into account.

The calculation of depreciation expenses is carried out taking into account that the different items are composed of elements that are not renewed every year, as well as the amortization term of the same, so they only collect a part of the percentage growth experienced in 2021/22.

8.10.2. Evolution of production costs

8.10.2.1. Employment and labour costs

Agriculture in 2022, with 73 000 workers affiliated to Social Security, which corresponds to 23.8% of the total employed (306 700) has a large presence in the province of Almería (SEPE, 2023). Hence, the importance of this sector in the productive market of Almeria, presenting itself as one of the engines of the provincial economy. The trend in hiring in the agricultural sector of Almeria shows significant annual variations (Fig. 111). Thus, in 2022 there is a decrease in employed persons in Agriculture above 12%, like that which occurred in 2018. In this case, it has returned to a number of workers similar to that of 2020, thus compensating for the rise in 2021 of 12.8% of employees in the agricultural sector (SEPE, 2023).

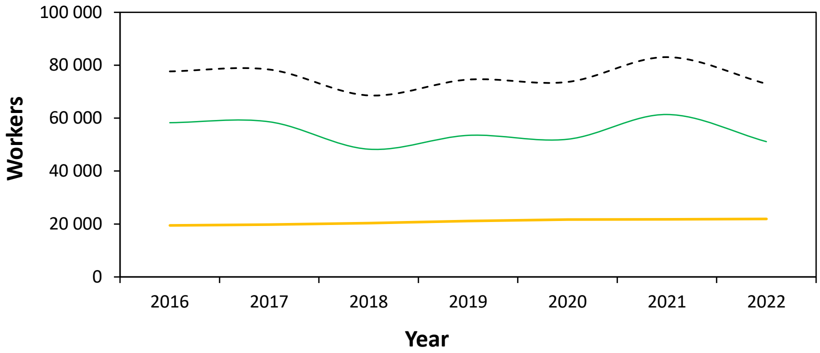


Figure 111. Evolution of the number of affiliated to the Security Social in the agriculture sector (—), workers in the special agricultural regime (——) and total of employed (- - -) in the agriculture sector in the province of Almería (SEPE, 2023).

6.10.2.2. Cost of seeds

At the end of the 2021/22 season, the price of seeds was 3.1% higher than the previous season (Fig. 112). This was mainly due to the effort made by companies in the sector in investment for the development of new varieties that adjust to the demands of farmers and consumers (CAJAMAR, 2022). The variation of December 2022 with respect to the price of seeds in Spain in December 2015 has been 6.9% (MAPA, 2023b).

The products that experienced the greatest growth in the price of seeds have been zucchini, pepper and watermelon, while the cost of eggplant has remained very stable (CAJAMAR, 2022).

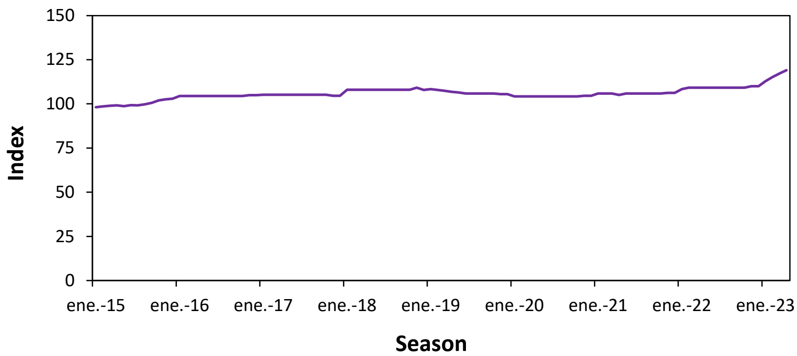


Figure 112. Evolution of the price index (base 100 for average value in 2015) for seed in Spain (MAPA, 2023b).

8.10.2.3. Cost of water

In the 2021/22 season, the price of water was 8.4% higher than the previous season due to the increase in the prices of the energy needed in pumping. This value has not been higher due to supply contracts between irrigation communities and electricity marketers (CAJAMAR, 2022).

8.10.2.4. Cost of fertilizers

During 2021/22, the increase in gas and electricity prices has affected the productive capacity of the producing companies that, together with the lower imports from Russia and Ukraine, have caused an increase in this expenditure item (CAJAMAR, 2022).

The price of fertilizers is highly dependent on the progress of energy markets, since natural gas is used in the production of these products, especially nitrogen. The average prices of fertilizers and nitrogen components increased by 65.6% from December 2015 to 2022 (Fig. 113). This has meant that the disbursement made by farmers in this season has doubled, with an increase of 102.1% (CAJAMAR, 2022).

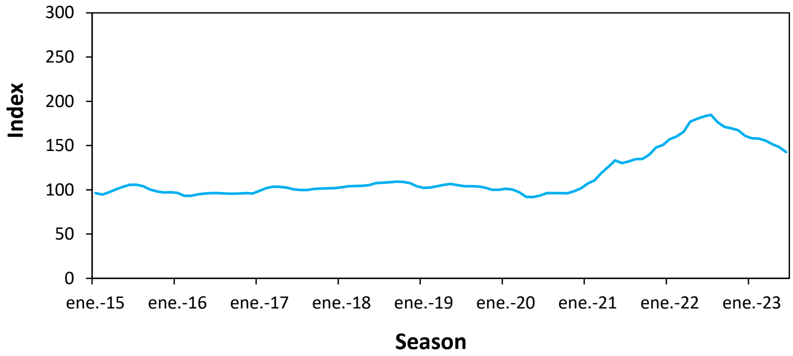


Figure 113. Evolution of the price index (base 100 for December 2014) for manufacture of basic chemicals, nitrogenous compounds, fertilizers, plastics and synthetic rubber in primary forms in Spain (INE. 2023c).

8.10.2.5. Cost of phytosanitary chemical products

The industrial price index for the manufacture of pesticides and other agrochemicals has not stopped growing since the end of the 2020/21 season (Fig. 114). The end-2022 increase over 2015 was 9.8%. In the most specific case of products used in agriculture for plant protection, this increase from 2015 to 2022 was 31.6% (INE, 2023b). This has led to an increase in the phytosanitary consignment of 6.1% in 2021/22 compared to the previous season (Table 47).

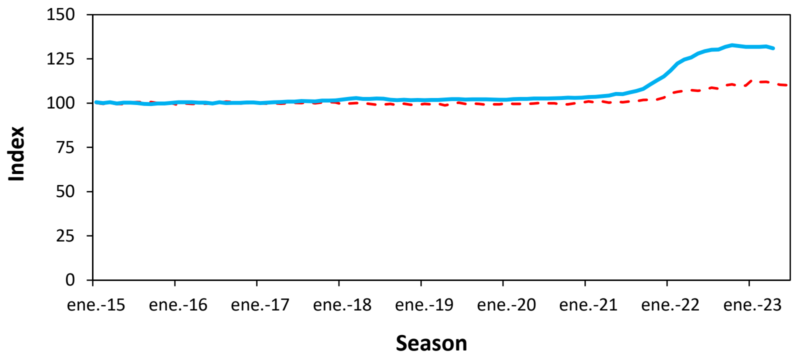


Figure 114. Evolution of the price index (base 100 for average value in 2015) of plant pathological protection (—) (MAPA, 2023b) and index (base 100 for December 2014) for manufacture of pesticides and other agrochemicals (- - -) in Spain (INE, 2023b).

8.10.2.5. Cost of biological control

After a few years of decrease in the biological control area, from 2016 to 2018, in 2019 the recovery of this area began (Fig. 115). During the 2021/22 season, a total of 26 739 ha was cultivated with biological pest control techniques, which is the highest figure since the widespread use of auxiliary insects began in 2007/08. This area was 2.8% higher than the previous season and allowed a return to a value similar to that of the 2015/16 season (26 600 ha) (CAJAMAR, 2022).

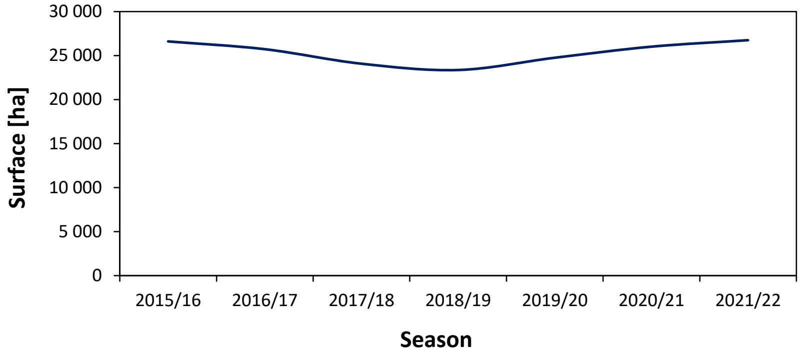


Figure 115. Evolution of the surface cultivated under biological control techniques in the greenhouses of the province of Almería (CAJAMAR, 216-2022).

Regarding the cost of using biological control for the different cultivated species, this has remained very stable for melon, watermelon, beans and tomatoes. However, it has increased in pepper (+7.6%), eggplant (+5.2%) and cucumber (+4.2%). The only decline has occurred in the strategies used in zucchini (-7.9%), although it is still the vegetable that has grown the most since 2007/08 (CAJAMAR, 2022).

The greater area cultivated with these techniques has also contributed to the increase in the average cost per hectare of this item, estimated at 7.1% compared to 2020/21 with an average expenditure of 1 267 €/ha (Table 47).

8.10.2.6. Cost of energy

During the 2021/22 season, the price of electricity suffered large increases, causing the cost of this item in the greenhouses of Almeria to increase by +49.6%. At the beginning of the season, energy and electricity prices were at elevated levels (Fig. 116) because of the energy transition and the growth in demand following the slowdown in economic activity during the pandemic. This situation of unreasonable prices was aggravated by the war in Ukraine. Thus, the price of energy in December 2022 was 160% higher than in December 2015 (Fig. 116).

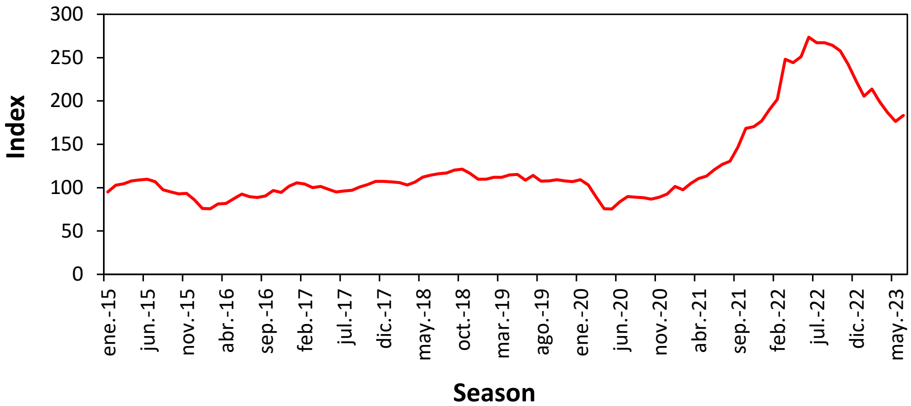


Figure 116. Evolution of the price index [a] for energy consumption in Andalucía (INE, 2023a).

[a] The index is calculated as the quotient between the average price of the current month and the average price of December of the previous year, 2014 (multiplied by 100). So, they have no units (INE, 2023).

8.10.2.7. Financial costs

During the 2021/22 season, the Euribor, the main reference index for investment financing, has shown an upward trend, going from negative to positive values as of April 2022 (Fig. 117), with a value of -0.477% in January 2022 and 3,018% in December 2022 (BDE, 2023). This increase in the Euribor has produced an increase in financial costs of 8.8% in the 2021/22 season, after several periods in which this item had remained constant (Table 47).

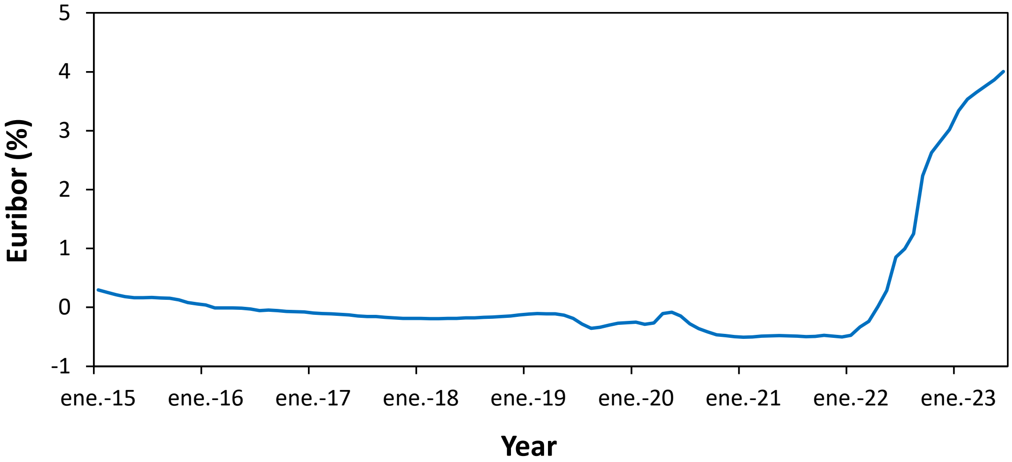


Figure 117. Evolution of Euribor at 12 months from 2015 to June 2023 (BDE, 2023).

8.10.2.8. Cost of greenhouses plastics

At the beginning of the 2021/22 season, the mismatch between the reactivation of the economy and the supply of raw materials and industrial products kept the price of oil at elevated levels. The war in Ukraine caused a new imbalance, which resulted in a rebound in the price of oil, and as a result of an increase in the cost of plastics, with an average price of 3.4 €/kg (CAJAMAR, 2022), 12.8% to the previous season and 18.7% higher than the price in the 2015/16 season (Fig. 118).

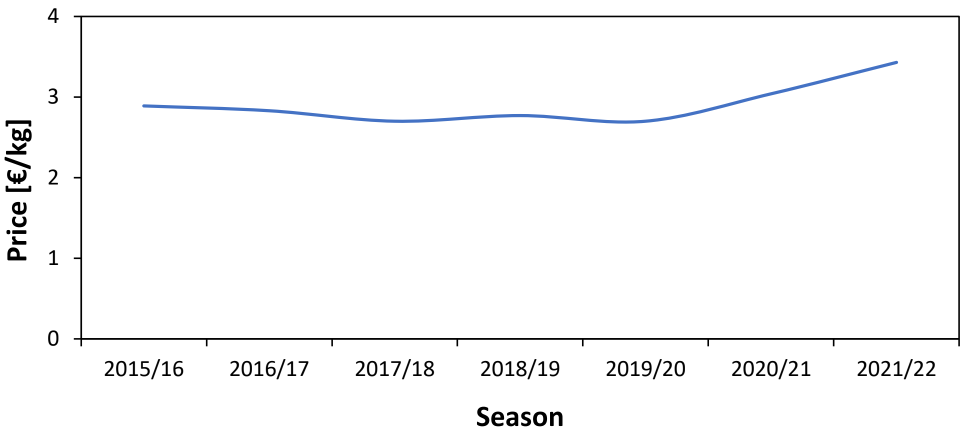


Figure 118. Evolution of the price of plastic for cultivation in greenhouses in Almería (CAJAMAR, 2022).

Table 47. Production cost of greenhouses in Almería in the season 2016/17 to 2021/22 (CAJAMAR, 2017-2022).

Season	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22
Labour	23 173	23 173	23 173	25 977	28 393	28 904	30 494
Seedlings	5 252	5 318	5 472	5 658	5 822	5 935	6 214
Water	1 650	1 636	1 693	1 761	1 780	1 807	1 959
Fertilizers	3 764	3 689	3 703	3 895	3 613	3 926	7 936
Phytosanitary	3 172	3 130	3 336	3 533	3 445	3 510	4 017
Chemical control	*2 308*	*2 231*	*2 266*	*2 273*	*2 289*	*2 327*	*2 461*
Biological control	*864*	*899*	*1 070*	*1 260*	*1 156*	*1 183*	*1 556*
Energy	1 246	1 257	1 299	1 302	1 146	1 284	1 921
Services	5 076	4 554	4 589	4 492	3 997	3 990	4 405
Transport	*1 883*	*1 886*	*1 902*	*1 903*	*1 864*	*1 908*	*2 181*
Communications	*392*	*393*	*420*	*424*	*426*	*411*	*407*
Financial costs and assurances	*2 801*	*2 276*	*2 267*	*2 166*	*1 708*	*1 671*	*1 817*
Other direct costs	1 635	1 638	1 638	1 643	1 646	1 665	1 795
Total direct costs	**44 967**	**44 394**	**44 903**	**47 961**	**49 843**	**51 020**	**58 740**
Substrate / soil *"arenado"*	2 280	2 252	2 314	2 517	2 373	2 373	2 459
Greenhouse structure	4 505	4 489	4 530	4 567	4 773	5 251	5 340
Plastic	3 224	3 080	3 106	3 251	3 333	3 750	3 911
Irrigation system	799	779	786	712	805	805	815
Irrigation pond	447	421	397	512	377	377	382
Other infrastructures	960	938	929	837	981	981	982
Total amortization costs	**12 215**	**11 958**	**12 061**	**12 395**	**12 643**	**13 537**	**13 888**
Total cost T_C [€/ha]	**57 182**	**56 352**	**56 964**	**60 356**	**62 486**	**64 557**	**72 628**
Production P_G [t] [a]	3 799 775	3 725 391	3 742 167	3 879 388	4 073 510	4 048 037	3 944 066
Greenhouse surface S_{SA} [ha] [b]	32 855	34 121	34 714	35 170	35 935	36 218	36 935
Productivity Y_{CS} [kg/m²] [c]	11.6	10.9	10.8	11.0	11.3	11.2	10.7
Production value V_P [thousand of €] [a]	2 723 438	2 329 881	2 270 336	2 523 651	2 478 880	2 538 735	3 156 647
Production value P_V [€/ha] [c]	**82 893**	**68 283**	**65 401**	**71 756**	**68 982**	**70 096**	**85 465**
Unitary cost U_C [€/kg] [c]	0.49	0.52	0.53	0.55	0.55	0.58	0.68
Average price A_P [€/kg] [c]	0.72	0.63	0.61	0.65	0.61	0.63	0.80
Revenue R_V [€/ha] [c]	**25 711**	**11 931**	**8 437**	**11 400**	**6 496**	**5 539**	**12 837**

[a] Values of P_G and V_P obtained from Table 32 (JA, 2021b; JA, 2022a). [b] Values of S_S obtained from Table 32 (JA, 2016; JA, 2020b; 2021c; JA, 2022b).
[c] Calculated: Y_{CS} [kg/m²]=P_G [t]/(10·S_{SA} [ha]); P_V [€/ha]=V_P [thousand €]·1000/S_{SA} [ha]; U_C [€/kg]=T_C [€/ha]·S_{SA} [ha]/(P_G [t]·1000); A_P [€/kg]=V_P [thousand €]/P_G [t]; R_V [€/ha]=P_V [€/ha]–T_C [€/ha].

8.10.3. Evolution of grower's revenue

As a result of the strong increases in the sales prices of most horticultural producers, the highest sales values of production were reached in the 2021/22 season (Table 47 - Fig. 119). With respect to the previous season (2020/21) there was an increase of 21.9% that compensated for the reductions of previous seasons. Compared to the 2015/16 season there was an increase of 3.1%. However, in this period from 2015/16 to 2021/22 the increase in production costs in the greenhouses of Almeria was 27.0%, and 12.5% compared to the previous season of 2021/22 (Table 47).

This gap between the increases in production costs (27.0%) and the average value of production (3.1%) has meant that the estimated value for all farmers (CAJAMAR, 2022) of profit for the farmer has decreased by 50.1% in the last 7 production seasons from 2015/16 to 2021/22 in which it was 12 837 €/ha (Table 47).

It should be noted that the calculated value of profit for the 2021/22 season for the greenhouses selected by the Junta de Andalucía (Table 45) was much higher (Fig. 110), of 48 223 €/ha (Table 45). This is due to the fact that the production levels reflected in these specific farms where the cost analysis was carried out (Table 46) are higher than the average values of the group of farmers, which is the one that has been taken into account for the estimation of the average profit (Table 47).

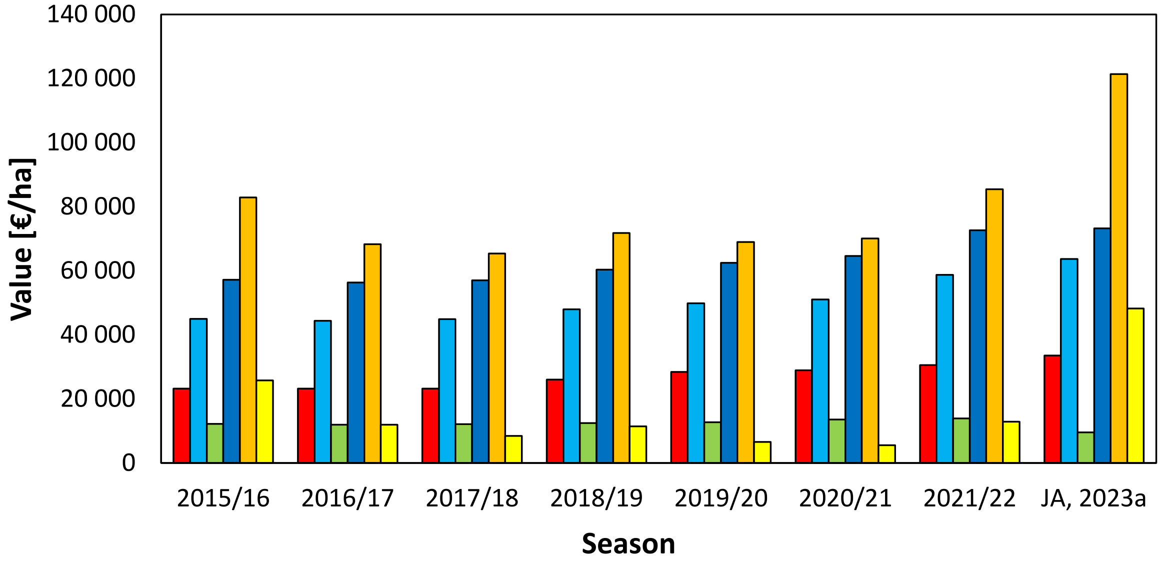


Figure 119. Evolution of production cost in the last 7 years: labour cost (■), direct costs (■), indirect-amortization costs (■), total costs (■), production value (■) and revenue (■). Data from Table 47 (CAJAMAR, 2016-2022) and Table 46 (JA, 2024a-b).

9. Types of greenhouses in Italy

Protected crops are the different forms of cultivation in which some structures are used to protect plants from adverse climatic factors, which could affect their normal development (NSA, 2023). Among the means of protection used in Italy for horticulture, floriculture, nursery or fruit growing, there are a very wide range of structures, which can differ for their complexity or duration.

Protected crops include from simple ground covered by a plastic film to the most modern and complex greenhouses, equipped with different degree of climate control systems to allow cultivate certain species in environments other than those of origin in which they can grow naturally.

The protection systems can be used for the entire cultivation period producing completely out of season (forcing), with stable greenhouses equipped with glass or plastic roofs, or only for some months for anticipate or delay production (semi-forcing), using simpler means of protection (Table 48).

Table 48. Means of protection used in horticulture, floriculture and fruit growing (NSA, 2023).

Means	Element	System
Means of defence	of the underground part of the plant	mulching
	of the epigean part of the plant	windbreak, anti-frost and antifreeze equipment, anti-hail nets, shading screens
Means of semi-forcing for early or delayed production	with protection of single plants	bells or plastic hoods
	with protections applied to entire crops that are not accessible to people	thermal blankets, tunnels
	with non-permanent protections applied to entire crops accessible to people	tunnel greenhouses
Means of forcing for off-season productions	greenhouses without above-ground wall structures	without climate control systems
		with climate control systems
	greenhouses with above-ground wall structures	without climate control systems
		with climate control systems

Italy is one of the leading countries in protected cultivation because of its mild climate in winter. The area under greenhouse cultivation in Italy was 30 820 ha in 2022 (Table 49), with 6 000 ha serving as permanent greenhouse structures (Bibbiani *et al*., 2016).

Greenhouse activities are relevant for the Italian agriculture owing to their production quality and technology development (Marucci *et al*., 2014). Diverse types of greenhouses and protection structures can be found, ranging from wooden structures covered with plastic film to glasshouses fully equipped for automatic climatic control and internal plant transportation (Pardossi and Tognoni, 1999).

Most greenhouses are very simple, covered with plastic films (PE, EVA), a limited use of microclimate control systems, with an emergency heating system (Pardossi and Tognoni, 1999), and a high labour demand with a limited availability of good-quality water (De Pascale *et al*., 2018). Greenhouse production is usually based on small-size farms (less than 1 ha) which are owned and operated by families (Pardossi and Tognoni, 1999).

Strawberry, vegetables and some flower crops (carnation) are usually cultivated in low-tech structures, whereas other flower crops and pot plants are grown in more sophisticated glasshouses (Pardossi and Tognoni, 1999).

Table 49. Area cultivated in the diverse types of greenhouses in the regions of Italy in the years 2019to 2022 (ISTAT, 2023b).

Regions	[ha]	%	[ha]	%	[ha]	%	[ha]	%
Year	2019		2020		2021		2022	
Valle d'Acosta	0	0.0	2	0.0	2	0.0	2	0.0
Piemonte	666	1.9	665	1.9	-	-	-	-
Liguria	74	0.2	76	0.2	41	0.1	41	0.1
Lombardia	1 818	5.1	1 949	5.5	2 002	5.7	2 905	9.4
Trentino Alto Adige	-	-	-	-	23	0.1	25	0.1
Veneto	3 489	9.8	3 285	9.2	3 345	9.6	3 680	11.9
Friuli-Venezia Giulia	67	0.2	77	0.2	9	0.0	3	0.0
Emilie-Romagne	1 126	3.2	1 114	3.1	900	2.6	587	1.9
Toscana	239	0.7	227	0.6	262	0.7	175	0.6
Umbria	17	0.0	17	0.0	6	0.0	6	0.0
Marche	36	0.1	36	0.1	35	0.1	30	0.1
Lazio	8 768	24.6	9 001	25.3	8 365	23.9	7 811	25.3
Abruzzo	160	0.4	160	0.5	105	0.3	105	0.3
Molise	5	0.0	5	0.0	3	0.0	3	0.0
Campania	10 085	28.3	9 994	28.1	8 960	25.6	7 409	24.0
Puglia	430	1.2	430	1.2	178	0.5	290	0.9
Basilicata	321	0.9	321	0.9	321	0.9	-	-
Sicilia	7 140	20.1	7 121	20.0	7 082	20.2	7 081	23.0
Calabria	520	1.5	524	1.5	527	1.5	107	0.3
Sardegna	631	1.8	569	1.6	569	1.6	560	1.8
Italy	**35 593**	**100**	**35 574**	**100**	**35 013**	**100**	**32 885**	**100**

9.1. Tunnel greenhouses

The tunnel greenhouses consist of galvanized metal arches with a variable width from 4 to 10 m and a maximum height of 2.9 to 4.2 m (Fig. 120).

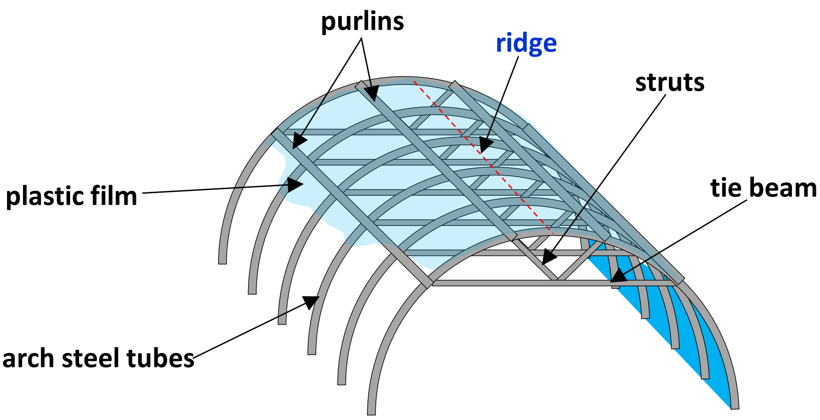


Figure 120. Structure of tunnel greenhouses used in Italy.

The cover can be in plastic film (Fig. 121) of seasonal or multi-year duration (max 4 years) or in rigid plastic (polymethacrylate, polyester, polyvinyl chloride) with a long life (8-10 years).

Figure 121. Tunnel plastic greenhouses in Italy (ILS, 2023).

Tunnel agricultural greenhouses are normally made with round tube arches diameter 60 mm and its field installation is quick and easy (ILS, 2023). The tunnel can be equipped with aluminium profiles for fixing the roof and window film. Side openings (manual or automated) can be installed to obtain natural ventilation inside the tunnel. The structure can be reinforced with tie rods depending on the location of installation (snow load) or the type of cultivation (hanging loads).

9.2. Multispan greenhouses

Multispan greenhouses have a solid structure with curved arches and rectangular tube pillars (Fig. 32), offering ample guarantees of resistance with static calculations to wind and snow and, at the same time, allows the hanging support of various types of cultivation (ILS, 2023). The construction of multispan greenhouses (Fig. 122) is also regulated in Italy by the European standard UNI EN 13031-1:2022 "*Serre - progettazione e costruzione - Parte 1: Serre per produzione commerciale*". For this type of greenhouses, an investment of around 18-43 €/m^2 is required for the structure (RS, 2023).

Figure 122. Multispan greenhouses in Italy (ILS, 2023).

9.2.1. Medium-tech unheated multispan greenhouses

For this type of greenhouses, an investment of around 25-80 €/m^2 is required considering the structure and different equipment for irrigation and simple climate control systems. Climate control is more efficient than in tunnel greenhouses and the indoor environment is independent from the external one. In the case of vegetables, they are often equipped with emergency heating in case of frost. Cultivation techniques are more advanced and can include hydroponic systems, with many cultivation operations partially or fully automated. These greenhouses are used not only for the cultivation of vegetables out of season, for cut flowers of high value (for example the rose) and for ornamental plants in pots.

9.2.2. High-tech heated multispan greenhouses

For this type of greenhouses with heating systems, the investment required is greater than 80 €/m^2 and can reach or even exceed 160 €/m^2, as consequence of the investment necessary for the boiler, heat water distribution pipes and pumps. The climate control systems can also include forced ventilation, cooling and humidification systems (e.g. pad-fan system), artificial lighting, thermal or shading screens (Fig. 123) and carbonic enrichment. The indoor climate can be completely independent of the external one, maximizing the efficiency of space use and minimizing the use of labour, allowing crops production greater than 50 kg/m^2.

Figure 123. Tomato crop in a hight-tech multispan greenhouse in Italy of the company Sfera Società Agricola Srl.

However, these greenhouses produce the maximum consumption of energy and are associated with higher costs, both variable due to the cost of fuel and fixed due to the greater depreciation of infrastructure and equipment.

10. Cultivation in Italian greenhouses

10.1. Area and production of greenhouses in Italy

10.1.1. Distribution of greenhouses in Italy

The greenhouses are widespread all over the Italian peninsula (Fig. 124) that extends from the north parallel 47.5 to the south at parallel 37.5 (Pardossi and Tognoni, 1999). The southern part has hot and dry climate in spring-summer and an average winter temperature of about 0 °C, while the northern zone is temperate with freezing temperatures during winter (Pardossi and Tognoni, 1999).

Figure 124. Map of Italian regions with different surfaces of greenhouses: 5 000-10 000 ha (■), 2 000-5 000 (■), 1 000-2 000 ha (■) and <1 000 ha (■).

These favourable climatic conditions in the southern region make it possible to use simple and cheap structures also for winter cropping of warm-season species such as *solanaceae* and *cucurbitaceae*.

About 60% of the greenhouses are in southern regions (Fig. 124), especially along the seacoast which has a mild winter climate, where most of the greenhouses consist of low-cost structures covered with plastic films (Bibbiani *et al*., 2016). The distribution of greenhouses cultivation in 2023 is spread over the country (Table 51) with the greater concentration in Lazio (21.7%), Campania (21.4%), Sicilia (20.0%), Veneto (10.6%) and Lombardia (10.3%).

In Sicilia, where one of the largest greenhouse area is located (7 029 ha in 2023), about 500 hours of sunlight are available during winter with an average global radiation around 8 $MJ \cdot m^{-2} \cdot day^{-1}$ and a mean temperature of 10–12 °C. High temperatures (30–35 °C) occur in summer all over the country, and consequently this season is a rest period for most greenhouses, eventually used for soil solarization in the south (Pardossi and Tognoni, 1999). The cultivation of pot plants is concentrated in the north in glasshouses with climate control systems and saving energy technologies (Pardossi and Tognoni, 1999).

Greenhouse horticulture, as open field cultivation, reduced area cultivated by 12% in 2022, interrupting last year's increase (Table 50). In the last year 2023 an increase of 7% have allow to recovery partially the average value of the last years.

Vegetable crop production in greenhouses covers about 5% of the whole vegetable cultivation area in Italy and over 65% of the area under protected cultivation (De Pascale *et al*., 2018). The main vegetables are tomato, which represents 20.2%, lettuce, zucchini, melon, watermelon, pepper and eggplant (Table 50), while rose, carnation, chrysanthemum, gladiolus, cyclamen, geranium, poinsettia, ficus and philodendron are the most important flower and foliage crops (Pardossi and Tognoni, 1999).

Table 50. Area cultivated in greenhouses of Italy of the different crops from 2016 to 2023 (ISTAT, 2024).

Crops	2016	2017	2018	2019	2020	2021	2022	2023
Tomato	7 158	7 080	7 229	7 614	7 607	7 349	6 816	7 117
Lettuce	4 549	4 519	4 484	4 707	4 528	4 592	5 518	5 580
Zucchini	4 530	4 438	4 512	4 114	4 214	3 983	3 633	3 777
Melon	3 556	3 498	2 926	2 815	2 872	2 831	2 368	2 417
Watermelon	2 383	2 391	2 420	2 586	2 399	2 345	2 282	2 253
Pepper	2 366	2 030	1 976	1 918	1 879	1 652	1 590	1 575
Eggplant	1 727	1 551	1 528	1 539	1 527	1 576	1 493	1 673
Asparagus	1 155	1 123	1 194	1 208	1 232	1 201	1 170	1 160
Green bean	807	791	780	721	695	653	654	681
Cucumber	578	526	513	579	610	574	550	644
Spinach	220	431	510	486	444	475	515	695
Radish	433	437	436	441	469	475	510	567
Chicory	216	219	241	258	274	332	333	356
Endive	279	272	274	227	263	258	282	517
Carrot	213	221	214	247	269	267	265	221
Celery	188	196	190	198	203	190	186	203
Total	**35 574**	**35 259**	**35 135**	**35 593**	**35 574**	**35 013**	**32 884**	**35 229**

10.1.2. Evolution of the surface area of greenhouses in Italy

Unlike what happened in Spain, the greenhouse area has remained more or less stable in Italy, around 35 000 ha (Table 51, Fig. 125), with reduction greater than 32% for pepper and melon and augmentation of 22.7% for lettuce and 11.5% for cucumber. The greenhouse area has been reduced by 2809 ha (-27.2%) in Campania between 2016 and 2023, while in the same period the area increased by 1566 ha (+75.5%) in Lombardia, remaining stable in the other main producing regions (Table 51).

Table 51. Evolution of greenhouse surface and crop protected in different regions of Italy (ISTAT, 2024).

Year	Lazio	Campania	Sicilia	Veneto	Lombardia	Italy
2016	7 845	10 332	7 676	3 360	2 076	35 574
2017	8 029	10 505	7 217	3 027	2 087	35 259
2018	8 188	10 441	7 213	3 001	1 802	35 135
2019	8 768	10 085	7 140	3 489	1 818	35 593
2020	9 001	9 994	7 121	3 285	1 949	35 574
2021	8 365	8 960	7 082	3 345	2 002	35 013
2022	7 811	7 409	7 081	3 680	2 905	30 820
2023	7 629	7 523	7 029	3 748	3 642	35 230

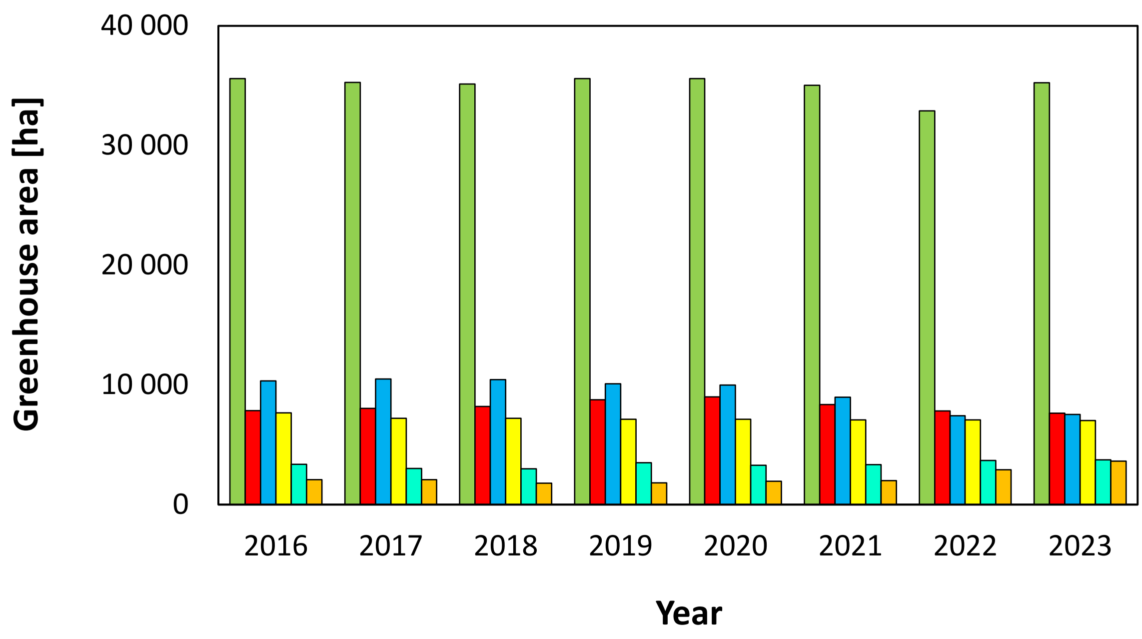


Figure 125. Evolution of the greenhouse area in Italy (■), Lazio (■), Campania (■), Sicilia (■), Veneto (■) and Lombardia (■) (ISTAT, 2024).

10.2. Production of crops in Italian greenhouses

The main crops in Italian greenhouses are tomatoes and lettuce (Table 52). Lettuce is the main crop in Campania, and their surface increased from 2021 to 2022 by 81% in this region and by 20% in the country (Table 52).

Table 52. Cultivated area in greenhouses [ha] in the main regions of Italy in 2021 and 2022 (ISTAT, 2023b).

Crops	Lazio	Campania	Sicilia	Veneto	Lombardia	Italy
			2021			
Tomato	2 255	932	3 043	339	58	7 349
Lettuce	1 562	1 224	28	881	603	4 592
Zucchini	1 813	342	1 104	414	51	3 983
Melon	486	442	296	684	281	2 831
Watermelon	841	466	745	72	128	2 345
Pepper	184	395	747	206	16	1 652
Eggplant	188	359	724	145	12	1 576
Asparagus	16	1 064	6	89	3	1 201
Green bean	93	213	185	53	11	653
Cucumber	48	50	193	189	15	574
Spinach	4	182		122	157	475
Radish	364	103			3	475
Chicory	52	55	2	42	149	332
Endive	101	71	5	15	35	258
Carrot	234			23	0	267
Celery	88	38	0	27	6	190
Chard	29	7		20	9	94
Fennel	7		0	22	1	86
Pea		20	3	3		34
Beet		8			0	15
Total	8 365	8 960	7 082	3 345	2 002	35 013
			2022			
Tomato	1 960	882	3 038	337	47	6 816
Lettuce	1 582	2 216	28	905	567	5 518
Zucchini	1 608	333	1 104	377	47	3 633
Melon	526	423	291	623	203	2 368
Watermelon	738	561	745	64	92	2 282
Pepper	171	344	747	213	11	1 590
Eggplant	199	351	724	113	10	1 493
Asparagus	16	1 036	6	89	2	1 170
Green bean	96	235	195	43	11	654
Cucumber	51	52	193	191	10	550
Spinach	2	152		148	203	515
Radish	396	106			2	510
Chicory	3	56	2	24	228	333
Endive	103	106	5	12	31	282
Carrot	235			19	0	265
Celery	90	37	0	22	6	186
Chard	30	7		27	9	98
Fennel	7		0	23	1	80
Pea		25	3	3		47
Beet		13			0	17
Total	7 811	7 409	7 081	3 680	2 905	30 820

Although the area cultivated within greenhouses in Italy in 2022 decreased a 12.0%, the increase of 8.2% in the productivity of the crops and the increase of 13.4% in the price, allowed an increase of 11.8% of the value of the production, from 1 144 million of € in 2021 to 1 278 million of € in 2022 (Table 53). In the last year 2023, the prices of products continued to increase, and the surface cultivated also increased, producing as consequence a growth of the value of the production to a maximum of 1 735 million of €.

Table 53. Area (S_G) and production (P_G), value of production (V_P [a]) productivity (Y_C) and average price (A_P) of crops cultivated in the Italian greenhouses in the last seasons (ISTAT, 2024).

Crops	Parameters	2016	2017	2018	2019	2020	2021	2022	2023
Tomato	S_G [ha]	7 158	7 080	7 229	7 614	7 607	7 349	6 816	7 117
	P_G [t]	447 054	442 562	465 939	524 926	513 660	536 502	485 917	521 371
	V_P [Thousands €]	241 409	411 582	312 179	435 688	452 021	498 947	587 959	630 859
	Y_C [kg/m^2]	6.2	6.3	6.4	6.9	6.8	7.3	7.1	7.3
Pepper	S_G [ha]	2 366	2 030	1 976	1 918	1 879	1 652	1 590	1 575
	P_G [t]	97 473	76 882	76 341	75 315	77 191	69 748	67 892	63 805
	V_P [Thousands €]	50 686	56 893	70 233	66 277	72 560	69 748	63 139	96 346
	Y_C [kg/m^2]	4.1	3.8	3.9	3.9	4.1	4.2	4.3	4.1
Cucumber	S_G [ha]	578	526	513	579	610	574	550	644
	P_G [t]	37 756	33 543	33 093	38 673	38 362	41 122	38 370	41 880
	V_P [Thousands €]	15 102	14 088	15 554	18 563	18 414	22 206	23 406	30 991
	Y_C [kg/m^2]	6.5	6.4	6.4	6.7	6.3	7.2	7.0	6.5
Watermelon	S_G [ha]	2 383	2 391	2 420	2 586	2 399	2 345	2 282	2 254
	P_G [t]	98 205	98 903	99 256	113 056	103 564	110 269	150 540	130 065
	V_P [Thousands €]	22 587	20 770	24 814	38 439	34 176	27 567	70 754	62 431
	Y_C [kg/m^2]	4.1	4.1	4.1	4.4	4.3	4.7	6.6	5.8
Zucchini	S_G [ha]	4 530	4 438	4 512	4 114	4 214	3 983	3 633	3 777
	P_G [t]	204 598	202 436	214 849	210 050	210 883	213 916	184 997	192 963
	V_P [Thousands €]	149 356	188 265	210 552	203 749	210 883	239 585	209 047	223 837
	Y_C [kg/m^2]	4.5	4.6	4.8	5.1	5.0	5.4	5.1	5.1
Melon	S_G [ha]	3 556	3 498	2 926	2 815	2 872	2 831	2 368	2 417
	P_G [t]	108 879	111 950	94 491	87 397	90 122	92 376	80 948	81 499
	V_P [Thousands €]	62 061	58 214	54 805	56 808	58 579	56 349	61 520	85 574
	Y_C [kg/m^2]	3.1	3.2	3.2	3.1	3.1	3.3	3.4	3.4
Eggplant	S_G [ha]	1 727	1 551	1 528	1 539	1 527	1 576	1 493	1 674
	P_G [t]	88 064	75 641	78 254	81 367	83 452	85 774	84 688	96 645
	V_P [Thousands €]	44 032	47 654	52 430	57 770	62 589	73 766	71 985	98 578
	Y_C [kg/m^2]	5.1	4.9	5.1	5.3	5.5	5.4	5.7	5.8
Green bean	S_G [ha]	807	791	780	721	695	653	654	681
	P_G [t]	17 179	16 497	16 368	15 698	15 441	15 903	15 781	17 091
	V_P [Thousands €]	28 345	30 354	23 570	25 588	43 851	46 117	31 563	13 673
	Y_C [kg/m^2]	2.1	2.1	2.1	2.2	2.2	2.4	2.4	2.5
Lettuce	S_G [ha]	4 549	4 519	4 484	4 707	4 528	4 592	5 518	5 580
	P_G [t]	153 064	146 771	151 803	154 466	150 103	158 452	196 016	192 963
	V_P [Thousands €]	65 817	82 192	91 082	108 126	102 070	109 332	158 773	167 878
	Y_C [kg/m^2]	3.4	3.2	3.4	3.3	3.3	3.5	3.6	3.5
Total	S_G [ha]	**35 574**	**35 259**	**35 135**	**35 593**	**35 574**	**35 013**	**32 885**	**35 230**
	P_G [t]	**1 495 313**	**1 447 024**	**1 492 668**	**1 568 825**	**1 552 806**	**1 551 175**	**1 578 157**	**1 652 496**
	V_P [Thousands €]	**679 396**	**910 012**	**855 219**	**1 011 008**	**1 055 143**	**1 143 617**	**1 278 145**	**1 735 121**
	Y_C [kg/m^2]	**4.2**	**4.1**	**4.2**	**4.4**	**4.4**	**4.4**	**4.8**	**4.7**
	A_P [€/kg]	**0.54**	**0.76**	**0.70**	**0.78**	**0.82**	**0.86**	**0.98**	**1.05**

[a] Estimation from production (Table 53) and average prices (Table 54).

In general, greenhouse production in Italian greenhouse is very stable in the time for surface (Fig. 126) and for productivity (Fig. 127) and consequently for the total production (Fig. 128) resulting of these two parameters.

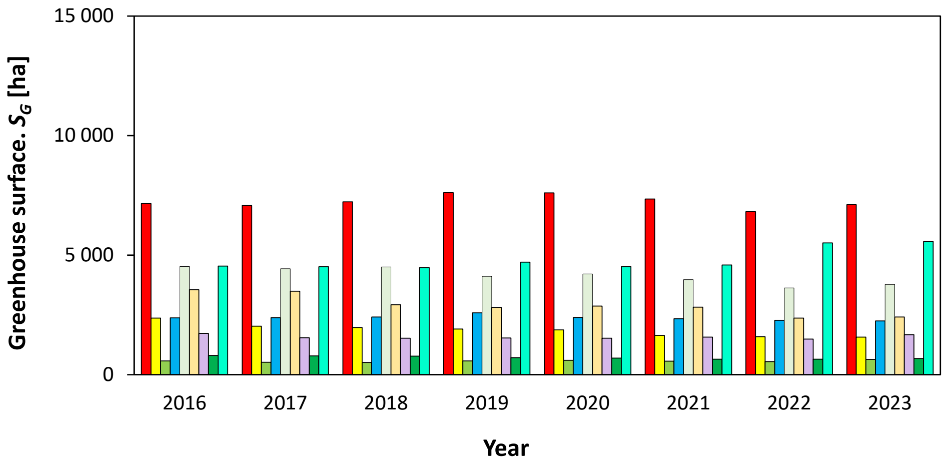


Figure 126. Evolution of the surface area of greenhouses in Italy: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■) and lettuce (■) (Data from Table 53).

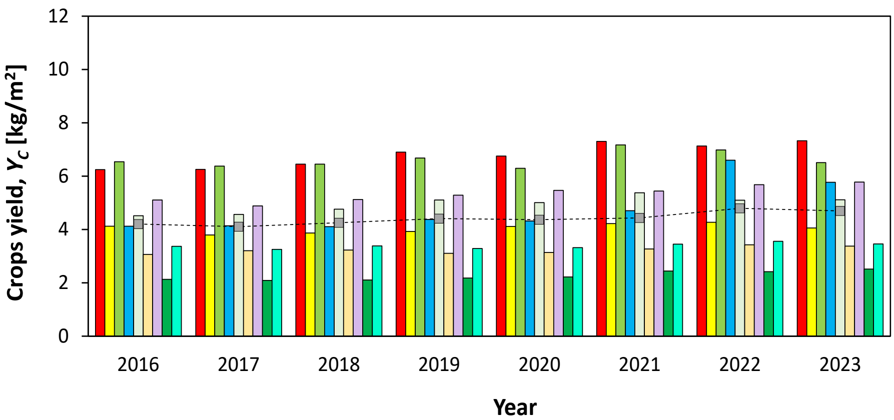


Figure 127. Evolution of greenhouse crop productivity in Italy: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■), lettuce (■) and average of all products (-■-) (Data from Table 53).

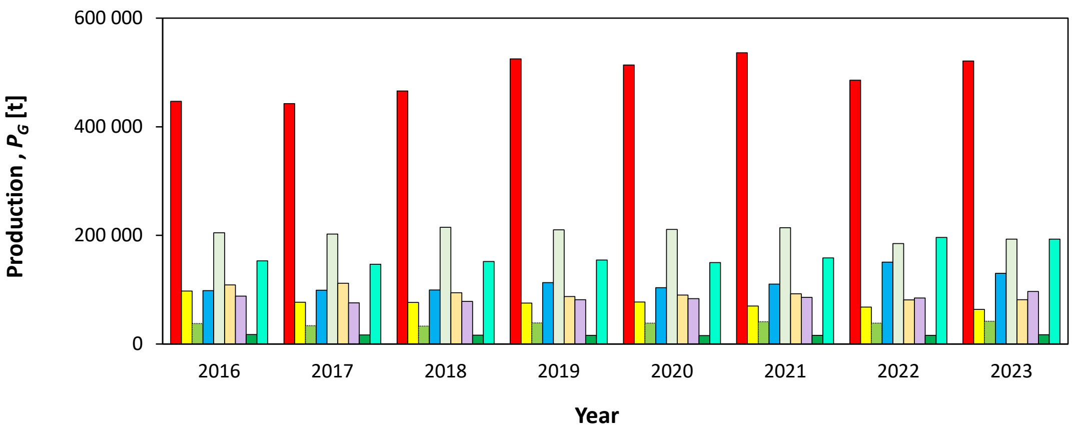


Figure 128. Evolution of the production of the main crops in Italy: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■) and lettuce (■) (Data from Table 53).

10.4. Commercialisation of greenhouse production in Italy

In the last two years, prices of the vegetables have increased as consequence of the generalized augmentation of the inflation in the European countries. The prices of fruit and vegetables produced in greenhouse have increased a 93.5% in average from 2016 to 2023 (Table 54). The crops with the greatest increase in sales price (Fig. 129) has been pepper (+190%) followed by tomato (+124%).

Table 54. Average price [€/kg] obtained by farmers for greenhouse production in Italy in the last seasons (ISMEA, 2024).

Crops	2016	2017	2018	2019	2020	2021	2022	2023
Standard tomato	0.54	0.93	0.67	0.83	0.88	0.93	1.21	1.21
Cherry tomato	0.77	1.57	0.97	1.12	1.18	1.21	1.51	1.64
Pepper	0.52	0.74	0.92	0.88	0.94	1.00	0.93	1.51
Cucumber	0.40	0.42	0.47	0.48	0.48	0.54	0.61	0.74
Watermelon *	0.23	0.21	0.25	0.34	0.33	0.25	0.47	0.48
Courgette	0.73	0.93	0.98	0.97	1.00	1.12	1.13	1.16
Melon *	0.57	0.52	0.58	0.65	0.65	0.61	0.76	1.05
Eggplant	0.50	0.63	0.67	0.71	0.75	0.86	0.85	1.02
Green bean	1.65	1.84	1.44	1.63	2.84	2.90	2.00	0.80
Lettuce	0.43	0.56	0.60	0.70	0.68	0.69	0.81	0.87
Average	0.54	0.76	0.70	0.78	0.82	0.86	0.98	1.05

* Price including production in open field.

Green beans have shown great price instability with variations of more than 100%, which have resulted in exceptionally low prices during 2023 (Fig. 129).

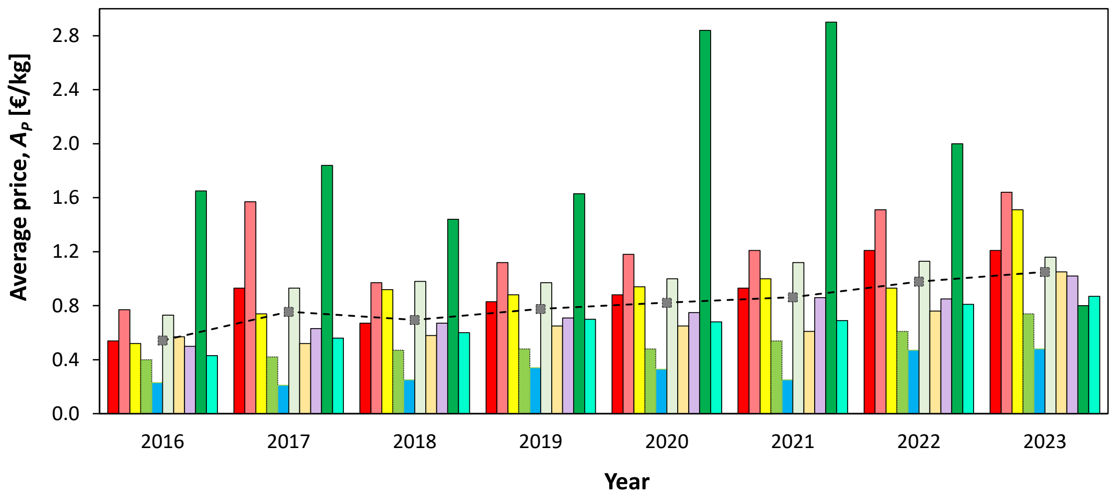


Figure 129. Evolution of the price of the main crops in Italy: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■), lettuce (■) and average of all products (-■-) (Data from Table 54).

As a result of the stabilization of production (Fig. 128) and the sharp increase in prices (Fig. 129), the value of production in 2023 has been 155% higher than that of 2016 (Fig. 130).

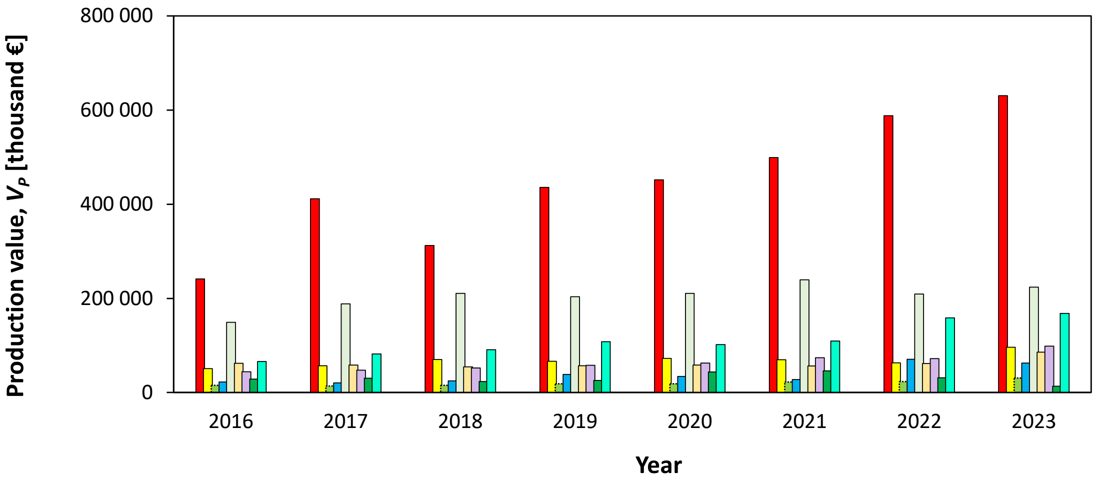


Figure 130. Evolution of the value of the production of the main crops in Italy: tomato (■), pepper (■), cucumber (■), watermelon (■), zucchini (■), melon (■), eggplant (■), green bean (■) and lettuce (■) (Data from Table 53).

11. Production cost in Italian greenhouses

11.1. Methodology for the monitoring of agricultural production costs in Italian greenhouses

11.1.1. Characteristics of monitoring

The monitoring of production costs of agricultural production carried out by the *Istituto di Servizi per il Mercato Agricolo Alimentare* (ISMEA) is based on the following assumptions (ISMEA, 2024):

- analysis of the individual production process subject to observation, with the identification of the various cost items that affect the determination of the total cost and definition of a detailed "Extended Survey Form".

- identification of types of companies (or clusters), companies similar in technical, organizational, orographic location, size and destination of the raw material, which are the most representative of the product under investigation. The company clusters are defined by product (or product families), to capture the peculiarities of each sector.

11.1.2. Unit and object of the analysis

The statistical unit for monitoring the costs of agricultural production is the agricultural holding, specialized in the agricultural product under analysis, in this case the *Cherry* tomatoes. The object of the analysis is the single production process to which all the costs of direct and indirect production factors are traced, considering the real Input costs, the direct fixed costs and those common to other activities and pro-quota imputed and the general costs relating to the farm as a whole. The fixed labour (in terms of wages) enters into the calculation of the cost of production as a function of the quantity of labour expressed in units of time dedicated to the activity linked to the product under analysis (tomato), as well as family labour, for which there is no real monetary outlay, is equated with fixed labour.

11.1.3. The calculation of production costs: direct costs

The total cost considers all the production phases carried out in the company and therefore also includes the cost of arrangement in containers (baskets, boxes, etc.) if already carried out during the collection and if essential in order to be transferred to the next phase (wholesale, large-scale distribution, etc.). It is the sum of two components: direct costs and indirect costs.

Direct costs are calculated starting from the data collected in the company and updated monthly by enhancing the inputs production at market prices (ISMEA network for recording the prices of current means of production).

Direct costs include (ISMEA, 2024):

- Fertilizers.
- Plant protection.
- Miscellaneous materials.
- Seeds and Seedlings.
- Energy products (fuel, electricity, lubricants).
- Water for crop irrigation.
- Contract work.
- Labour, fixed, family and adventitious (attributed as a function of time on the crop).
- Other direct costs (product certifications, product insurance, etc...).

11.1.4. Calculation of production costs: indirect costs

Indirect costs are attributed pro-rata to the production process under analysis and include (ISMEA, 2024):

- Depreciation of buildings, plants, machines and equipment.
- Cost of land use (both owned and rented).
- Rentals for corporate facilities.
- Land rentals.
- Fees (for irrigation, electricity, etc…).
- Membership fees.
- Administrative expenses, for technical consultants, etc…
- Company certification fees.
- Taxes and duties.
- Expenses for other insurance excluding crop insurance.

11.2. Production cost of the production of cherry tomato inside greenhouses in Italy

The cultivation of tomatoes is typical of the central-southern regions of Italy, where most of the production is carried out (Table 52). In the horticultural sector, there is less margin of variability than in open field production, in relation to the greater uniformity of cultivation techniques: nevertheless, a certain heterogeneity remains linked to the geographical area of reference and the related soils (Palmieri, 2016). Sicily is the region that holds the Italian record for table tomato production, concentrated mostly on the south-eastern side of the island, where crops in a protected environment are widespread (Martoran, 2013). For cherry tomatoes and *datterino* they are about 30% higher prices than for the types of bunches, salad and ox heart, because it need more manpower in cultivation tasks and yield (Martoran, 2013).

11.2.1. Greenhouse structure costs

The cost of the structure and the rent of the land accounts for about 10%, while that of the plastic used for roofing, side walls and mulching represents almost 7% (Martoran, 2013). Greenhouses with a structure weight greater than 16 kg/m^2 of covered area made with galvanized steel or aluminium profiles, can need an investment of 94.10 €/m^2, whereas tunnel and tunnel greenhouses with structure weight between 4 and 5 kg/m^2 can be installed by 4.40 € /m^2 (MPAAF, 2023). Motorization for the automatic control of opening the side ventilation cost about 12.75 €/m^2.

11.2.2. The cost of seedlings

A seedling ready for transplanting costs 0.30-0.70 €, a price that takes into account the cost of the seed and the work of the nursery, representing for 20-22 thousand seedlings needed for one hectare a total amount of 6 000-15 000 €/ha (Tables 55-58). The cost of the seedlings can be reduced by buying the seed directly from the seed companies, and then having the seedlings produced by a local nursery (Sportelli, 2013).

11.2.3. Cost of crop protection and pollination

The use of nets to prevent the access of insect vectors of viruses determines an increase in the relative humidity of the air. Hight humidity increases the phytopathological risks with the consequent repercussions on the nature and frequency of the control interventions, which make the management of cultivation more complicated, especially if organic farming is used (Martoran, 2013). The use of phytosanitary devices represents about 6-7% (Tables 55-58). Pollination of tomato crops takes place through bumblebees (*Bombus terrestris*) by placing a hive every 1 000 m^2, renewed every 60 days (Martoran, 2013), with a cost of 33-35 €/hive.

11.2.4. Fertilization costs

In addition to organic fertilization, fertigation is used using nutritional solutions with variable ionic ratio depending on the phenological stage, the season, the quality of the irrigation water and the variety cultivated (Martoran, 2013). Bottom fertilization and fertilization during the crop cycle represent about 6-10% of the direct costs (Tables 55-58).

11.2.5. Labour costs

The item that has the greatest impact on production costs is labour, about 26-33% (Tables 55-58) of the total in function of the different cultivation operations necessaries: plant tying, application of clips, leaf removal, detailing, application of treatments and harvesting (Martoran, 2013).

Table 55. Production costs (€/ha) of cherry tomatoes in unheated greenhouses in Italy in the 2021/22 season, for ownership growers (ISMEA, 2024a, c).

Month	sep-21	oct-21	nov-21	dic-21	ene-22	feb-22	mar-22	abr-22	Average 21-22
Average yield of a cycle [kg/m^2]									**5.50**
Input costs	**39 510**	**37 556**	**37 735**	**38 596**	**39 736**	**40 325**	**42 591**	**42 999**	**39 510.38**
Fertilizers	*4 605*	*4 224*	*4 347*	*4 483*	*4 589*	*4 742*	*5 202*	*5 292*	4 605.34
Phytosanitary	*1 834*	*1 847*	*1 847*	*1 812*	*1 815*	*1 815*	*1 846*	*1 847*	1 834.37
Seedlings	*13 165*	*12 688*	*12 688*	*12 892*	*12 950*	*12 950*	*14 264*	*14 264*	13 164.87
Other direct costs	*13 042*	*12 794*	*12 837*	*13 107*	*13 113*	*13 199*	*13 259*	*13 259*	13 041.88
Fuels	*805*	*701*	*715*	*719*	*744*	*833*	*1 006*	*1 045*	805.05
Electric energy	*2 279*	*1 871*	*1 871*	*1 871*	*2 711*	*2 711*	*2 711*	*2 990*	2 278.51
Third party work	*3 780*	*3 431*	*3 431*	*3 711*	*3 813*	*4 076*	*4 302*	*4 302*	3 780.37
Labour	**27 352**	**27 352**	**27 352**	**27 352**	**27 352**	**27 352**	**27 352**	**27 352**	27 351.82
Overheads	**13 641**	**13 641**	**13 641**	**13 641**	**13 641**	**13 641**	**13 641**	**13 641**	13 640.56
Total direct costs	**80 503**	**78 549**	**78 728**	**79 588**	**80 728**	**81 318**	**83 583**	**83 992**	**80 502.76**
Implicit costs	2 425	2 425	2 425	2 425	2 425	2 425	2 425	2 425	2 425.40
Total cost [€/ha]	**82 928**	**80 974**	**81 153**	**82 014**	**83 154**	**83 743**	**86 009**	**86 417**	**82 928.16**
Unitary cost [€/kg]	**1.48**	**1.45**	**1.45**	**1.46**	**1.48**	**1.50**	**1.54**	**1.54**	**1.48**

* Company located in the Ragusa district in Sicily, integrated production, up to 10 ha, multispan greenhouses with galvanized steel and plastic roofing sheets/films, cherry and datterino tomatoes, title of possession as property, company well, 6-month production cycle.

Table 56. Production cost (€/ha) of the production of cherry tomato inside greenhouses in Ragusa (Sicilia, Italy) in the season 2021/22 (ISMEA, 2023b).

Month	sep-21	oct-21	nov-21	dic-21	jan-22	feb-22	mar-22	apr-22	Average 21-22
Average yield of a cycle [kg/m^2]									**5.60**
Input costs	**37 686**	**35 473**	**35 671**	**36 567**	**38 120**	**38 867**	**41 076**	**41 615**	37 686.15
Fertilizers	*6 016*	*5 518*	*5 678*	*5 856*	*5 995*	*6 195*	*6 795*	*6 913*	6 015.96
Phytosanitary	*2 898*	*2 923*	*2 923*	*2 859*	*2 864*	*2 862*	*2 917*	*2 919*	2 898.49
Seedlings	*10 137*	*9 770*	*9 770*	*9 927*	*9 971*	*9 971*	*10 983*	*10 983*	10 136.70
Other direct costs	*8 674*	*8 521*	*8 548*	*8 714*	*8 718*	*8 771*	*8 808*	*8 808*	8 674.40
Fuels	*631*	*550*	*560*	*564*	*583*	*653*	*789*	*819*	630.98
Electric energy	*3 190*	*2 620*	*2 620*	*2 620*	*3 797*	*3 797*	*3 797*	*4 187*	3 190.40
Third party work	*6 139*	*5 572*	*5 572*	*6 027*	*6 192*	*6 619*	*6 987*	*6 987*	6 139.23
labour	**31 202**	**31 202**	**31 202**	**31 202**	**31 202**	**31 202**	**31 202**	**31 202**	31 202.00
Overheads	**3 402**	**3 402**	**3 402**	**3 402**	**3 402**	**3 402**	**3 402**	**3 402**	3 401.66
Total direct costs	**72 290**	**70 077**	**70 274**	**71 170**	**72 724**	**73 471**	**75 679**	**76 219**	**72 289.82**
Implicit costs	**10 303**	**10 303**	**10 303**	**10 303**	**10 303**	**10 303**	**10 303**	**10 303**	**10 302.59**
Total cost [€/ha]	**82 592**	**80 380**	**80 577**	**81 473**	**83 026**	**83 774**	**85 982**	**86 522**	**82 592.41**
Unitary cost [€/kg]	**1.5**	**1.46**	**1.47**	**1.48**	**1.51**	**1.52**	**1.56**	**1.57**	**1.50**

* Company located in the Ragusa district in Sicily, integrated production, up to 10 ha, multispan greenhouses with galvanized steel and plastic roofing sheets/films, cherry and datterino tomatoes, title of possession as rent, company well, 6-month production cycle.

Table 57. Production costs (€/ha) of cherry tomatoes in unheated greenhouses in Italy in the 2022/23 season, for ownership growers (ISMEA, 2024a, c).

Month	ene-22	feb-22	mar-22	abr-22	Average
Average yield of a cycle [kg/m^2]					**5.50**
Input costs	**42 163**	**43 435**	**43 967**	**44 092**	**43 414**
Fertilizers	*7 230*	*7 288*	*7 280*	*7 235*	*7 258*
Phytosanitary	*2 917*	*2 919*	*2 917*	*2 922*	*2 919*
Seedlings	*10 943*	*10 943*	*10 943*	*10 943*	*10 943*
Other direct costs	*8 858*	*8 857*	*8 999*	*9 076*	*8 947*
Fuels	*839*	*852*	*813*	*779*	*820*
Electric energy	*3 705*	*4 906*	*4 906*	*4 906*	*4 606*
Third party work	*7 671*	*7 671*	*8 109*	*8 233*	*7 921*
Labour	**32 027**	**32 027**	**32 027**	**32 027**	**32 027**
Overheads	**3 402**	**3 402**	**3 402**	**3 402**	**3 402**
Total direct costs	**77 592**	**78 864**	**79 396**	**79 521**	**78 843**
Implicit costs	**10 303**	**10 303**	**10 303**	**10 303**	**10 303**
Total cost [€/ha]	**87 895**	**89 166**	**89 698**	**89 823**	**89 146**
Unitary cost [€/kg]	**1.48**	**1.5**	**1.54**	**1.54**	**1.62**

* Company located in the Ragusa district in Sicily, integrated production, up to 10 ha, multispan greenhouses with galvanized steel and plastic roofing sheets/films, cherry and datterino tomatoes, title of possession as property, company well, 6-month production cycle.

Table 58. Production cost (€/ha) of the production of cherry tomato inside greenhouses in Ragusa (Sicilia, Italy) in the season 2022/23 (ISMEA, 2023b).

Month	sep-22	oct-22	nov-22	dic-22	Average
Average yield of a cycle [kg/m²]					**5.60**
Input costs	**43 372**	**44 290**	**44 733**	**44 859**	**44 313**
Fertilizers	*5 535*	*5 579*	*5 573*	*5 538*	*5 556*
Phytosanitary	*1 846*	*1 847*	*1 846*	*1 849*	*1 847*
Seedlings	*14 212*	*14 212*	*14 212*	*14 212*	*14 212*
Other direct costs	*13 339*	*13 338*	*13 568*	*13 693*	*13 484*
Fuels	*1 070*	*1 087*	*1 037*	*994*	*1 047*
Electric energy	*2 646*	*3 503*	*3 503*	*3 503*	*3 289*
Third party work	*4 724*	*4 724*	*4 993*	*5 069*	*4 878*
labour	**28 075**	**28 075**	**28 075**	**28 075**	**28 075**
Overheads	**13 641**	**13 641**	**13 641**	**13 641**	**13 641**
Total direct costs	**85 087**	**86 006**	**86 448**	**86 574**	**86 029**
Implicit costs	**2 425**	**2 425**	**2 425**	**2 425**	**2 425**
Total cost [€/ha]	**87 513**	**88 431**	**88 874**	**88 999**	**88 454**
Unitary cost [€/kg]	**1.51**	**1.52**	**1.56**	**1.57**	**1.58**

* Company located in the Ragusa district in Sicily, integrated production, up to 10 ha, multispan greenhouses with galvanized steel and plastic roofing sheets/films, cherry and datterino tomatoes, title of possession as rent, company well, 6-month production cycle.

12. Possibilities of implementation of TheGreefa technology in mediterranean greenhouses: Case studies

Based on the market assessment and the analysis of the greenhouse production in Spain and Italy, five case studies have been selected. The agricultural system of Almería, represents the largest concentration of greenhouses in Europe and one of the main poles of intensive agriculture in the world. A case study on water recovery and energy efficiency in greenhouses is conducted.

The Almería greenhouses represent an ideal example of the challenges of intensive Mediterranean agriculture, especially in the important areas of water and energy efficiency. For characterise the greenhouses in Almería, three case studies have been selected: unheated *Almería*-type greenhouse naturally ventilated, unheated multispan greenhouse with climate controller and multispan greenhouses heated with natural gas.

These case studies in Almería have been supported by the network of farmers' associations by the Andalusian Cooperative Society AFE to which the University of Almería is linked, through the data obtained through the survey carried out with farmers (Section 7). Three companies have also contributed to data for unheated multispan greenhouses (Biosabor SAT and Agrícola Vasán SL) and multispan greenhouse heated with natural gas (Natural Growers SAT).

The analysis of each case study take into account water, pesticides and fertilizers and energy consumption and their associated costs and environment impact. Production costs, energy, water, fertiliser and phytosanitary consumption have been measured for tomato crops in a unheated *Almería*-type greenhouse (seasons 2017/18 and 2023/24) and for unheated multispan greenhouses for tomato, pepper, cucumber and zucchini crops (seasons from 2020-21 to 2023-24) in the University of Almería-ANECOOP Experimental Station. The measured production costs in the experimental greenhouses have been compared to these of greenhouses of Almería unheated reported by the Prices and Markets Observatory of the Government of Andalusia for seasons 2021/22 and 2022/23 for 7 different alternatives of crops cycles (section 8).

To represent the production of horticultural crops in Italy, two case studies have been selected regarding the possible installation of the climate control system using absorbent salts developed in TheGreefa project: tomato production in multispan greenhouses with and without heating system.

Tomato production costs of unheated multispan greenhouses in Italy have been obtained from the data reported by the ISMEA (Section 11.2) and energy and water consumption and the associated production costs have been measured by Sfera Agricola in a commercial heated greenhouse,

A Life Cycle Impact Assessment (LCIA) has been developed estimating the main environmental impacts factors for the five case studies using the EXCEL EUPHOROS environmental simulation model (Torrellas et al., 2013). The calculated values have been compared to these reported in the bibliography.

12.1. Case Study 1 – Unheated *Almería*-type greenhouse

The first case study corresponds to greenhouses with a vertical structures made of galvanized steel tubes, with a double wire mesh as a horizontal structure on the roof (Fig. 30). These greenhouses have natural ventilation systems with very simple climate controllers and drip irrigation on "*enarenado*" sandy soil (sand mulching).

12.1.1. Production cost of unheated Almería-type greenhouse

In addition to having the data published by the government of Andalusia (Tables 45-46) and by the technical service of the financial entity CAJAMAR (Table 47) the estimation of the production cost for this type of low technology greenhouse was carry out for an experimental greenhouse of the University of Almería (Fig. 131) growing tomato in a long cycle (Table 59).

Figure 131. *Almería*-type greenhouse (a) and tomato crop in the season 2017/18 in *enarenado* sand mulching (b) and in the season 2023/24 in coconut substrate (c) in the UAL-ANECOOP Experimental Station in Almería (Spain).

The estimation of production costs is based in the following assumptions:

- It is considered as reference a modern *Almería*-type greenhouse with structure "*raspa y amagado*" (Figs. 131a) with roof and side vents, metal structure with incorporation of artificial soil and sand mulching "*enarenado*" in the season 2017/18 (Fig. 131b) and coconut substrate in 2023/24 (Fig. 131c).
- Tomato yield was measured in the season 2017/18 and 2022/23 for both tomato crops developed in an experimental greenhouse (Fig. 131b-c). Variable costs were obtained from the Experimental Farm Foundation UAL-ANECOOP where the greenhouse is located, and that are directly paid by the University of Almería.
- The price of different infrastructures and equipment have been obtained from the analysis of production cost of Almería greenhouse developed in 2015 (JA, 2015) and from the reference prices of the granting of subsidies for supporting investments in agricultural farm within the framework of the Andalusian Rural Development Program 2014-2020 (BOJA, 2020). The different cost from the season 2017/18 have been actualised in function of the general inflation in Spain and taken into account the evolution of prices of every input supplied by the Spanish Agricultural Ministry (MAPA, 2023c). The auxiliary infrastructures considered are an irrigation pond of 500 m^3 and a warehouse of 100 m^2.
- The depreciation periods for each asset item have been consider as the useful life (Table 59).
- It has been considered that all the production obtained has been sold at the average tomato price during the periods of production in seasons 2017/18 and 2022/23 (JA, 2024b).
- The cost of acquiring land is not taken into account.

The total investment cost of the greenhouse and its equipment varies between 15 and 20 €/m^2 (Table 59), being the lowest of the five cases analysed as consequence of the lower use of steel in its structure.

Table 59. Production costs of tomato cultivated measured in an *Almería*-type greenhouse in the seasons 2017/18 (costs updated to the 2022/23 season) and 2023/24, located in the Experimental Farm University of Almería-ANECOOP.

Greenhouse type	Almería-type in "*Raspa y amagado*"				
Farm area [m^2]	28 152	**Greenhouse surface [m^2]**		1 917	
Farm type	Experimental	**Location**		Almería (Spain)	
Crop specifications					
Commercial type		On vine or branch		Pears	
Variety		*Ventero*		Experimental	
Breeding company		Seminis, Sant Joan Despí		HM Clause Iberica, Almería	
Transplant – end of the crop		11/09/17 - 24/04/18		27/09/2023 - 21/03/2024	
Cycle length [days]		225		194	
Type of soil		Sand mulching "*Enarenado*"		Coconut fiber substrate	
Average marketable yield Y_{CS} [kg/m^2]		**10.8**		**6.6**	
Type of cost	**Subtype of cost**	**€/ha**			
Supplies		**24 823**		**19 127**	
Seedlings	*Seeds*	*3 900*		*4 562*	
	Nursery	*2 146*		*1 145*	
Fertilizers	*Fertilisers and manure*	*5 182*		*2 505*	
Phytosanitary	*Phytosanitary products*	*1 589*		*263*	
	Auxiliary insects	*810*		*500*	
	Auxiliary biological control	*4609*		*3 679*	
Water and Energy	*Water*	*3 453*		*2 746*	
	Electricity	*2 096*		*1 386*	
	Fuel	*0*		*0*	
Others	*Pollination hives*	*250*		*495*	
	Materials	*575*		*1 598*	
	Tools and utensils	*213*		*250*	
Transport		**2 181**		**1 153**	
Labour		**30 675**		**24 206**	
Contracted external services		**1 224**		**508**	
Total variable or direct costs, C_V [€/ha]		**58 903**		**44 994**	
Greenhouse component	**Useful life N_Y [years]**	**Cost I_C [€/ha]**	**Amortization**	**Cost I_C [€/ha]**	**Amortization**
Arenado soil - substrate	3	7 249	*2 416*	7 503	*2 501*
Greenhouse structure	15	109 186	*7 279*	113 008	*7 534*
Plastic cover	3	14 000	*4 667*	14 490	*4 830*
Insect-proof screens	10	3 898	*390*	4 034	*403*
Irrigation system	15	19 364	*1 291*	20 042	*1 336*
Irrigation pond	30	10 762	*359*	11 139	*371*
Climate controller	10	3 433	*343*	3 553	*355*
Heating systems	25	0	*0*	0	*0*
Auxiliary building	30	9 771	*326*	10 113	*337*
Investment cost [€/m^2]	**Amortization [€/ha]**	**17.8**	**17 070**	**18.4**	**17 668**
Repairs and maintenance		400		3 037	
Insurance		192		200	
Financial expenses		80		90	
Total fixed or indirect costs C_F [€/ha]		**17 743**		**20 995**	
Total cost [€/ha]		**76 645**		**65 990**	
Unitary cost [€/kg]		0.71		1.00	
Average price A_P [€/kg]		1.03		0.94	
Total value crop [€/m^2]		11.12		6.21	
Production value P_V [€/ha]		**111 240**		**62 111**	
Annual operating income I_Y [€/ha]		**34 595**		**-3 879**	

In these greenhouses, tomato production ranges between 6 and 15 kg/m^2, depending on the type of cycle. In the 2022/23 season, the prices of the different types of tomatoes ranged between 0.88 and 1.71 €/kg, above production costs between 0.52 and 0.73 €/kg, resulting in an annual profit of 51 000-102 000 €/ha. However, in some years this profit may become negative, because of the drop in sales prices. These greenhouses represent approximately 55% of the 76 600 ha recorded in Spain in 2022.

The main cost corresponds to the labour, ranging between 0.28-0.37 €/kg and similar to these reported by the Andalusian government (Table 46) and CAJAMAR (Table 47).

12.1.2. Energy and water consumption of unheated Almería-type greenhouse

Electricity and water consumption measured in both seasons were very similar (Table 60). Its electricity consumption, mainly used to operate automatically the vent openings and for the irrigation system, is about 1.0-1.5 kWh/m^2, which means a cost of 1 200-2 300 €/ha. Since they do not have heating, the total energy consumption is 35-60 GJ/ha. Water consumption for tomato cultivation varies between 30 and 34 L/kg, with a cost of 2 700-3 500 €/ha.

Table 60. Energy and water consumption measured in the experimental unheated *Almería*-type greenhouse of the University of Almeria.

Crops	Tomato 2022-23	Tomato 2023-24
Energy comspuption		
Electricity price [€/kWh]	0.143	0.132
Ventilation electrical consumption [kWh/m^2]	0.350	0.411
Total electrical consumption [kWh/m^2]	1.576	1.053
Electrical consumption [GJ/ha]	56.7	37.9
Water comspuption		
Water consumption [m^3/ha]	3 258	2 238
Water price [€/m^3]	1.06	1.23
Water requirements [m^3/t]	30.2	33.9

12.1.3. Environmental impacts of unheated Almería-type greenhouse

The total amount of steel estimated in the structure was 1 kg/m^2. We have used this value instead the weight of 8 kg/m^2 corresponding to a multispan greenhouse with the dimensions used in the LCIA model (Table 62). The consumption of phytosanitary products was reduced in the season 2023/24 as consequence of the shorted period of the crop (Table 61) and the increase of the use of auxiliary insects (Table 59). The first case study analysed, corresponding to the Almería-type greenhouse, produced the lower environmental impact as consequence of the reduced use of steel in the structure. The equivalent gas emissions ranged between 208 and 248 kg CO_2 eq/kg, very similar to these reported in the bibliography (Table 58).

Table 61. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for tomato crops in unheated *Almería*-type greenhouses or the University of Almería (UAL) and calculated by Martin-Gorriz *et al.*, 2011 (MG) and by García Martínez, 2019 (GM) by functional unit (1 tonne of marketable tomatoes).

Crops	UAL 2017-18	UAL 2023-24	MG 2011	GM 2019
Yield [kg m^{-2}]	10.80	6.61	5.13	10.00
ADP - Abiotic depletion [kg Sb eq/tn]	1.66	2.00	0.01	0.79
AAP - Air acidification [kg SO_2 eq/tn]	1.05	1.20	1.75	0.68
EUP - Eutrophication [kg PO_4eq/tn]	0.35	0.42	2.70	0.25
GWP - Global warming [kg CO_2 eq/tn]	208.79	248.18	276.8	94.4
POP - Photochemical oxidation [kg C_2H_4/tn]	0.05	0.06	-	0.03
CED - Cumulative energy demand [MJ/tn]	4 346	5 210	2 242	1 725
Water consumption [m^3/tn]	30.17	33.86	38.00	44.80

Table 62. Input values for the calculation of LCA with the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for the crops grown in the experimental unheated *Almería*-type greenhouse of the University of Almeria.

Crops	**Tomato 2022-23**	**Tomato 2023-24**
Yield [kg m^{-2}]	10.80	6.61
Plant density [plant m^{-2}]	1.0	1.0
Stems per plants [stem $plant^{-1}$]	1	1
Cultivation period [weeks]	32	28
Greenhouse structure		
Number of spans [spans]	5	5
Span width [m]	8.6	8.6
Greenhouse length [m]	44.58	44.58
Roof vent openings [unit]	3	3
Height under gutter [m]	4.15	4.15
Height of the ridge [m]	4.6	4.6
Material of greenhouse walls	Threelayer (PE-EVA-PE)	Threelayer (PE-EVA-PE)
Material of greenhouse cover	Threelayer (PE-EVA-PE)	Threelayer (PE-EVA-PE)
Greenhouse useful life [years]	25	25
Cover material useful life [years]	3	3
Walls material useful life [years]	3	3
Distance from greenhouse supplier [km]	56	56
Climte control system		
Heating systems	None	None
Energy source	-	-
Gas natural consumption [m^3 m^{-2}]	-	-
Crop system		
Type of soil	Artificial soil "*Enarenado*"	Coconut substrate
Total electricity consumption [kWh m^{-2}]	1.6	1.1
Water consumption [L m^{-2}]	325.8	223.8
Irrigation system	Drip - no recirculation	Drip - recirculation
Fertilation		
N [kg m^{-2}]	0.007	0.005
P_2O_5 [kg m^{-2}]	0.012	0.008
K_2O [kg m^{-2}]	0.017	0.011
Phytosanitary products		
Fungicides [kg m^{-2}]	0.003	0.002
Insecticides [kg m^{-2}]	0.034	0.021
Waste treatment		
Distance to landfill [km]	20	20
Distance to incinerator plant [km]	20	20
Distance to composting plant [km]	20	20
Distance to recycling centre [km]	60	60

12.1.4. Possibilities of implementation of TheGreefa technology in unheated Almería-type greenhouse

This type of greenhouse seems the least suitable for the installation of climate control systems using thermochemical fluids. Its installation presents several drawbacks:

- The lack of airtightness in the greenhouse, as consequence of the holes produced by the union of the lower and upper wire grids that hold the cover plastic in the structure (Fig. 30). Leakage airflow reduces the efficiency of active heating or cooling systems.
- The low productivity of these greenhouses and the reduced capacity of investment of the growers makes it difficult to incorporate high technology with an elevated investment cost as this proposed by TheGreefa.

- The low environmental impact of these greenhouses is difficult to be reduced incorporating new systems. To obtain a reduction of the impact it will be necessary to increase production (still unknown for the application of absorbent salts in horticultural greenhouses in warm climates) in a greater rate that the augmentation that the incorporation of the new devices and installations can produce in the emissions and consumption.

12.2. Case Study 2 – Unheated multispan greenhouses in Spain

Unheated multispan greenhouses (Fig. 132) represent around 2% of the greenhouse area in Spain. The cost of this type of greenhouse varies from 25 to 38 €/m^2.

Figure 132. Unheated multispan greenhouse in the UAL-ANECOOP Experimental Station in Almería.

Inside the unheated multispan greenhouses of the UAL (Fig. 132), ten crops were developed in the seasons 2020/21 to 2023/24 (Fig. 133). Four different combinations of short cycle crops were developed: cucumber-tomato (2020/21), cucumber-pepper (2021/22), tomato zucchini and tomato-pepper (2022/23) and tomato (autumn-winter 2023-24).

Figure 133. Crops developed in the unheated multispan greenhouse of the University of Almería: cucumber – 27/10/2020 (a), tomato – 21/05/2021 (b), cucumber – 22/09/2021 (c), pepper – 27/06/2022 (d), tomato – 28/10/2022 (e), pepper – 02/06/2023 (f), zucchini – 05/07/2023 (g), tomato – 21/02/2024 (h).

12.2.1. Production cost of unheated multispan greenhouses in Spain

In these greenhouses, productions greater than 15 kg/m^2 can be achieved, depending on the combination of crops. The production costs of the different crops and cycles vary greatly, between 0.40 and 1.5 €/kg (Tables 63-64), corresponding to 50-100 thousand €/ha. As in the previous case, in some years farmers may make losses, if depreciation costs are considered, when sales prices are low. Higher investment costs make it difficult to obtain profits if products are sold at the average price. Normally, farmers with this type of greenhouses tend to obtain better sales prices through direct contracts with distribution companies.

12.2.2. Energy and water consumption of unheated multispan greenhouses in Spain

Its electricity consumption for the windows and the fertigation system is similar to that of the previous case, 1.0-1.5 kWh/m^2 (Table 65), which represents a cost of 1 200-2 300 €/ha (Tables 63-64). As it does not have an energy consumption per heating, its value as in the previous case is reduced to 35-60 GJ/ha (Table 65). Water consumption ranges from 2000 to 5200 m^3/ha (Table 65) depending on crop combinations, for which consumption varies from 12 to 150 L/kg, with a cost of 1200-5000 €/ha.

12.2.3. Environmental impacts of unheated multispan greenhouses in Spain

As for Almería type, the structure of the greenhouse and the irrigation system generate the greatest impact. As consequence of the greater use of metal in the construction of the greenhouse, the impacts are generally higher than those of the first case, with emissions between 150 and 1000 kg CO_2 eq/tn (Table 66).

Table 66. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for tomato crops in unheated multispan greenhouses or the University of Almería (UAL) and calculated by Martínez-Blanco *et al.*, 2011 (MB) and by Torrellas *et al.*, 2012 (TR) by functional unit (1 tonne of marketable tomatoes).

Crops	UAL 2020-21	UAL 2022-23	UAL 2023-24	MB 2011	TR 2012
Yield [kg m^{-2}]	6.19	5.73	4.78	15.90	16.50
ADP - Abiotic depletion [kg Sb eq/tn]	7.92	7.60	6.63	1.06	1.26
AAP - Air acidification [kg SO_2 eq/tn]	6.54	5.95	5.31	0.94	0.92
EUP - Eutrophication [kg PO_4eq/tn]	3.71	3.40	3.01	0.35	0.50
GWP - Global warming [kg CO_2 eq/tn]	998.88	979.70	851.55	153.0	197.8
POP - Photochemical oxidation [kg C_2H_4/tn]	0.41	0.35	0.31	0.03	0.03
CED - Cumulative energy demand [MJ/tn]	19 678	18 888	16 560	2 554	3 067
Water consumption [m^3/tn]	16.85	64.28	61.61	39.11	28.78

12.2.4. Possibilities of implementation of TheGreefa technology in unheated multispan greenhouses in Spain

One of the main difficulties for the installation of TheGreefa system in unheated multispan are common to the first case, the low environmental impact of naturally ventilated greenhouses.

Some of the unheated multispan greenhouses belong to medium-sized companies with a greater capacity of investment than in the case of individual growers of Almería-type greenhouses. However, the price of each absorber at this steady of development seem to be unapproachable as climate control system to improve vegetable production.

Nonetheless, the thermochemical fluids (TCF) could be used as a security system to avoid extremes temperatures or humidity levels that can cause die of plants and auxiliary insects. In this case, a low number of absorber units (reducing investment cost) could be used for a short period of time (reducing electricity consumption).

Table 63. Production costs of crops cultivated in unheated multispan experimental greenhouses of UAL in the seasons 2020/21 and 2022/23.

Crop		**Cucumber 2020**	**Tomato 2021**	**Season 2020-21**	**Cucumber 2021**	**Pepper 2022**	**Season 2021-22**
Cycle		1/9/20 to 31/12/20	05/02/21 - 01/07/21	**Total**	10/09/21 - 13/12/21	23/02/22 - 26/07/22	**Total**
Greenhouse surface [m²]		**1 080**	**1 080**	**1 080**	**1 080**	**1 080**	**1 080**
Days of crop		113	146	259	94	153	247
Marketable yield, Y_C [kg/m²]		**9.08**	**6.19**	**15.3**	**6.37**	**1.88**	**8.25**
Supplies		**11 745**	**15 046**	**26 791**	**13 338**	**10 986**	**24 323**
Seedlings	*Seeds*	*4 083*	*3 800*	*7 883*	*4 000*	*4 015*	*8 015*
	Nursery	*750*	*862*	*1 612*	*548*	*520*	*1 068*
Fertilizers	*Fertilizers*	*1 604*	*2 304*	*3 908*	*3 816*	*2 049*	*5 865*
Phytosanitary	*Phytosanitary*	*450*	*1 061*	*1 510*	*186*	*277*	*463*
	Auxiliary insects	*2 030*	*1 780*	*3 810*	*807*	*350*	*1 157*
	Biological control	*450*	*1 390*	*1 840*	*340*	*300*	*640*
Water and Energy	*Water*	*495*	*692*	*1 187*	*2 101*	*1 891*	*3 993*
	Electrical energy	*920*	*808*	*1 728*	*797*	*897*	*1 694*
Others	*Pollination hives*	*0*	*450*	*450*	*0*	*0*	*0*
	Materials	*830*	*1 661*	*2 491*	*615*	*610*	*1 225*
	Tools and utensils	*134*	*238*	*372*	*128*	*76*	*204*
Transport		**2 339**	**2 758**	**5 096**	**2 713**	**941**	**3 654**
Labour		**13 821**	**13 341**	**27 161**	**12 093**	**14 139**	**26 232**
External services		**239**	**1 401**	**1 640**	**147**	**0**	**147**
Total variable or direct costs, C_V [€/ha]		**28 144**	**32 545**	**60 688**	**28 291**	**26 066**	**54 357**
Coconut fibre substrate		3 927	5 073	9 000	3 806	6 194	10 000
Greenhouse structure		116 970	151 130	268 100	107 328	174 693	282 021
Plastic cover		5 454	7 046	12 500	5 043	8 207	13 250
Insect-proof screens		4 319	5 581	9 900	4 235	6 894	11 129
Irrigation system		7 984	10 316	18 300	7 167	11 665	18 832
Irrigation pond		4 437	5 733	10 170	3 983	6 483	10 466
Climate controller		1 405	1 815	3 220	1 266	2 060	3 326
Auxiliary building		3 927	5 073	9 000	3 572	5 814	9 386
Total investment cost, C_I [€/m²]		**14.8**	**19.2**	**34.0**	**13.6**	**22.2**	**35.8**
Amortization costs, $C_A=C_I/N_Y$ [€/ha]		**8 453**	**10 921**	**19 374**	**7 824**	**12 734**	**20 558**
Repairs and maintenance		356	57	413	348	847	1 195
Insurance		2	223	225	8	254	261
Financial expenses		0.8	1.0	1.8	1.1	1.8	2.9
Total fixed or indirect costs, C_F [€/ha]		**8 812**	**11 202**	**20 014**	**8 181**	**13 837**	**22 018**
Total cost, T_C [€/ha]		**36 955**	**43 747**	**80 702**	**36 471**	**39 903**	**76 375**
Unitary cost, $U_C=T_C/Y_C$ [€/kg]		0.41	0.71	0.53	0.57	2.12	0.93
Average price, A_P [€/kg]		0.57	0.60	0.58	0.80	0.84	0.81
Total value crop, $P_V=A_P \cdot Y_C$ [€/m²]		5.18	3.71	8.89	5.10	1.58	6.68
Revenue of production, $P_V=A_P \cdot Y_C$ [€/ha]		**51 756**	**37 140**	**88 896**	**50 960**	**15 792**	**66 752**
Annual operating income, $I_Y=P_V-T_C$ [€/ha]		**14 801**	**-6 607**	**8 194**	**14 489**	**-24 111**	**-9 623**

Table 64. Production costs of crops cultivated in unheated multispan experimental greenhouses of UAL in the seasons 2022/23 and 2023/24.

Crop	Tomato 2022	Zuchini 2023	Season 2022-23	Pepper 2023	Tomato 2023-24
Cycle	**08/09/2022 - 13/04/2023**	28/04/2023 - 14/07/2023	**Total**	31/01/2023 - 20/07/2023	02/09/2023 - 23/02/2024
Greenhouse surface [m²]	**1 080**	**1 080**	**1 080**	**1 890**	**2 970**
Days of crop	**217**	77	294	170	174
Marketable yield, Y_C [kg/m²]	**5.73**	**0.85**	**6.58**	**2.66**	**4.78**
Supplies	**26 199**	**10 602**	**36 802**	**14 446**	**17 163**
Seeds	*3 667*	*3 495*	*7 162*	*4 300*	*4 000*
Nursery	*850*	*460*	*1 310*	*903*	*686*
Fertilizers	*8 107*	*2 640*	*10 748*	*2 834*	*3 210*
Phytosanitary	*936*	*211*	*1 147*	*239*	*351*
Auxiliary insects	*3 636*	*1 246*	*4 882*	*2 863*	*2 095*
Biological control	*1 420*	*520*	*1 940*	*650*	*510*
Water	*3 925*	*1 222*	*5 147*	*1 887*	*3 614*
Electrical energy	*1 686*	*376*	*2 062*	*770*	*1 215*
Pollination hives	*470*	*0*	*470*	*0*	*490*
Materials (plastics solarization, raffia, …)	*1 357*	*221*	*1 578*	*1 884*	*525*
Tools and utensils	**145**	*210*	*355*	*275*	*466*
Transport	**6 552**	**1 751**	**8 303**	**1 284**	**2 307**
Labour	**28 051**	**6 097**	**34 147**	**12 350**	**18 141**
External services	**493**	**184**	**677**	**135**	**508**
Total variable or direct costs, C_V [€/ha]	**61 295**	**18 634**	**79 929**	**28 215**	**38 119**
Coconut fibre substrate	7 467	2 649	10 116	4 712	6 179
Greenhouse structure	218 433	77 508	295 941	137 836	180 754
Plastic cover	10 333	3 667	14 000	6 521	8 551
Insect-proof screens	9 121	3 237	12 358	5 756	7 548
Irrigation system	14 293	5 072	19 364	9 019	11 827
Irrigation pond	7 944	2 819	10 762	5 013	6 573
Climate controller	2 534	899	3 433	1 599	2 096
Auxiliary building	7 212	2 559	9 771	4 551	5 968
Total investment cost, C_I [€/m²]	**27.7**	**9.8**	**37.6**	**17.5**	**22.9**
Amortization costs, $C_A=C_I/N_Y$ [€/ha]	**15 917**	**5 648**	**21 566**	**10 044**	**13 172**
Repairs and maintenance	676	193	869	963	2 432
Insurance	204	58	263	122	211
Financial expenses	2.0	0.6	2.5	0.5	2.0
Total fixed or indirect costs, C_F [€/ha]	**16 799**	**5 900**	**22 699**	**11 130**	**15 816**
Total cost, T_C [€/ha]	**78 094**	**24 534**	**102 628**	**39 346**	**53 936**
Unitary cost, $U_C=T_C/Y_C$ [€/kg]	1.36	2.89	1.56	1.48	1.13
Average price, A_P [€/kg]	1.51	0.26	1.35	1.51	1.14
Total value crop, $P_V=A_P \cdot Y_C$ [€/m²]	8.65	0.22	8.87	4.02	5.45
Revenue of production, $P_V=A_P \cdot Y_C$ [€/ha]	**86 523**	**2 210**	**88 733**	**40 166**	**54 492**
Annual operating income, $I_Y=P_V-T_C$ [€/ha]	**8 429**	**-22 324**	**-13 895**	**820**	**556**

Table 65. Energy and water consumption measured in experimental unheated multispan greenhouses of the University of Almeria.

Crop	Cucumber	Tomato	Total 20-21	Cucumber	Pepper	Total 21-22	Tomato	Zucchini	Total 22-23	Pepper 2023	Tomato 2023-24
Energy consumption											
Electricity price [€/kWh]	0.138	0.153	0.145	0.167	0.153	0.159	0.150	0.119	0.143	0.119	0.132
Electricity for ventilation [kWh/m²]	0.174	0.224	0.398	0.144	0.235	0.379	0.333	0.118	0.452	0.210	0.230
Total electricity [kWh/m²]	0.666	0.528	1.194	0.478	0.587	1.064	1.126	0.316	1.442	0.646	0.924
Electrical consumption [GJ/ha]	24.0	19.0	43.0	17.2	21.1	38.3	40.5	11.4	51.9	23.3	33.3
***Water consumption* [L/kg]**											
Water consumption [m³/ha]	1 143	1 043	2 185	2 408	2 833	5 242	3 683	1 171	4 854	1 809	2 945
Water price [€/m³]	0.43	0.66	0.54	0.87	0.67	0.76	1.07	1.04	1.06	1.04	1.23
Water requirements [L/kg] or [m³/t]	12.6	16.8	14.3	37.8	150.7	63.5	64.3	137.8	73.8	68.0	61.6

Table 67. Input values for the calculation of LCA with the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for the crops grown in the experimental unheated multispan greenhouses of the University of Almeria.

Crops	Cucumber	Tomato	Total 20/21	Cucumber	Pepper	Total 21/22	Tomato	Zuchini	Total 22-23	Pepper 2023	Tomato 2023-24
Yield [kg m^{-2}]	9.08	6.19	15.27	6.37	1.88	8.25	5.73	0.85	6.58	2.66	4.78
Plant density [plant m^{-2}]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Stems per plants [stem $plant^{-1}$]	1	1	1	1	2	1	1	1	1	2	1
Cultivation period [weeks]	16	21	37	13	22	35	31	11	42	24	25
Greenhouse structure											
Number of spans [spans]	3	3	3	3	3	3	3	3	3	5	8
Span width [m]	8	8	8	8	8	8	8	8	8	8-9	8-9
Greenhouse length [m]	45	45	45	45	45	45	45	45	45	45	45
Roof vent openings [unit]	3	3	3	3	3	3	3	3	3	5	8
Height under gutter [m]	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Height of the ridge [m]	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Material of greenhouse walls	Polycarbonate (PC)										
Material of greenhouse cover	Three layer (PE-EVA-PE)										
Greenhouse useful life [years]	25										
Cover material useful life [years]	3										
Walls material useful life [years]	15										
Distance greenhouse-supplier [km]	56										
Crop system											
Type of soil	Coconut substrate										
Electricity consumption [kWh m^{-2}]	0.7	0.5	1.2	0.5	0.6	1.1	1.1	0.3	1.4	0.6	0.9
Water consumption [L m^{-2}]	114.3	104.3	218.5	240.8	283.3	524.2	368.3	117.1	485.4	180.9	294.5
Irrigation system	Drip - no recirculation										
Fertigation											
N [kg m^{-2}]	0.028	0.022	0.050	0.022	0.091	0.113	0.026	0.007	0.033	0.102	0.021
P_2O_5 [kg m^{-2}]	0.030	0.022	0.052	0.023	0.093	0.115	0.027	0.007	0.034	0.105	0.023
K_2O [kg m^{-2}]	0.158	0.024	0.182	0.120	0.158	0.278	0.029	0.008	0.037	0.174	0.024
Phytosanitary products											
Fungicides [kg m^{-2}]	0.002	0.002	0.004	0.002	0.00011	0.002	0.005	0.00005	0.005	0.00013	0.004
Insecticides [kg m^{-2}]	0.102	0.291	0.393	0.102	0.00009	0.102	0.183	0.00006	0.183	0.00011	0.148
Waste treatment											
Distance to landfill [km]	20	20	20	20	20	20	20	20	20	20	20
Distance to incinerator plant [km]	20	20	20	20	20	20	20	20	20	20	20
Distance to composting plant [km]	20	20	20	20	20	20	20	20	20	20	20
Distance to recycling center [km]	60	60	60	60	60	60	60	60	60	60	60

12.3. Case Study 3 – Heated multispan greenhouses in Spain

They are made up of galvanized steel structures with natural ventilation, climate control, cultivation in substrate and heating system by means of boiler and hot water pipes. The greenhouse cover can be made up of a single sheet of plastic or a double inflated layer (Fig. 134) with the aim of reducing its thermal conductivity and reducing energy consumption. The value of the heated multispan greenhouses with its equipment varies between 45 and 55 €/m^2.

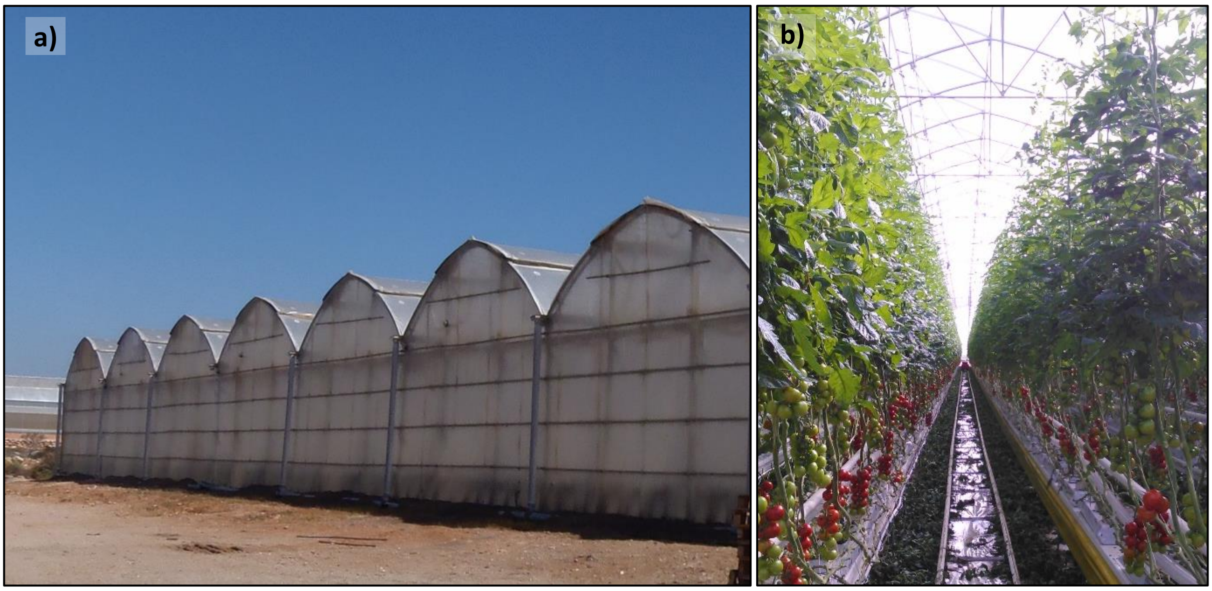


Figure 134. Heated multispan commercial greenhouse with double cover (a) and tomato crop inside (b) of the company Natural Growers in Almería.

12.3.1. Production cost of heated multispan greenhouses in Spain

In these greenhouses, production is increased to values of 8 to 21 kg/m^2, depending on the type of cycle and crop (Table 68). Heated multispan greenhouse increased the production cost by the consumption of energy and by the investment necessary in the heating system (boiler, heating pipes, pumps, insulation and control system).

The production costs of the different crops and cycles vary, between 0.8 and 2.3 €/kg, resulting in an annual profit depending on the sales prices, also very variable. In the 2022/23 season, the use of natural gas heating could generate large economic losses, for the average prices of natural gas and crops. These greenhouses represent approximately 1% of the total in Spain.

12.3.2. Energy and water consumption of heated multispan greenhouses in Spain

The consumption of electricity increased from 1.4 kWh/kg to 2.8 kWh/kg as consequence of operation of pumps for impulsion of hot water, the motors to move of thermal screens and the ventilator to inflate the double cover (Table 69). Energy consumption for heating depends a lot on the climate zone in which they are located in Spain, varying between 5 600 and 16 000 GJ/ha. In double-cover greenhouses located in Almeria, annual energy consumption was 4 632 MJ/ha, lower than in heated greenhouse of central and northern Europe (Tables 19, 21 & 22), which in the 2022/23 season meant a cost of around 72 800 € (Table 68), due to the excessive cost of natural gas.

Water consumption varies between 12 000 and 20 000 m^3/ha depending on the crops and their production, with unit values of 60 to 150 L/kg (Table 69), at a cost of 8 000-15 000 €/ha.

Table 68. Production costs 18 updated to the 2022/23 of crops cultivated in the season 2013/14 in three heated multispan greenhouses of the company Natural Growers in Almería.

Greenhouse type		Plastic multispan with inflated double cover		
Farm area [m²]		158 140		
Farm type		Commercial	**Location**	Almería (Spain)
Greenhouse surface [m²]		35 200	11 600	7 200
Crop specifications				
Crops		Cucumber	Tomato "*Cherry*"	Tomato "*Branch*"
Cycle		Long		
Cycle length [days]		280	308	308
Average marketable yield Y_{CS} [kg/m²]		**20.98**	**8.21**	**19.79**
Type of cost	**Subtype of cost**	**€/ha**		
Supplies		**107 762**	**110 164**	**111 041**
Seedlings	*Seeds*	*3 759*	*5 200*	*6 200*
	Nursery	*1 099*	*3 230*	*2 417*
Fertilizers	*Fertilizers*	*5 037*	*7 996*	*7 996*
Phytosanitary	*Phytosanitary*	*3 678*	*4 333*	*4 383*
	Auxiliary insects	*1 458*	*1 066*	*1 066*
	Biological control	*635*	*815*	*765*
Water and Energy	*Water*	*14 399*	*8 987*	*8 987*
	Electrical energy	*4 006*	*4 006*	*4 006*
	Energy for heating	*72 792*	*72 792*	*72 792*
Others	*Pollination hives*	*0*	*990*	*990*
	Materials	*690*	*610*	*1 312*
	Tools and utensils	*210*	*140*	*128*
Transport		**2 713**	**1 781**	**3 896**
Labour		**39 829**	**45 168**	**45 814**
External services		**1 147**	**520**	**1 722**
Total variable or direct costs C_V [€/ha]		**151 451**	**157 633**	**162 473**
Greenhouse component		**Initial cost I_C**	**Useful life N_Y [years]**	**Amortization**
Soil maintenance "enarenado"		10 116	5	*2 023*
Greenhouse structure		295 941	25	*11 838*
Plastic cover		14 000	3	*4 667*
Insect-proof screens		12 358	10	*1 236*
Irrigation system		19 364	25	*775*
Irrigation pond		10 762	30	*359*
Climate controller		3 433	10	*343*
Heating systems		152 000	25	*6 080*
Auxiliary building		9 771	30	*326*
Investment cost [€/m²]		**52.8**	**Amortization [€/ha]**	**27 646**
Repairs and maintenance		1 094	1 266	1 195
Insurance		2 258	2 467	1 384
Financial expenses		213	389	256
Total fixed or indirect costs C_F [€/ha]		**31 210**	**31 768**	**30 480**
Total cost, T_C [€/ha]		**182 661**	**189 401**	**192 953**
Unitary cost, $U_C=T_C/Y_C$ [€/kg]		0.87	2.31	0.98
Average price, A_P [€/kg]		0.88	1.66	0.97
Total value crop, $P_V=A_P \cdot Y_C$ [€/m²]		18.40	13.63	19.16
Revenue of production, $P_V=A_P \cdot Y_C$ [€/ha]		**184 048**	**136 341**	**191 648**
Annual operating income, $I_Y=P_V-T_C$ [€/ha]		**1 387**	**-53 059**	**-1 305**

Table 69. Energy and water consumption measured in three heated multispan greenhouses of the company Natural Growers in Almería with prices updated to the 2022/23 season.

Crop	Cucumber "*Almeria*"	Tomato "*Cherry*"	Tomato "*Branch*"
Energy consumption			
Electricity price [€/kWh]	0.143	0.143	0.143
Ventilation electrical consumption [kWh/m²]	0.242	0.242	0.242
Total electrical consumption [kWh/m²]	2.800	2.800	2.800
Electrical consumption [GJ/ha]	100.8	100.8	100.8
Natural gas price [€/m³]	0.607	0.607	0.607
Natural gas consumption [m³/m²]	11.99	11.99	11.99
Heating energy consumption [kWh/m²]	128.7	128.7	128.7
Heating energy consumption [GJ/ha]	4632	4632	4632
Water consumption			
Water consumption [m³/ha]	19 198	11 982	11 982
Water price [€/m³]	0.75	0.75	0.75
Water requirements [L/kg] or [m³/t]	91.5	145.9	60.5

Table 70. Input values for the calculation of LCA with the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for the crops grown in three heated multispan greenhouses of the company Natural Growers in Almería with organic production (without use of insecticides or fungicides).

Crops	Cucumber	Tomato (*Cherry*)	Tomato (*Branch*)
Yield [kg m⁻²]	20.98	8.21	19.79
Plant density [plant m⁻²]	1.8	1.6	1.6
Stems per plants [stem plant⁻¹]	1	2	2
Cultivation period [weeks]	40	44	44
Greenhouse structure			
Number of spans [spans]	11	7.25	4.5
Span width [m]	8	8	8
Greenhouse length [m]	200	200	200
Roof vent openings [unit]	22	14.5	9
Height under gutter [m]	4.3	4.3	4.3
Height of the ridge [m]	6.4	6.4	6.4
Material of greenhouse walls	Polycarbonate (PC)		
Material of greenhouse cover	Double Three layer (PE-EVA-PE)		
Greenhouse useful life [years]	25		
Cover material useful life [years]	3		
Walls material useful life [years]	15		
Distance from greenhouse supplier [km]	54		
Climate control system			
Heating systems	Boiler and water pipes		
Energy source	Natural gas		
Gas natural consumption [m³ m⁻²]	11.99		
Crop system			
Type of soil	Artificial soil "*Enarenado*"		
Total electricity consumption [kWh m⁻²]	2.8	2.8	2.8
Water consumption [L m⁻²]	1919.8	1198.2	1198.2
Irrigation sytem	Drip irrigation - without recirculation		
Fertigation			
N [kg m⁻²]	0.003	0.006	0.006
P_2O_5 [kg m⁻²]	0.001	0.002	0.002
K_2O [kg m⁻²]	0.019	0.028	0.028
Waste treatment			
Distance to landfill [km]	20	20	20
Distance to incinerator plant [km]	20	20	20
Distance to composting plant [km]	20	20	20

12.3.3. Environmental impacts of heated multispan greenhouses in Spain

Heating the greenhouse generates an increase in gas emissions from 200-1 000 kg CO_2 eq/tn in unheated greenhouses to 1 400-3500 kg CO_2/tn (Table 71).

Table 71. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for the crops grown in three heated multispan greenhouses of the company Natural Growers (NG) in Almería with organic production (without use of insecticides or fungicides) and calculated by Pérez Neira *et al.*, 2018 (PN) for tomato crops by functional unit (1 tonne of marketable tomatoes).

Crops	**Cucumber**	**T. *Cherry***	**T. *Branch***	**PN 2018**
Yield [kg m^{-2}]	20.98	8.21	19.79	15.30
ADP - Abiotic depletion [kg Sb eq/tn]	11.83	30.35	12.59	-
AAP - Air acidification [kg SO_2 eq/tn]	1.45	3.78	1.57	-
EUP - Eutrophication [kg PO_4eq/tn]	0.17	0.90	0.23	-
GWP - Global warming [kg CO_2 eq/tn]	1 389.7	3 568.9	1 481.2	920.0
POP - Photochemical oxidation [kg C_2H_4/tn]	0.11	0.28	0.11	-
CED - Cumulative energy demand [MJ/tn]	24 927	63 967	26 544	13 140
Water consumption [m^3/tn]	91.51	145.94	60.55	-

12.3.4. Possibilities of implementation of TheGreefa technology in heated multispan greenhouses in Spain

In these greenhouses the new climate control system based in TCF can be used instead of heating system in new greenhouses, because the need of heating in Almería it's not too big, or as complement of existing heating system in old greenhouses.

The initial investment cost of the heating system (152 000 €/ha) is comparable to the cost of the natural gas used in two years (145 600 €/ha). A reduction of about 30% in the energy used for heating, as this observed in the demonstrator of TheGreefa project installed in Switzerland, can provide a reduction of the heating cost of 22 000 €/ha per year in heated greenhouses of Almería.

12.4. Case Study 4 – Unheated multispan greenhouse in Italy

For this type of greenhouse, an investment of around 20-80 €/m^2 is required. The structure is made up of galvanised steel beams for posts, arches, horizontal braces, reinforcement reinforcements, beams and crossheads (Fig. 135). The roof covering is normally made of 180 µm polyethylene film with a duration of 36 months and the side walls are usually made of rigid plastic, with maximum heights around 5.5 m.

Figure 135. Unheated multispan commercial greenhouse (a) and tomato crop inside (b) in Italy (COSER. 2024; De Marinis, 2023).

12.4.1. Production cost of unheated multispan greenhouses in Italy

In these unheated greenhouses, tomato production is between 5 and 7 kg/m^2. Both the unit production costs (1-2 €/kg) and the sales prices (1-1.7 €/kg) are higher than those in Almeria (Table 72). As in the case of Almeria, in some years farmers may make losses, if depreciation costs are considered, when sales prices are low. These greenhouses represent approximately 70% of the total in Italy. In these greenhouses, production is not very high, so many farmers opt for high-value crops such as Cherry tomatoes. As in the case of Spain, the high investment requires farmers to ensure sales prices higher than average to avoid incurring losses.

12.4.2. Energy and water consumption of unheated multispan greenhouses in Italy

Its electricity consumption for operating the windows and the fertigation system is similar to that of greenhouses in Spain, 1.0-2.7 kWh/m^2, which represents a cost of 1000-4000 €/ha. In these unheated greenhouses, the energy consumption is 20-100 GJ/ha (Table 73). Similarly, the water consumption for tomato cultivation is around 5000 m^3/ha and 85 m^3/t, in accordance with the consumption reported in the greenhouses of Almeria, although with a cost of less than 1000 €/ha. This value is below what is necessary in Almeria, where the scarcity of water means that more energy is required to obtain it from wells or desalination, thus increasing its price.

Table 73. Energy and water consumption estimated for commercial unheated multispan greenhouses in Italy for the season 2022/23.

Energy consumption		***Source***
Electricity price [€/kWh]	0.210	ARERA (2023)
Total electrical consumption [kWh/m²]	1.9	Estimated from ISMEA (2024 a)
Electrical consumption [GJ/ha]	67	Calculated
Water consumption		
Water consumption [m³/ha]	4 570	Bacci *et al.* (2005)
Water price [€/m³]	0.25	CBTC, 2024
Water requirements [m³/t]	82.7	Calculated

Table 72. Production costs estimated for tomato cultivated in commercial unheated multispan greenhouses in Italy in the season 2022/23 (ISMEA, 2024 a-c).

Greenhouse type	Multispan		
Farm area [m^2]	100 000	**Greenhouse surface [m^2]**	10 000
Farm type	Average of commercial	**Location**	Ragusa (Italy)
Crop specifications			
Commercial type	*Cherry*	**Crop type**	Grafted
Cycle	6 months	**Cycle length**	180 days
Average marketable yield Y_{CS} [kg/m^2]			**5.55**
Type of cost	**Subtype of cost**		**€/ha**
Input costs			**40 550**
Fertilizers			*6 637*
Phytosanitary			*2 909*
Pollinators			-
Seedlings			*10 540*
Other direct costs			*8 811*
Fuels			*726*
Electric energy			*3 898*
Third party work			*7 030*
Labour			**31 614**
Overheads			**3 402**
Input costs			**75 566**
Total variable or direct costs, C_V [€/ha]			**40 550**
Greenhouse component	**Useful life N_Y [years]**	**Cost I_C [€/ha]**	**Amortization I_C/N_Y [€/ha]**
Coconut fibre substrate	3	13 585	*4 528*
Greenhouse structure	20	175 000	*8 750*
Plastic cover	3	16 400	*5 467*
Insect-proof screens	10	450	*45*
Heating system	20	0	*0*
Irrigation system	25	21 500	*860*
Irrigation pond	10	9 915	*992*
Climate controller	10	8 208	*821*
Auxiliary building	30	0	*0*
Machinery	10	10 000	*1 000*
Investment cost [€/m^2]	**Amortization [€/ha]**	25.5	*22 462*
Repairs and maintenance			-
Insurance			-
Financial expenses			-
Total fixed or indirect costs C_F [€/ha]			**10 303**
Total cost [€/ha]			**108 331**
Unitary cost [€/kg]			**1.96**
Average price A_P [€/kg]			**1.60**
Total value crop [€/m^2]			8.83
Production value P_V [€/ha]			**88 331**
Annual operating income I_Y [€/ha]			**-20 000**

12.3.3. Environmental impacts of heated multispan greenhouses in Spain

The metal structure of these multispan greenhouses generate emissions between 750 and 1200 kg CO_2 eq/tn, very close of theses reported by Cellura et al. 2012 (Table 75) and the values calculated for the same type de greenhouse in Spain (Table 66).

Table 74. Input values for the calculation of LCA with the EXCEL EUPHOROS environmental simulation model (Torrellas *et al*., 2013) for the tomato crops grown in unheated multispan greenhouses in Italy

Crops	
Yield [kg m^{-2}]	5.53
Plant density [plant m^{-2}]	2
Stems per plants [stem plant^{-1}]	2
Cultivation period [weeks]	26
Greenhouse structure	
Number of spans [spans]	12
Span width [m]	8
Greenhouse length [m]	104
Roof vent openings [unit]	12
Height under gutter [m]	4.5
Height of the ridge [m]	6.5
Material of greenhouse walls	Polycarbonate (PC)
Material of greenhouse cover	Double Threelayer (PE-EVA-PE)
Greenhouse useful life [years]	20
Cover material useful life [years]	3
Walls material useful life [years]	15
Distance from greenhouse supplier [km]	200
Climte control system	
Heating systems	None
Energy source	-
Gas natural consumption [m^3 m^{-2}]	0
Crop system	
Type of soil	Stone wool substrate
Total electricity consumption [kWh m^{-2}]	1.9
Water consumption [L m^{-2}]	457.0
Irrigation sytem	Stone wool substrate
Fertilation	
N [kg m^{-2}]	0.077
P_2O_5 [kg m^{-2}]	0.049
K_2O [kg m^{-2}]	0.149
Phytosanitary products	
	0.121
	0.016
Waste treatment	
Distance to landfill [km]	20
Distance to incinerator plant [km]	20
Distance to composting plant [km]	20
Distance to recycling centre [km]	60

Table 75. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas *et al*., 2013) for tomato grown in heated multispan greenhouses in Italy and calculated by Cellura *et al*., 2012 (CL) by functional unit (1 tonne of marketable tomatoes).

Crops	**Tomato "*Cherry*" 2022-23**	**CL - Tomato**	**CL – Tomato "*Cherry*"**
Yield [kg m^{-2}]	5.53	-	-
ADP - Abiotic depletion [kg Sb eq/tn]	5.73	-	-
AAP - Air acidification [kg SO_2 eq/tn]	4.71	5.70	9.80
EUP - Eutrophication [kg PO_4eq/tn]	3.52	2.10	3.70
GWP - Global warming [kg CO_2 eq/tn]	868.8	740.0	1 245.9
POP - Photochemical oxidation [kg C_2H_4/tn]	0.21	0.30	0.50
CED - Cumulative energy demand [MJ/tn]	14 141	16 200	23 000
Water consumption [m^3/tn]	82.64	88.90	77.70

12.4.4. Possibilities of implementation of TheGreefa technology in unheated multispan greenhouses in Italy

As for Spanish greenhouses, the TCF climate control system could be used in these unheated greenhouses as a security system to avoid extremes climate condition that put the survival of crops at risk.

12.5. Case Study 5 – Heated multispan high-tech greenhouses in Italy

These greenhouses (Fig. 136) represent approximately 20% of the surface area in Italy. The supporting structure is made of galvanized steel and the roof covering can be made of flexible or rigid sheet (polycarbonate). The side enclosures are usually made of polycarbonate with maximum heights around 6.5 m. They have a side and roof ventilation system with motorized opening by means of a climate controller with temperature probes. They have heating systems, usually using hot water supplied by boilers with natural gas, oil or even wood pellet burners. These greenhouses require an investment in structure and equipment of between 80 and 160 €/m^2.

Figure 136. Heated multispan commercial greenhouse of Sfera Società Agricola Srl (a) and tomato crop in substrate on heating pipes (b) in Italy.

12.5.1. Production cost of heated multispan greenhouses in Italy

In these greenhouses, tomato production can reach 50 kg/m^2 with production costs between 1.0 and 1.4 €/kg, resulting in an annual profit that can exceed 100 000 €/ha. In these greenhouses the cost of energy for heating represents between 20 and 40% of the total costs. The different energy sources such as gas, diesel or biomass have similar energy cost by unit of tomato produced ranging from 0.49 €/kg for the natural gas to 0.56 € for the combination of diesel fuel and wood chips (Table 76). The use of the heating system increases the unitary total cost to 1.32-1.59 €/kg. The economic risk is increased, so both profits and losses can be much greater than in unheated greenhouses. In the season 2022/23 tomato *Cherry* reached an average price of 1.65 €/kg, allowing obtain a profit in both analysed greenhouses (Table 76)

Table 76. Estimation of production costs of tomato cultivated in commercial high-tech multispan greenhouses in Italy heated with natural gas in the seasons 2013/14 (costs from Battistel, 2014 updated to the 2022/23 season) and heated with diesel and wood pellets in the seasons 2022/23 (energy measured by Sfera Agricola).

Greenhouse type		Heated multispan	
Greenhouse surface [m²]		50 000	119 232
Location		Italia	Grosseto (Italia)
Crop specifications			
Commercial type		Tomato "*Cherry*"	Tomato "*Cherry*"
Cycle length [days]		320	343
Type of soil		Stone wool substrate	Stone wool substrate
Average marketable yield Y_{CS} [kg/m²]		**50.0**	**15.0**
Type of cost		**€/ha**	
Supplies		**365 387**	**117 094**
Seedlings and nursery		13 200	*13 200*
Fertilizers		*27 500*	*27 500*
Auxiliary insects		*2 620*	*2 620*
Pollinators		*4 913*	*4 913*
Phytosanitary		*1 530*	*1 530*
Water		*2 500*	*250*
Electrical energy		*41 400*	*23 940*
CO_2 supply		*19 650*	*0*
Other Supplies		*7 074*	*7 074*
Heating energy consumption - gas		*245 000*	*0*
Heating energy consumption - diesel fuel		*0*	*36 068*
Heating energy consumption - wood		*0*	*47 325*
Transport		**11 275**	**3 383**
Labour		**149 940**	**44 982**
External services		**47 200**	**0**
Total variable or direct costs, C_V [€/ha]		**573 802**	**165 459**
Greenhouse component	**Useful life N_Y [years]**	**Cost I_C [€/ha]**	**Amortization**
Substrate	3	*13 585*	*4 528*
Greenhouse structure	20	*429 000*	*21 450*
Plastic cover	3	*16 400*	*5 467*
Insect-proof screens	10	*450*	*45*
Heating system	20	*248 900*	*12 445*
Irrigation system	25	*21 500*	*860*
Irrigation pond	10	*9 915*	*992*
Climate controller	10	*8 208*	*821*
Investment cost [€/m²]	**Amortization [€/ha]**	**74.8**	**46 607**
Repairs and maintenance		6 000	6 000
Insurance		6 000	6 000
External services		9 000	9 000
Financial expenses		21 000	5 000
Total fixed or indirect costs C_F [€/ha]		**42 000**	**26 000**
Total cost [€/ha]		**662 409**	**238 066**
Unitary cost [€/kg]		1.32	1.59
Average price A_P [€/kg]		1.65	1.65
Total value crop [€/m²]		82.7	24.8
Production value P_V [€/ha]		**826 500**	**247 950**
Annual operating income I_Y [€/ha]		**164 091**	**9 884**

12.5.2. Energy and water consumption of heated multispan greenhouses in Italy

Due to the need to pump hot water from the heating system, the total electricity consumption is 10-15 kWh/m^2 in theses greenhouses (Table 77), well above the unheated greenhouses of Spain and Italy, and much higher than the heated greenhouses of Almeria. Energy consumption for heating depends a lot on the climate zone in which they are located in Italy, varying between 5 000 and 10 000 GJ/ha, which corresponds to a cost of 100 000-250 000 €/ha. In the 2022/23 season, the use of natural gas heating rose by more than 200%.

Water consumption varies between 1 000 and 5 000 m^3/ha, with unit values of 2 to 9 L/kg, at a cost of 200-1 200 €/ha (Table 76).

Table 77. Energy and water consumption estimated for a commercial multispan high-tech greenhouses heated with natural gas and measured in a greenhouse heated with diesel and wood pellets (by Sfera Agricola) in Italy for the season 2022/23.

Heating energy source	Natural gas	References	Diesel and wood pellets
Energy consumption			
Electricity price [€/kWh]	0.276	ARERA (2023)	0.210
Total electrical consumption [kWh/m²]	15.0	Battistel (2014)	11.4
Electrical consumption [GJ/ha]	540		410
Natural gas price [€/m³]	0.980	ARERA (2023)	-
Natural gas consumption [m³/m²]	25.0	Battistel (2014)	-
Diesel fuel price [€/m³]	-	-	1.050
Diesel fuel consumption [L/m²]	-	-	3.44
Wood price [€/tons]	-	-	75.0
Wood consumption [kg/m²]	-	-	63.1
Heating energy consumption [kWh/m²]	270.8	Calculated	350.9
Heating energy consumption [GJ/ha]	9 747	Calculated	12 631
Water consumption			
Water consumption [m³/ha]	10 000	Battistel (2014)	300
Water price [€/m³]	0.25	CBTC (2024)	0.25
Water requirements [m³/t]	20.0	Calculated	2.0

12.5.3. Environmental impacts of heated multispan greenhouses in Italy

These greenhouses generate higher emissions of around 1400 kg CO_2 eq/tn. The use of biomass for heating contribute to reduce global warming emissions. However, the increase in production obtained using the natural gas can compensate the emission by functional unit, kg of tomato produced (Table 78).

Table 78. Total environmental impacts factors provided by the EXCEL EUPHOROS environmental simulation model (Torrellas *et al*., 2013) for *Cherry* tomato grown in commercial multispan high-tech greenhouses heated with natural gas and with diesel and wood pellets in Italy for the season 2022/23 by functional unit (1 tonne of marketable tomatoes).

Crops	Natural gas	Diesel and wood pellets
Yield [kg m^{-2}]	50.00	15.00
ADP - Abiotic depletion [kg Sb eq/tn]	11.79	9.72
AAP - Air acidification [kg SO_2 eq/tn]	2.50	5.16
EUP - Eutrophication [kg PO_4eq/tn]	1.16	2.01
GWP - Global warming [kg CO_2 eq/tn]	1 444.0	1 415.6
POP - Photochemical oxidation [kg C_2H_4/tn]	0.15	0.24
CED - Cumulative energy demand [MJ/tn]	25 552	24 120
Water consumption [m³/tn]	20.00	2.00

12.5.4. Possibilities of implementation of TheGreefa technology in heated multispan greenhouses in Italy

Of the five case studies analysed, heated greenhouses in Italy seem the most suitable for a possible implementation of climate control systems using thermochemical fluids. The two main arguments are its greater investment capacity and the high energy consumption required by greenhouses located in colder areas than in Almería.

The main aspects to take into account when installing the new climate control system are:

- One alternative of installation is to consider the use of TheGreefa systems for security. In this case it is not necessary to design a system to maintain optimal conditions but for avoid damage limits.
- A hight investment to maintain optimal conditions inside the greenhouse will be difficult to be compensated by un increase of production, but a minor investment can be compensated if the system prevents the loss of all the production by temperature or humidity damage in plants and fruits.
- The distribution pipes need to be placed under the plant to avoid shadow and reduction of radiation.
- Water price is low, and economy of water will have not an important impact in the production costs, but in the future water supply will be a problem, and the capacity of TheGreefa to recover a part of evapotranspiration water need to be considered.
- The continuous increase of temperature in greenhouses, mainly in Mediterranean region, will be necessary in the future new system to cooling greenhouse without the use of water evaporation.

Table 79. Input values for the calculation of LCA with the EXCEL EUPHOROS environmental simulation model (Torrellas *et al.*, 2013) for *Cherry* tomato grown in commercial multispan high-tech greenhouses heated with natural gas and with diesel and wood pellets in Italy for the season 2022/23.

Heating energy source	**Natural gas**	**Diesel and wood pellets**
Yield [kg m^{-2}]	50.00	15.00
Plant density [plant m^{-2}]	2	2
Stems per plants [stem $plant^{-1}$]	2	2
Cultivation period [weeks]	46	49
Greenhouse structure		
Number of spans [spans]	12	45
Span width [m]	8	9.6
Greenhouse length [m]	104	276
Roof vent openings [unit]	12	60
Height under gutter [m]	4.5	4.6
Height of the ridge [m]	6.5	6.8
Material of greenhouse walls	Polycarbonate (PC)	Polycarbonate (PC)
Material of greenhouse cover	Double Threelayer (PE-EVA-PE)	Double Threelayer (PE-EVA-PE)
Greenhouse useful life [years]	20	20
Cover material useful life [years]	3	3
Walls material useful life [years]	15	15
Distance from greenhouse supplier [km]	200	200
Climate control system		
Heating systems	Boiler and water pipes	Boiler and water pipes
Energy source	Natural gas	Gasoleo
Gas natural consumption [m^3 m^{-2}]	25.0	-
Diesel fuel consumption [L m^{-2}]	-	3.44
Crop system		
Type of soil	Stone wool substrate	Stone wool substrate
Total electricity consumption [kWh m^{-2}]	15	11
Water consumption [L m^{-2}]	1 000	30
Irrigation system	Drip irrigation - without recirculation	
Fertigation		
N [kg m^{-2}]	0.182	0.055
P_2O_5 [kg m^{-2}]	0.116	0.035
K_2O [kg m^{-2}]	0.355	0.106
Phytosanitary products		
Fungicides [kg m^{-2}]	0.286	0.086
Insecticides [kg m^{-2}]	0.038	0.011
Waste treatment		
Distance to landfill [km]	20	20
Distance to incinerator plant [km]	20	20
Distance to composting plant [km]	20	20
Distance to recycling center [km]	60	60

13. Final conclusions

The main problems in Mediterranean greenhouses are low temperatures and high relative humidity at night in the winter months and high temperatures and low relative humidity in the central hours of the spring-summer day. In recent years, several heat waves have been recorded that generate excessive temperatures for horticultural crops for 2-3 days.

In the unheated *Almeria*-type greenhouses, it would be difficult to implement the climate control system using absorbent salts due to the low investment capacity of these low-tech farms.

Of the different case studies analysed in Spain and Italy, the most susceptible to incorporating this type of technology would be medium-large sized companies (20-50 ha) with multispan greenhouses. Growers of these greenhouses consider that the proposed technology by TheGreefa project is of high quality and could help to control fungal diseases produced for excessive humidity inside the greenhouses.

In heated greenhouses TheGreefa could be a future alternative to the natural gas heating system, reducing environmental impact. In unheated multispan greenhouses of Spain TheGreefa climate control system could be used as a security system to avoid extreme conditions of temperature and humidity that can produce the total loss of cultivation and production, causing great economic losses.

However, grower think that there is not enough knowledge of the capacity of the system in real conditions. They also consider as the main barriers to invest in this technology the excessive cost and the difficulty in installation in their greenhouses. The farmers consulted indicated that they would be willing to make an investment of 5 000 – 15 000 €/ha with a return-on-investment period of 2- 10 years.

Annexe A - Analysis of technology and profitability of greenhouse for tomato crop - Questionnaire

A.- Personal data

Q.1 Age________________

Q.2 Years dedicated to agriculture _______

Q.3 Your relationship to the farm:

Adjacent	1
Owner	2
Tenant	3
Don't know/no answer (*DK/NA*)	15

Q.4 Education level:

None	1
Basic	2
High school graduate	3
University	4
Courses	5
Other	6
DK/NA	15

B.-Crops management

Q.5 Is a phytosanitary treatment system or substitute used?

Hormonal attractants	1
Colour attractants	2
Integrated control	3
Biological control	4
Ecological crop	5
Other (specify):	6
DK/NA	15

Q.6 Is a waste containers used?

Yes	1
No	2
DK/NA	15

Q.7 Destination of the crop waste?

Shredded for composting – Green fertization	1
Cattle	2
Dump	3
Other (specify):	4
DK/NA	15

Q.8 Are the following waste treated?

Irrigation equipment	1
Substrates	2
Chromotropic plates	3
Biological control packaging	4
Fertilizer and phytosanitary containers	5
Trellis plastic elements	6
Thermal blanket	7
Greenhouse plastic cover	8
Plastic double-roof	9
Plastic soil mulching	10
DK/NA	15

C.- Machinery and labor

Q.7 What type of machinery is used for the application of phytosanitary treatments?

Fixed Applicators	Fogging nozzles		1
	Hose + gun (hooked to a fixed pipe)		2
	Other (specify):		3
Portable Applicators	Canon		4
	Cart		5
	Backpack		6
	Treatment machine	Over-heating rails	7
		On wheels	8
	Other (specify):		9
None			10
DK/NA			15

Q.7 What types of vehicles are usually used on the farm?

Tourism	1
Van	2
All terrain	3
Truck	4
Motorcycle	5
Bicycle	6
Tractor	7
None	8
DK/NA	15

D.- Labor

Q.8 Number of workers that are usually employed on the farm?

Fixed maliy	1
Family eventual	2
Nom-family fixed	3
Eventual non-family	4
DK/NA	15

E.- Soil

Q.8 Soil type:

Indigenous natural soil	1
Sanded «*Enareanado*»	2
Perlita substrate	3
Rock wool substrate	4
Coconut fiber substrate	5
Hydroponic without substrate	6
Other	7
DK/NA	15

Q.9 For hydroponic systems, what is the substrate type?

Rockwool	1
Perlite	2
Vermiculite	3
Coconut fibre	4
Other (specify):	5
DK/NA	15

What is the system type?

Recirculating	1
Non-recirculating	2
DK/NA	15

Q.10 Is substitution of soil manure performed?

No	1
Yes	2
DK/NA	15

If so, what type of surface?

Entire surface	1
Under plants rows	2
DK/NA	15

At what frequency?

1-2 years	1
3-4 years	2
More than 5 years	3
DK/NA	15

What type?

Chicken	1
Sheep	2
Bovine	3
Compost	4
Prepared sacks	5
Other (specify):	6
DK/NA	15

E - Fertigation system

Q.11 What irrigation system is installed?

Blanket	1
Sprinkler	2
Drip	3
Hydroponic (drip + peg)	4
DK/NA	15

Q.12 Is a filter system used?:

No	1
Yes	2
DK/NA	15

Q.13 Is an irrigation controller installed?

No	1
Yes	2
DK/NA	15

Q.14 How is fertilisation performed?

Spreader	1
Venturi	2
Injectors	3
Broadcast	4
Other (specify):	5
DK/NA	15

F - Auxiliary buildings

Q.15 Auxiliary buildings:

Storage sheds	Surface _____	1
Irrigation huts	Surface _____	2
Irrigation pond	Surface _____	3
DK/NA		15

Q.16 Type of pond:

Concrete	1
Earth and plastic	2
Other	3
DK/NA	15

Q.17 Is rain water collected?

No	1
Yes, inside the greenhouse	2
Yes, outside the greenhouse	3
DK/NA	15

Q.18 Are there electricity connection in the farm?

No	1
Yes	2

DK/NA	15

Q.19 Know you the electricity consumption in the farm?

No	1
Yes	2
DK/NA	15

Q.20 Are there solar panel in the farm?

No	1
Yes	2
DK/NA	15

Q.21 Are you interested in the installation of solar panels in the farm?

No	1
Yes	2
DK/NA	15

F.- Management of the farm

Q.22 Is the product subject to a certification system or standards for agricultural field practices?

No		1
Yes	Global Gap	2
	UNE 155.000 (AENOR)	3
	Naturane (e.g., ANECOOP)	4
	Integrated production (e.g., Council of Andalucía)	5
	Ecological production	6
	Other (e.g., supermarket chains) (specify):	7
DK/NA		15

Q.23 Have you contract some insurance for the farm?

No	1
Yes	2
DK/NA	15

If so, what type of element are ensured?

Machinery	1
Crop production	2
Greenhouse structure	3
Others	4
DK/NA	15

G.- Greenhouse structure

Q.24 Number of greenhouses on the farm:

1	1
2	2
3	3
> 3	4
DK/NA	15

Q.25 Year of construction of the greenhouse (most representative): ____

Q.26 Type of property of the greenhouses:

Greenhouse in property	1
Lease	2
Partnership with the owner of the greenhouse	3
Other (specify):	4
DK/NA	15

Q.27 Type of greenhouse:

Multi-span cylindrical type	4
Multi-span gothic type	5
Venlo	6
Other (specify):	8
DK/NA	15

Q.28 Type of interior support:

Wooden supports	1
Metal tubes	2
Steel beam	3
Profile (specify dimensions):	4
Other (specify):	5
DK/NA	15

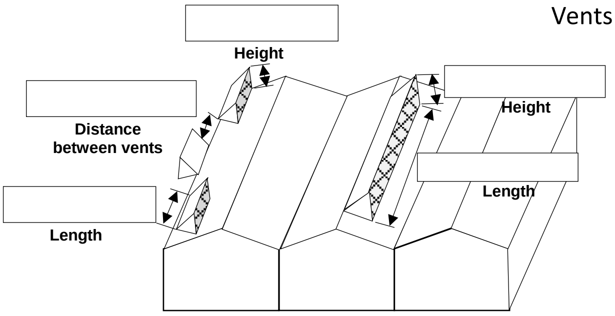
Q.29 Type of perimeter support:

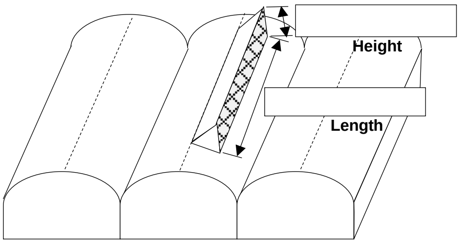
Wooden poles	1
Metal tubes	2
Steel beam	3
Profile (specify dimensions):	4
Other (specify):	5
DK/NA	15

Q.30 Type of roof ventilation installed?

Roof vents mounted alternately in all the spans	6
Single continuous ridge ventilation system in all the spans	7
Single continuous ridge ventilation system in alternating spans	8
Yes, other (specify):	9
Without roof ventilation	10
Full roof opening	11
Don't know	15

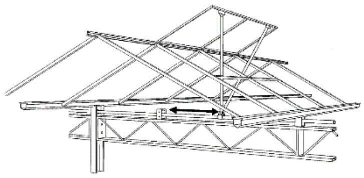
Vents dimensions:



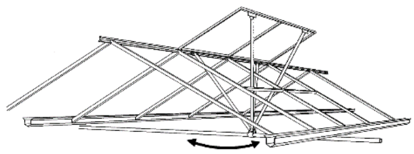


Q.31 Type of roof windows

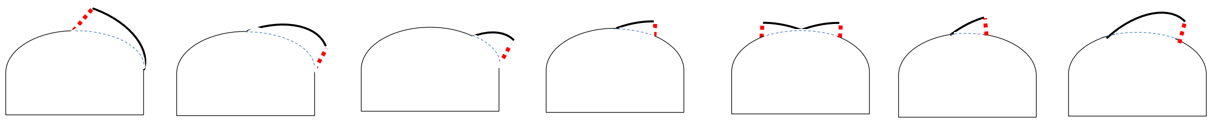
Venlo greenhouse	
Swing mechanism	1
Truss rail mechanism	2
Multispan greenhouse	
Half arch turning around the gutter	4
Half arch closing over the gutter	5
1/4 arch closing over the gutter	6
1/4 arch turning around the ridge	7
Butterfly	8
Superzenith (1/4 arch in the ridge)	9
Half arch centered	10
Other (specify):	12
Without roof ventilation	14
DK/NA	15



Truss rail mechanism for ventilation windows in a Venlo-type greenhouse



Swinging mechanism for ventilation windows in a Venlo-type greenhouse



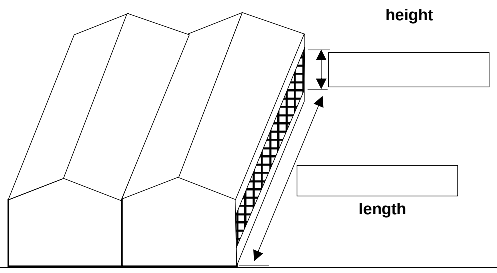
Q.32 Operation of roof windows:

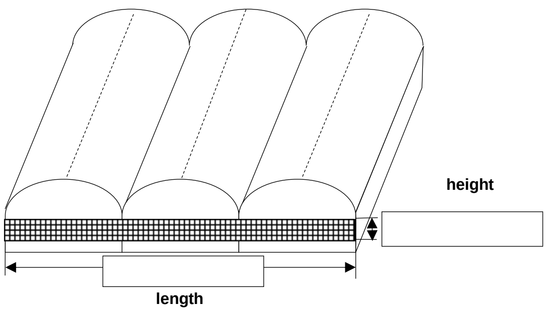
Manual	1
Semiautomatic (manually operated motor)	2
Automatic (motor operated by climate controller)	3
Fixed opening	4
Other (specify):	5
DK/NA	15

Q.33 Is side ventilation installed?

Yes, in parallel side wall to the direction of the ridge	1
Yes, in the front wall perpendicular to the ridges	2
In both	3
Other (specify):	15

Dimensions of side vents:





Q.34 Type of side vents

No side ventilation	1
Sliding lateral bands	2
Sliding window (pulleys)	3
Roll-up window	4
Folding window	5
Other (specify):	6
DK/NA	15

Q.35 Operation of side vents

Manual	1
Semiautomatic (manually operated motor)	2
Automatic (motor operated by climate controller)	3
Fixed opening	4
Other (specify):	5
DK/NA	15

Q.36 Does the greenhouse have a double door?

No	1
Yes	2
DK/NA	15

Q.37 Energy saving system:

Inflatable double wall roof	1
Inflatable double side wall	2
Inside plastic cover	3
Floating thermal blanket	4
Thermal screens	5
Other (specify):	6
DK/NA	15

Q.38 Types of insect-proof screens in the vents:

Nothing	1
Mosquito screens (10 × 16 threads/cm^2)	2
Standard screens (10 × 20 threads/cm^2)	3
Antithrip screens (15 × 30 threads/cm^2)	4
Other (indicate density): __________×_____ threads/cm2	5
DK/NA	15

H.- Climate-control systems

Q. 39 Is a climate-control system installed?

No	1
Yes	2
DK/NA	15

Q.40 What type of screen is used?

None	1
Thermal screen	2

Shading screen	3
Mixed screen (thermal and shading)	4
Other (specify):	5
DK/NA	15

Q.41 What type of forced ventilation system is installed?

None	1
Fan extractors	2
Destratification fans (interior)	3
Other (specify):	4
DK/NA	15

Q.42 What type of water evaporative cooling system is installed?

None	1
High pressure fogging (metal pipes)	2
Low pressure fogging (only water)	3
Mixed fogging compressed air + water	4
Evaporator panels and extractors (*Cooling system*)	5
Other (specify):	6
DK/NA	15

Q.43 Are other advanced climate control systems installed?

None	1
CO_2 supply plant	2
Hot air furnaces for CO_2 supply	3
CO_2 pure injection	6
Photoperiod artificial lighting	7
Photosynthetic artificial lighting	4
Other (specify):	5
DK/NA	15

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