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Achieving sustainable greenhouse cultivation

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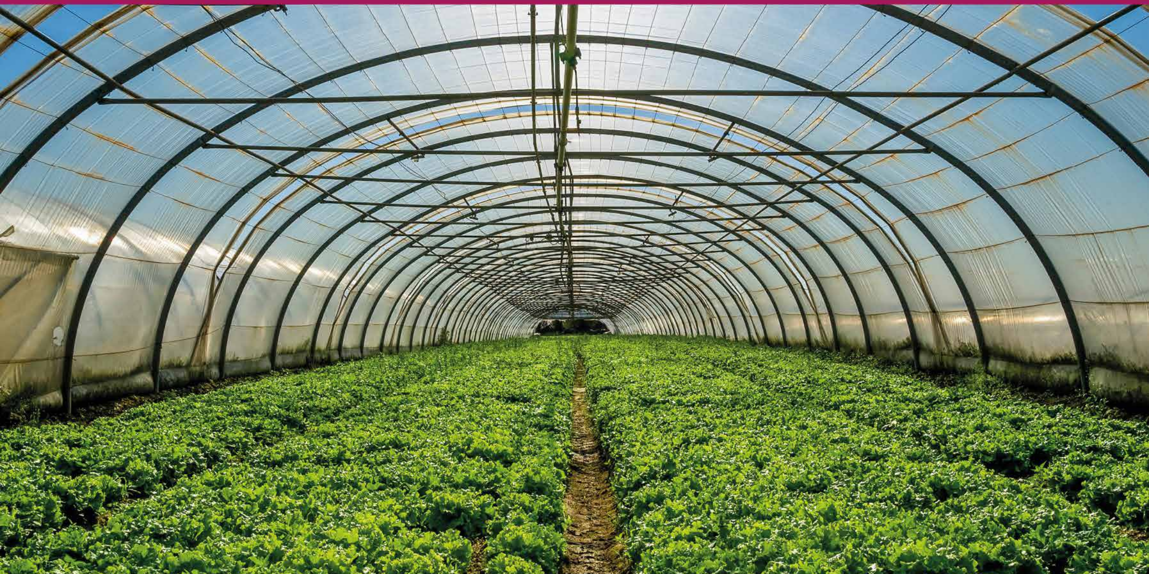

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Contents

Chapter 1

Achieving sustainable greenhouse production: present status, recent advances and future developments

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1 Introduction

The current world population of 7.7 billion is expected to reach 9.7 billion in 2050 (United Nations, 2019) and eating patterns are changing. It is anticipated that the demand for plant food will increase by 60% by 2050 (Alexandratos and Bruinsma, 2012). Furthermore, strong urbanization has already been taking place for several decades, and more than half of the world population is now living in cities. At present, there are about 33 megacities with more than 10 million inhabitants each (United Nations, 2018). Consumers are getting more interested in the quality of their food. Quality includes a good taste, nice shape and colour, good shelf life, but also refers to food safety and healthy food. The society is increasingly demanding that plants are produced sustainably. The use of fossil fuel and pesticides should be substantially reduced, and ultimately, should be abandoned. Growers need to be restrictive when using natural resources such as phosphorous for plant nutrition. These resources are not endless and can pollute the environment. Soil and water pollution with nutrients or chemicals must be prevented. Furthermore, water saving and salinization (De Pascale, this book) are important issues. Emission

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of light from supplemental lighting is considered as environmental pollution and in many places light emission is no longer accepted (e.g. the Netherlands). Also, good working conditions for employees are considered crucial. In many countries supermarkets dominate the supply chain and are requesting cheap products and are increasingly demanding guarantees on quantity, quality and sustainability of the products and the production process. Nevertheless, the risks remain largely at the side of growers, especially for those that are small and not associated.

This whole context sets demanding goals on production systems to sustainably produce crops with very high yield and quality on a limited land area, and preferably nearby urban areas. Greenhouse systems, when properly managed, improve growth conditions for plants in order to increase yield and quality and to extend the growing season. Protected cultivation, controlled environment agriculture (CEA) and greenhouse horticulture are often used as synonyms, all three terms referring to crop production systems that allow manipulation of the crop environment. Over the past 50 years the level of environment control in greenhouses has grown rapidly through increased use of technology and improved knowledge. The level of control has improved due to introduction of:

1. heating,
2. cooling or dehumidification by controlling the window opening, cooling by pad-and-fan or even mechanical cooling,
3. CO_2 supply,
4. fogging,
5. extending the photoperiod by low-intensity supplementary light or shortening by black-out screens,
6. lighting with high-intensity supplementary light to increase assimilation, initially only by HPS lamps with fixed spectrum, and nowadays also by LEDs where spectrum can be chosen,
7. biological and/or integrated pest and disease management,
8. soilless cultivation, crop growth on an artificial substrate, with a dripper for water and nutrients for each plant or plants can even be grown without any substrate.

In modern greenhouses, climate, irrigation and fertilization are often fully computer controlled. Meanwhile, automation is gradually improving labour conditions for workers and helps to reduce production costs, deal with shortage of skilled labour and so on (Van Henten, this book). The height of greenhouses has increased to create a more stable climate and to accommodate the use of technology, for example screens, lamps and hanging gutters with rooting medium, as well as to grow a taller canopy; nowadays the gutter height of newly built greenhouses is often about 6 to 7 m in the Netherlands. An increased level of technology implies higher investment costs. The economically optimal level of control depends on the type of product produced, the market segment aimed for, and also the climate and socioeconomic factors (e.g. labour skills, investment capacity of growers, policies and subsidies). This is called the adaptive greenhouse: greenhouse design based on local boundary conditions (Van Henten et al., 2006).

The effects of increasing the level of control of the production process are clearly revealed by an analysis of the statistical data on yield in the Netherlands. The annual production per unit greenhouse area (kg m^{-2}) for tomato, sweet pepper and cucumber has increased substantially over the past few decades (Fig. 1). For tomato and sweet pepper, the yield doubled in the last three decades and this increase is even more when the companies are included that use supplementary lighting. Besides the application of new technology (e.g. soilless systems, higher greenhouse transmissivity, CO_2 enrichment) and cultivation knowledge, improved cultivars (more productive, more resistant to diseases) also contributed to this yield increase. Yield of modern greenhouse

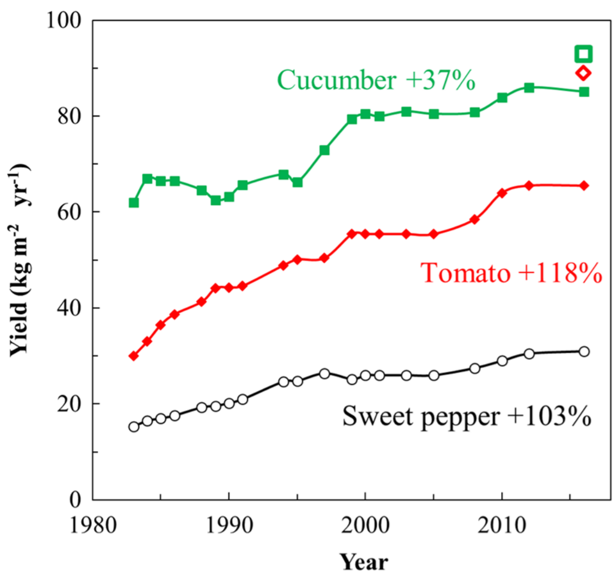

Figure 1 Average annual yields for cucumber (closed green squares), tomato harvested as individual fruits (closed red diamonds) and red sweet pepper (open black circles) in Dutch greenhouses without use of supplementary lighting. For cucumber (open green square) and tomato (large fruits on the vine; open red diamond) grown with supplementary light, the yield is also shown for the year 2016. Data were derived from annual statistical overviews as updated from De Gelder et al. (2012) with later data until 2016 (Vermeulen, 2017).

tomato cultivars (hybrids) was shown to be about 40% higher than that of old cultivars when cultivated under identical conditions (Higashide and Heuvelink, 2009). This increase was not related to a higher harvest index but rather due to increased light-use efficiency (LUE), which results in an increase in total dry matter production.

2 The state of current greenhouse horticulture

The worldwide area of greenhouses (Table 1), defined as permanent structures (so excluding simple low or high tunnels), is estimated at 473 000 ha (Hadley,

Table 1 Non-exhaustive overview of greenhouse vegetable production worldwide

Region/country	Vegetables production area (ha)	References
Asia + Oceania	*175 800*	Stanghellini et al. (2019)
China	82 000	Rabobank (2018)
South Korea	56 400	USDA (2018)
Japan	43 000[a]	MAFF (2018)
Europe	*178 000–210 000*	Stanghellini et al. (2019)/ Rabobank (2018)
Spain	70 000	Rabobank (2018)
Italy	42 800	Rabobank (2018)
France	11 500	Rabobank (2018)
The Netherlands	5 000	Rabobank (2018)
Poland	6 700	Rabobank (2018)
Américas	*16 500*	Stanghellini et al. (2019)
Mexico	16 500	Aurélio (2017)
Canada	1 560	Rabobank (2018)
USA	1 050	Hortidaily (2019)
Africa	*30 300*	Stanghellini et al. (2019)
Morocco	20 000–24 000	Freshplaza (2018), Rabobank (2018)
Near East	*74 800*	Stanghellini et al. (2019)
Turkey	41 400–45 500	Rabobank (2018), Tüzel and Öztekin (2016)
Israel	11 000	Rabobank (2018)

[a] Total greenhouse area including ornamentals and fruit crops.
Italics are aggregated values over several countries, while the non-italics are values for individual countries.
Greenhouses for ornamentals are not included, for lack of information (Hickman, 2018). However, in equatorial countries both in Africa (e.g. Kenia) and in America (e.g. Colombia) ornamentals are produced in greenhouse (usually at high elevation) for export, and the acreage can be several times over the acreage of vegetable production (Stanghellini et al., 2019).
Source: adapted from Stanghellini et al. (2019).

2017) or even at 500 000 ha (Rabobank, 2018). Europe has the largest area of greenhouses (210 000 ha), followed by Asia (180 000 ha), Africa (44 700 ha), the Middle East (27 000 ha), North-Central America (23 000 ha), South America (14 000 ha) and Oceania (1300 ha) (Rabobank, 2018). When other types of structures (e.g. low and high tunnels and Chinese solar greenhouses) are included, worldwide greenhouse area easily surpasses 3 million ha (Hadley, 2017). The expansion of global greenhouse horticulture is closely linked to the increasing use of plastic since the 1950s. On an area basis, about 90% of world's greenhouses are plastic-covered structures whereas about 10% consists of glasshouses (47 000 ha; Hadley, 2017). In China, the area covered by glasshouses is only about 1% of the total (Costa et al., 2004) but in countries such as the Netherlands it reaches 100% of the total area (9500 ha). Plastic greenhouses are the most common greenhouse type in Mediterranean countries, where greenhouse tomato is the most important crop. In many places the greenhouse area is (rapidly) increasing, be it for vegetables (e.g. Mexico, Turkey and Morocco, mainly tomato) or cut flower production (e.g. Ecuador and Colombia, Kenya and Ethiopia).

3 Sustainability

The term 'sustainability' can be defined in several ways, in essence the term points to long-term ability of systems and processes to sustain the well-being of future generations (UN World Commission on Environment and Development). Environmental impact categories typically used in a life cycle assessment (LCA) are energy use, abiotic depletion, acidification, eutrophication, global warming and photochemical oxidation (see Anton, this book). Human toxicity and aquatic toxicity are also relevant measures. Usage of resources per unit horticultural product, for example water, fertilizer, energy and land usage, can be used as indicators for sustainability.

Though there are some negative aspects (e.g. plastic waste, energy use, water and soil pollution), greenhouse horticulture can positively contribute to sustainability: higher yields per unit area which reduces land use, improved water-use efficiency, more and better options for biological control (given the closed environment) and hence less pesticide use. These aspects differ between soilless cultivation in greenhouses and soil-based greenhouse production systems. For example, water use in soilless cultivation (substrates like stone wool and NFT systems) is potentially much lower than in soil-based (conventional) systems. Whether this potential is realized depends on the irrigation strategy, the application of recirculation and the quality of the irrigation water. Soilless cultivation systems can in principle realize zero water losses, because the nutrient solutions can be recirculated (Beerling et al., 2014), although in practice 100% recirculation is often not achieved. Water and nutrient-use efficiency differs significantly between growers/greenhouses, even in the most advanced production systems. For example in the Netherlands, for the top 20% tomato growers, the discharge is almost zero, whereas for the bottom 20% tomato growers it is 746 m^3 ha^{-1} $year^{-1}$ which is about 10% of the annual overall nutrient solution used (Beerling et al., 2014). Comparing a closed versus an open soilless cultivation system, a reduction in fertilizer use per kg of product of 20% up to 78% has been observed in closed systems, without any reduction in yield or product quality (Pardossi et al., 2011; Giuffrida and Leonardi, 2012). When grown on substrates there are no specific requirements for soil quality since the growing system is separated from the soil. Hence, land unfit for soil-based production (poor soils and contaminated soils, for example because of high heavy metal or salinity levels), or land infected with soil-borne diseases can be used for production of vegetables and ornamentals on substrates.

4 Current and future trends

The beginning of this chapter describes the trend of increasing control over the production process in recent decades. We expect rapid further developments in even more precise control and automation of the production process. In this section we will briefly describe some of these developments.

There are a wide range of typologies of greenhouses, ranging from net and screen houses (Tanny, this book), solar greenhouses, low-tech greenhouses that are unheated and have simple climate control systems, to high-tech greenhouses with advanced and fully automatized climate control (Montero, this book). While in the past greenhouses were mainly found in cool climates, to protect plants from low temperatures, nowadays greenhouses are spread in all regions to protect plants from unfavourable conditions (wind, rain, hail, heat, cold). Water saving has become an important driver for expansion of the greenhouse industry, in particular in arid and semi-arid regions. To save water, collection and re-use of irrigation water is essential (De Pascale, this book), which can be most efficiently done in soilless culture, costs and the available knowhow are still a limitation for certain countries. Greenhouse production can be highly sustainable, but more investment and incentives are needed to improve sustainability and circularity (EIP-AGRI, 2019). LCA can help to guide these developments (Anton, this book).

In northern countries energy saving is still of crucial importance, even though energy efficiency has increased tremendously. In the Netherlands CO_2 emissions from greenhouse horticulture decreased from 8.1 Mton in 2010 to 5.7 Mton in 2015 (Van der Velden and Smit, 2017), and primary energy use per unit product in 2015 was 58% less than in 1990 (Van der Velden and Smit, 2017). The most important routes to save energy are (Hemming, this book):

1 maximizing the use of natural sunlight;
2 maximizing insulation;
3 efficient use of energy by different technologies and control strategies;
4 replacing fossil fuels by sustainable energy sources.

In many countries the main energy sources are fossil fuels such as natural gas and oil. Considering general changes in energy economy and policy, we expect a strong increase in the relative importance of electricity as an energy input in greenhouses. All-electric greenhouses will arise with consequences for the control of the production system.

We expect that application of new technologies will continue to rapidly expand in the next few years. The use of biological control methods (predators, parasites, antagonists etc.) is nowadays a common way to control most pests and a number of diseases in medium to high-tech greenhouses (Messelink, this book). The use of biostimulants is rapidly increasing (Dorais, this book; Mattson and Currey, this book; De Pascale, this book). In practice many positive results have been reported with respect to yield increase, disease suppression, water saving and so on, though there have also been a number of tests where the effects of biostimulants were disappointing (Dorais, this book). Our understanding of biostimulants is still in its infancy and urgently needs to be improved, in order to make full use of the potential benefits (Bulgari et al., 2015). Furthermore, more transparency is needed by companies in order to know precisely what growers are truly applying to crops.

Organic greenhouse production is still relatively small but it is an expanding segment (Dorais, this book). Organic food is gaining market share worldwide, for example in the EU (Rabobank, 2018). The share of organic fruit and vegetable sales (in total fresh fruit and vegetable sales) has already passed 10% in wealthy countries such as Switzerland, Sweden, Austria and Denmark (Fig. 2). Despite the fact that many people associate organic horticulture with a low level of technology, the opposite holds true as well. Successful organic horticulture goes often together with significant use of technology, though with regulatory limitations in some countries, for instance relating to prohibiting use of rooting media (instead of soil) or specific chemicals. In the light of major global challenges and trends, aquaponics, which combines fish production with plant production, is receiving attention within the greenhouse sector (Alsanius, this book). This parallels ongoing efforts to increase circularity.

In greenhouses crops are often grown in soilless conditions, using stone wool or peat- or coir-based substrates. Efforts are being undertaken to develop more environmentally friendly substrates (Zheng, this book). An integrated rootzone management (IRM) approach is necessary to achieve optimal

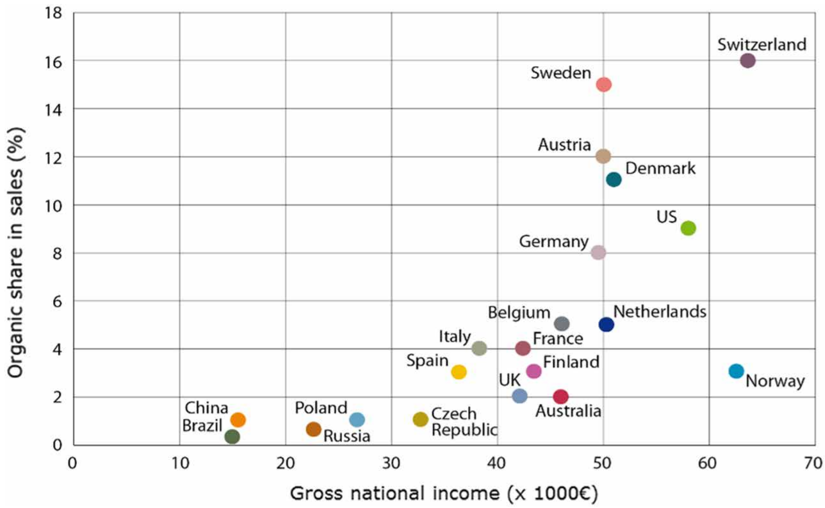

Figure 2 Share of organic fresh fruit and vegetable sales vs. gross national income in purchasing power parity, 2016 for 20 European countries. Source: reprinted from Rabobank (2018).

rootzone conditions, using in-situ rootzone sensors and artificial intelligence (Zheng, this book).

Nutrient management continues to move towards more precise nutrient applications to limit environmental nutrient loading and to enhance plant yield and quality at harvest and post-harvest stages (Mattson and Currey, this book). Precisely meeting plant nutritional needs requires an integrated approach relying on the adoption of several technologies. Greater ability to sense the nutrient solution composition, rootzone environment or plant status in real-time will allow for more agile decision making and correction of nutrient disorders before yield and quality are impaired (Mattson and Currey, this book).

In recent years there have been interesting developments with respect to light use in greenhouses (both natural and artificial light). Examples include introduction of diffuse greenhouse covers (glass, plastics) and screens which have resulted in yield increases of up to 10% (Hemming, this book). In shade-tolerant plants the use of a diffuse cover requires less shading which could increase yield by up to about 50% in anthurium (Li et al., 2014). Light transmission in greenhouses has been substantially improved over the last couple of decades (Hemming, this book). In order to improve yield and quality, and obtain year-round production, growers are making increasing use of supplemental light in greenhouses. High pressure sodium lamps are still the most commonly used light source, but rapid developments in LED technology have encouraged implementation of LED lighting in the greenhouse sector. Modern LEDs are a more energy efficient light source than high pressure sodium lamps and are an important next step in controlling growth and quality of plants. Though at present fixed light spectra are typically used, in the future dynamic illumination strategies may be adopted where the light spectrum is varied in relation to the development phase of the crop as well as in relation to other growth conditions. There are huge efforts worldwide in researching plant responses to LED lighting, and the expectation that the costs for this technology will further reduce will support a widespread implementation of LED lighting in horticulture. Recent reviews on supplementary light in greenhouse horticulture are provided by Kozai et al. (2016) and Stanghellini et al. (2019).

The availability of efficient LEDs has also boosted the development of vertical farms ('plant factories' with artificial light, PFAL) (Kozai, this book). The development of these high-tech indoor farms fits neatly into the general trend of ever-increasing control over the production process. Although there is still a lot to learn about producing crops in vertical farms, it offers a novel opportunity to produce high-value plant products. Many developments on vertical farming are expected in the coming years and differences between conventional horizontal greenhouse horticulture and vertical farming will tend to become smaller.

An integrated approach to crop growth and development and the technical aspects of greenhouse cultivation and climate management is provided by Stanghellini et al. (2019). Plant Empowerment is a new approach to growing crops in greenhouses, also known as 'Next Generation Growing' (Geelen et al., 2019). It is based on a combination of physical and physiological principles rather than practical experiences, human feelings and 'green' fingers. Plant Empowerment aims to optimize growth by supporting the plant in keeping its balances regarding energy, water and assimilates in equilibrium (Geelen et al., 2019).

Turning to our understanding of crop physiology, there is already a significant body of knowledge about plant responses to growth conditions. This knowledge often derives from single-factor experiments, where one factor is changed at a time, while other conditions are kept constant (Kubota, this book). Responses of plants to the environment are seldom linear, and show many interactions (Poorter et al., 2013). Therefore, research should not only study plant responses under constant conditions, but also analyse multiple interacting factors under fluctuating conditions (Kubota, this book; Gruda, this book; Marcelis et al., 2018). In addition, it is not only growth but other quality attributes that might also need to be improved, and which may require different optimum conditions and interact in different ways with the crop genotype (Gruda, this book). More research on optimal phenotyping of greenhouse crops will be also needed to optimize selection of the most competitive genotypes for increased resource use efficiency, yield and quality.

We expect many efforts to be made to develop autonomous greenhouses, in particular in the most technological advanced countries. In an autonomous greenhouse most of the manual work is replaced by robots and both the above-ground and below-ground climates are controlled without daily interference by the grower. Simulation models, sensors for plants and their environment (Körner, this book) will play a crucial role in autonomous greenhouses, especially by supporting more robust decision support systems (Gupta et al., 2010; Canãdas et al., 2017; Aiello et al., 2018). The whole greenhouse will be controlled from a distance, that is, the physical location of the grower controlling the greenhouse could now be far removed from the greenhouse. Despite the many challenges in replacing human labour by machines, more robots are gradually being introduced in greenhouses (Van Henten, this book). This implies machines adapted to the plants they are helping to grow, but it will also imply that plant type and also the cultivation system will be adapted to the limitations posed by the use of machines (Van Henten, this book). Artificial intelligence, machine learning and use of big data will change the way greenhouses are controlled. Low-cost sensors (e.g. for soil, plant and air) for more precise climate control will play a role as well. Imaging sensors and machine vision approaches are also expected to play an increasingly important role in supporting greenhouse climate control as well as pest and disease monitoring (Mahlein, 2016; Sun et al., 2016). An indication of the potential of artificial intelligence can be seen in the first 'Autonomous greenhouse challenge' organized by Wageningen UR Greenhouse Horticulture in 2018 where five teams each operated a cucumber greenhouse at a distance by using artificial intelligence. One of the teams managed to realize a higher net profit (income minus costs) than a manually grown system using current commercial best practice (Hemming et al., 2019).

Circularity and clustering are two issues that should be considered together. A circular economy consists in minimizing waste generation and maintaining the economic value of products, materials and resources as long as possible (http://www.circulary.eu/about/). Circular horticulture or agriculture has now become a 'hot topic' in Europe (EIP-AGRI, 2019). The sector needs to face the challenge of 'zero waste' and minimize its environmental impact. Clustering can be used to improve sustainability, resulting in large greenhouse areas, preferably located next to industries storing or producing CO_2 or waste heat (EIP-AGRI, 2019). Clusters involve two major attributes: (1) geographical/spatial distribution and (2) a sectoral dimension. In greenhouse horticulture several examples of clustering exist: Westland (the Netherlands), Almeria (Spain) (Aznar-Sánchez and Galdeano-Gómez, 2011) or the Lake Naivasha Cluster (Kenya) (Bolo, 2006). Clusters of small greenhouse growers are viable either by acting as third-party suppliers to existing large firms, and making use of latter's packing and distributional facilities, or by working within cooperatives and making use of shared packing and distribution infrastructure. This is the case in Almeria, which allows small producers to compete more effectively with large companies

(Aznar-Sánchez and Galdeano-Gómez, 2011; Hadley, 2017). Clustering may also result in gains in terms of efficiency and environmental protection by optimizing logistics and recycling procedures. Indeed, logistics costs are a major issue when talking about recycling (EIP-AGRI, 2019). Clusters can also favour innovation and cooperation between companies but the capacity and willingness of the industry to collaborate needs to improve, as well as in the sharing of big data between producers.

Traditionally, vegetables (including fruit vegetables), cut flowers and potted or bedding plants are grown in greenhouses. With the legalization of cannabis for medicinal use in a number of countries, and in some countries even for recreational use, the cultivation of this high-value crop is rapidly expanding. As consistency and reliability of the product is extremely important, this is a crop typically suited for greenhouses and vertical farms. Furthermore, greenhouses and vertical farms are in particular suited for producing crops for which a guaranteed content of specific metabolites is essential, such as for pharmaceuticals and cosmetics industries, which may become an important new market segment for the greenhouse and vertical farming sector.

5 Conclusion

Greenhouse horticulture is a sector rapidly adopting new technologies. Greenhouse production can now be characterized by its extremely high production rates of high-quality produce. On many sustainability measures, greenhouses perform very well. Nevertheless, further improvements are of utmost importance, in particular in reducing the use of fossil energy and water. The high technology nature of greenhouse production makes it one of the agricultural sectors most suited to apply rules of circularity for greater sustainability.

Modern greenhouses will gradually develop towards autonomous greenhouses with a high level of automation, use of sensors, big data analytics and artificial intelligence, where all growth factors are precisely measured and controlled in an integrated way. These developments are not just about technology, but about the interplay between technology and biology. Technology will help and advise growers who need a high level of education and technical skill to make good use of these developments.

6 Where to look for further information

Complementary information on recent and future developments can be found in the chapters of this book and in other recent and less recent references focused on the greenhouse horticulture sector worldwide (FAO, 2013; Cajamar 2016; Yang et al., 2017; Stanghellini et al., 2019).

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Index