

BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving sustainable greenhouse cultivation

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Contents

Series list		xi
1	Achieving sustainable greenhouse production: present status, recent advances and future developments <i>Leo F. M. Marcelis, Wageningen University, The Netherlands; Joaquim Miguel Costa, Universidade de Lisboa, Portugal; and Ep Heuvelink, Wageningen University, The Netherlands</i>	1
	1 Introduction	1
	2 The state of current greenhouse horticulture	4
	3 Sustainability	5
	4 Current and future trends	6
	5 Conclusion	11
	6 Where to look for further information	11
	7 References	12
Part 1 Production systems		
2	Advances in greenhouse design <i>Juan I. Montero, formerly Institut de Recerca i Tecnologia Agroalimentaries, Spain; and Yi Zhang, Qichang Yang and Xinglin Ke, Institute of Environment and Sustainable Development in Agriculture, China</i>	17
	1 Introduction	17
	2 Advances in low-tech greenhouses	18
	3 High-tech greenhouses	31
	4 Chinese solar greenhouse	37
	5 References	43
3	Advances in screenhouse design and practice for protected cultivation <i>Josef Tanny, Agricultural Research Organization - Volcani Center, Israel</i>	53
	1 Introduction	53
	2 Structures and screen materials	54

3	Microclimate under screens	58
4	Crop evapotranspiration	64
5	Water-use efficiency	67
6	Product quality	68
7	Future trends and conclusion	70
8	References	71
4	Sustainable systems for integrated fish and vegetable production: new perspectives on aquaponics	75
	<i>B. W. Alsanius and S. Khalil, Swedish University of Agricultural Sciences (SLU), Sweden; A. Tadesse, Debre Berhan University, Ethiopia; A. K. Rosberg, K. J. Bergstrand, R. Hartmann, L. Mogren, M. Alam, M. Grudén and T. Naznin, Swedish University of Agricultural Sciences (SLU), Sweden; and A. Getahun, Addis Ababa University, Ethiopia</i>	
1	Introduction	75
2	Terminology of aquaponics systems	77
3	Aquaponics system design	78
4	Flows in aquaponics systems	89
5	Assessing aquaponics systems for food safety	104
6	Assessing aquaponics systems for sustainability	108
7	Future trends and conclusion	109
8	References	111
5	Advances in organic greenhouse cultivation	121
	<i>Martine Dorais, Université Laval, Canada</i>	
1	Introduction	121
2	Expansion of organic protected cultivation around the world	124
3	Types of greenhouse used for organic cultivation	125
4	Productivity and profitability of organic greenhouse cultivation	127
5	Species and variety selection	133
6	Seeds and seedlings	133
7	Soil and soilless organic greenhouse growing systems	134
8	Fertilisation management	141
9	Biostimulants	154
10	Water management	156
11	Plant protection	157
12	Quality value of organic greenhouse products	159
13	Environmental impact of organic greenhouse cultivation	160
14	Future trends and conclusion	162
15	Where to look for further information	163
16	References	163

6	Towards sustainable plant factories with artificial lighting (PFALs): from greenhouses to vertical farms <i>Toyoki Kozai, Japan Plant Factory Association, Japan; Yumiko Amagai, Chiba University, Japan; and Eri Hayashi, Japan Plant Factory Association, Japan</i>	177
	1 Introduction	177
	2 Characteristics of PFALs	180
	3 Resource consumption by resource elements: simulation studies	185
	4 Production cost and its components	187
	5 Reducing electricity consumption and improving cost performance	188
	6 Challenges for the next-generation smart PFALs	194
	7 Future trends and conclusion	200
	8 Acknowledgements	201
	9 References	201
 Part 2 Crop management		
7	Understanding crop responses to controlled climates in greenhouses <i>Chieri Kubota, The Ohio State University, USA</i>	205
	1 Introduction	205
	2 Research towards integrative optimizations and control of aerial environmental factors in greenhouses	206
	3 Case study: intermittent night-time humidity in integration control can manage tipburn	217
	4 Conclusion and future trends	219
	5 Where to look for further information	219
	6 References	220
8	Developments in growing substrates for soilless cultivation <i>Youbin Zheng, University of Guelph, Canada</i>	225
	1 Introduction	225
	2 Materials used in forming growing substrates	226
	3 Methods and technologies for assessing growing substrates	230
	4 Use of beneficial microorganisms to create a resilient rootzone	233
	5 Integrated rootzone management (IRM)	234
	6 Future trends and conclusion	235
	7 Where to look for further information	235
	8 References	236

9	Advances in irrigation management in greenhouse cultivation	241
	<i>Stefania De Pascale, University of Naples Federico II, Italy; Luca Incrocci, University of Pisa, Italy; Daniele Massa, Council for Agricultural Research and Economics, Italy; Youssef Rouphael, University of Naples Federico II, Italy; and Alberto Pardossi, University of Pisa, Italy</i>	
	1 Introduction	241
	2 Irrigation systems	242
	3 Irrigation management strategies	252
	4 Irrigation scheduling	260
	5 Coupling crop management practices with IE	273
	6 Future trends and conclusion	275
	7 References	276
10	Advances in nutrient management in greenhouse cultivation	285
	<i>Neil S. Mattson, Cornell University, USA; and Christopher J. Currey, Iowa State University, USA</i>	
	1 Introduction	285
	2 Controlled-release fertilizers	286
	3 Water-soluble fertilizers	287
	4 Foliar fertilizers	289
	5 Organic nutrient management of container-grown crops	290
	6 Open vs closed irrigation systems	292
	7 Nutrient management of crops in soilless substrates	293
	8 Nutrient management of hydroponic crops in water culture	295
	9 The role of beneficial microbes and biostimulants in crop nutrient management	296
	10 Nutrient management to improve postharvest shelf life	298
	11 Strategies to reduce fertilizer leaching	299
	12 Monitoring and managing nutrition	300
	13 Future trends	302
	14 Where to look for further information	303
	15 References	304
11	Advances in pest and disease management in greenhouse cultivation	311
	<i>Gerben J. Messelink and H. Marjolein Kruidhof, Wageningen University and Research, The Netherlands</i>	
	1 Introduction	311
	2 History of ecologically based IPM	313
	3 Main challenges in ecologically based IPM	317
	4 Components and rationale of ecologically based IPM	318
	5 Cultural control practices	321

6	Methods to enhance the establishment of BCAs through the supplementation of resources	331
7	Curative control measures	334
8	Food web complexities in BC	336
9	Case study	338
10	Conclusion and future trends	340
11	Where to look for further information	342
12	References	343
Part 3 System management		
12	Automation and robotics in greenhouses <i>E. J. van Henten, Wageningen University and Research, The Netherlands</i>	359
1	Introduction	359
2	A crop production cycle	361
3	State of the art in automation and robotics	364
4	Analysis of state of the art in automation and robotics	366
5	Some examples of research and development in automation and robotics	367
6	Challenges and future trends	372
7	Conclusion	375
8	Where to look for further information	375
9	References	376
13	Models, sensors and decision support systems in greenhouse cultivation <i>Oliver Körner, Leibniz Institute of Vegetable and Ornamental Crops (IGZ), Germany</i>	379
1	Introduction	379
2	Greenhouses as controllable units for decision making	380
3	The decision-making process	382
4	Growers' decision tools	385
5	Models for decision support	392
6	Case studies	396
7	Future trends and conclusion	401
8	Where to look for further information	402
9	References	403
14	Assessing the impact of environmental factors on the quality of greenhouse produce <i>Nazim Gruda, University of Bonn, Germany</i>	413
1	Introduction	413
2	Greenhouse production and produce quality	417

3	Assessing the impact of light on the quality of greenhouse produce	419
4	Assessing the impact of temperature on the quality of greenhouse produce	423
5	Assessing the impact of air humidity on the quality of greenhouse produce	426
6	Assessing the impact of CO ₂ enrichment on the quality of greenhouse produce	428
7	Assessing the impact of other factors on greenhouse product quality	430
8	Conclusion	434
9	Future trends	434
10	Where to look for further information	436
11	References	436
15	Sustainable use of energy in greenhouses <i>S. Hemming, J. C. Bakker, J. B. Campen and F. L. K. Kempkes, Wageningen University and Research, The Netherlands</i>	445
1	Introduction	445
2	Maximizing natural solar energy use	447
3	Maximizing insulation	455
4	Maximizing energy efficiency by climate control	458
5	Renewable energy sources	465
6	Case studies: integral design of new energy-saving greenhouse systems	466
7	Conclusion and future trends	475
8	References	476
16	Assessing the environmental impact of greenhouse cultivation <i>Assumpció Antón, Erica Montemayor and Nancy Peña, Institute of Agrifood Research and Technology (IRTA), Spain</i>	493
1	Introduction	493
2	Greenhouse structures	498
3	Greenhouse irrigation systems	499
4	Greenhouse climate systems	501
5	Use of substrates	502
6	Fertilization	503
7	Plant protection products	504
8	Waste management	506
9	Conclusion and future trends	507
10	Where to look for further information	510
11	References	511
	Index	515

Chapter 1

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

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- 1 Introduction
- 2 The state of current greenhouse horticulture
- 3 Sustainability
- 4 Current and future trends
- 5 Conclusion
- 6 Where to look for further information
- 7 References

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

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 CO₂ 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

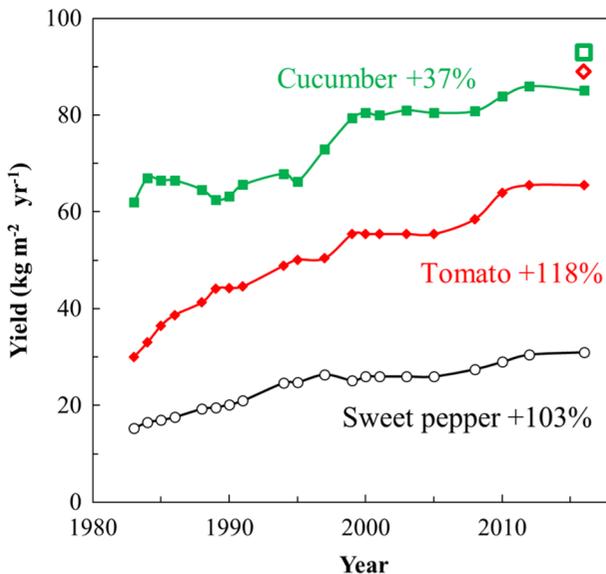


Figure 1 Average annual yields for cucumber (closed green squares), tomato harvested as individual fruits (closed red diamonds) and red sweet pepper (open black circles) in Dutch greenhouses without use of supplementary lighting. For cucumber (open green square) and tomato (large fruits on the vine; 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
<i>Asia + Oceania</i>	<i>175 800</i>	Stanghellini et al. (2019)
China	82 000	Rabobank (2018)
South Korea	56 400	USDA (2018)
Japan	43 000 ^a	MAFF (2018)
<i>Europe</i>	<i>178 000–210 000</i>	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)
<i>Américas</i>	<i>16 500</i>	Stanghellini et al. (2019)
Mexico	16 500	Aurélio (2017)
Canada	1 560	Rabobank (2018)
USA	1 050	Hortidaily (2019)
<i>Africa</i>	<i>30 300</i>	Stanghellini et al. (2019)
Morocco	20 000–24 000	Freshplaza (2018), Rabobank (2018)
<i>Near East</i>	<i>74 800</i>	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 m³ 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 CO₂ 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

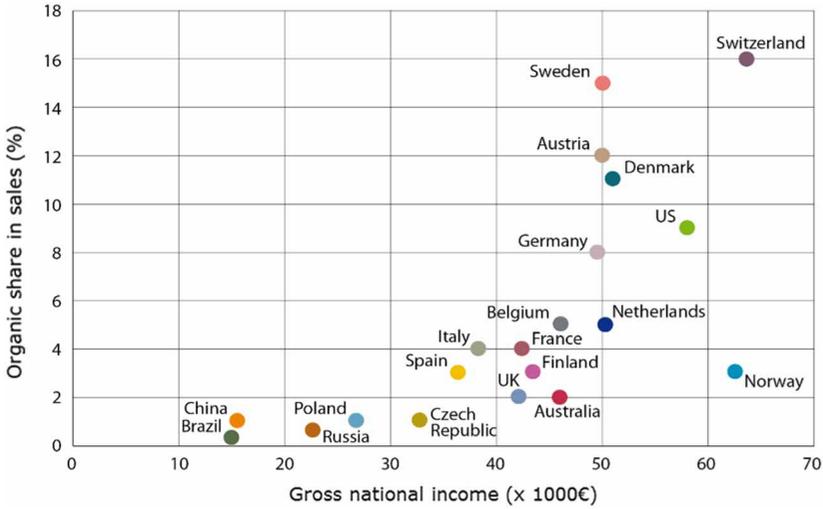


Figure 2 Share of organic fresh fruit and vegetable sales vs. gross national income in purchasing power parity, 2016 for 20 European countries. Source: reprinted from Rabobank (2018).

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; Canádas 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.circularity.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 CO₂ 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

- 1:1.5 volume extract method 232
- 1:5 volume extract method 232

- Acarodomatia 332
- The Adaptive Greenhouse 391
- Aeroponic systems 82
 - organic 140
- AGRIBALYSE® methodology 503
- Agricultural and natural organic materials, composting 228-229
- Air and leaf temperatures 206
- Air temperature and humidity 63-64
- Air velocity and turbulence 60-63
- Aluminium benches 365
- Ammonia nitrogen removal 81
- Antagonists 312
- Anthocyanin synthesis 422
- Anti-drip additives 25
- Apparent competition 337
- Apparent mutualism 337
- Aquaponics system 75-77
 - assessment, for food safety 104-108
 - assessment, for sustainability 108-109
 - flows in 89-104
 - future trends 109, 111
 - organic 141
 - system design 78-89
 - terminology of 77-78
- Artificial intelligence 10
- Artificial lighting 453-454
- Ascorbic acid synthesis 420
- Augmentative BC 316
- Automatic overhead pesticide sprayers 365-366
- Automation and robotics 359-361
 - challenges 372
 - environmental variation 372-373
 - incomplete information 373
 - object variation 372
 - task variation 373
 - variation in cultivation systems 373
- future directions 373
 - compliant actuators and end-effectors 374
 - cultivation systems modification 374
 - domain knowledge inclusion in robotic capabilities design and operation 374
 - human-robot co-working 375
 - sensing, multi-modal sensing, and active perception 374
 - research and development examples in 367-372
 - state of the art in 364-366
 - analysis of 366-367
- AWARE method 500-501
- AW. *see* Water available to the crop (AW)

- Bacterial taxa 101
- Baille equation 271, 272
- Banana screenhouse 62-63
- Banker plant method 332, 333
- BC. *see* Biological control (BC)
- BCAs. *see* Biological control agents (BCAs)
- Bench transportation systems 365
- Bioaccumulation, of heavy metals 106
- Biochar 229-230
 - amendment 147, 150
- Biochemical oxygen demand (BOD) 91
- Biodynamic farming 121
- Biofilm-based biofiltration 81
- Biofilter 77, 95
- Biofiltration 81
- Biofuels 466
- Biological control (BC) 340-341
 - food web complexities in 336-337
- Biological control agents (BCAs) 311, 319, 325

- definitions of 312
- establishment, enhancement
 - methods 331-334
 - forms of 316
- Biological food hazards 106-108
- Biostimulants 7, 154-156
- Black screens 56
- BOD. *see* Biochemical oxygen demand (BOD)
- Bot's model, adaptation of 23
- Cage culture systems 78
- Canada 125
- Canary Islands 19
- Carbon loops 97-99
- Cascade crops 260
- CEA. *see* Controlled environment agriculture (CEA)
- CFD. *see* Computational fluid dynamics (CFD)
- CFs. *see* Characterization factors (CFs)
- Characterization factors (CFs) 496, 497, 498
- Chemical control 316
 - practices 321
 - crop cultivar choice 324-325
 - fertilization 329-330
 - greenhouse (micro)climate 325-329
 - insect pests exclusion from
 - greenhouse 323-324
 - sanitation 321-323
- Chemical food hazards 105-106
- Chemical oxygen demand (COD) 91
- China 5
- Chinese solar greenhouses (CSG) 18
 - design 37-38
 - parameter model diagram of 40
 - research trends in 42-43
 - typologies 38-42
- Circular economy 10
- Climate-based method 264
- Closed greenhouse 33, 452
- Closed-loop systems 257, 259
- Clustering 10-11
- Co-culture 77
- Codex Alimentarius 104, 123
- COD. *see* Chemical oxygen demand (COD)
- Colombia 5
- Combined heat and power (CHP) 452, 460, 501, 502
- Compost 145-147, 148-149
- Computational fluid dynamics (CFD) 19, 20, 30
- Condensation 25
- Conservation BC 316
- Controlled Atmosphere Temperature Treatment 323
- Controlled environment agriculture (CEA) 379
- Controlled-release fertilizers (CRF) 286-287, 299
- Convention on Biological Diversity 340
- CRF. *see* Controlled-release fertilizers (CRF)
- Crop monitoring and crop protection 371
- Crop production compartment 81-86
- Crop production cycle 361-364
- Crop response understanding, to controlled climates in greenhouses 205-206
 - case study 217-219
 - future trends 219
 - research
 - air temperature and light intensity 206-208
 - canopy structure, canopy management and light, and diffuse light 210-212
 - CO₂ and light intensity 208-210
 - humidity, light and air circulation 212-215
 - timing and environmental control, and integrative control 215-216
- Crop rotation 322
- CROPS project 368
- Crop transpiration 35, 427, 458, 461
- CSG. *see* Chinese solar greenhouses (CSG)
- Cultural control 316
- Culture system 77
- Curative control measures 334-335
- 'Cut-off' approach 507
- Daily global radiation integrals (DGRI) 207-208
- Daily light integral (DLI) 208, 209-210, 214
- Data-based models 393, 394-396, 401
- Daylight Greenhouse 473-475
- Decay-rate method 20
- Decision support systems (DSS) 292, 302
- Decoupled aquaponics 76, 77
- Decoupled systems 86
- Deep flow technique (DFT) 77
- Deep geothermal heat 465-466
- Deep-water culture (DWC) 295
- Deficit irrigation 252-256
- Denitrification 96
- Denmark 401-402

- Depreciation cost, for cultivation system and building 192-193
 Deterministic models 394
 DFT. *see* Deep flow technique (DFT)
 DGRI. *see* Daily global radiation integrals (DGRI)
 Dielectric sensors 267-269
 Diffuse light 33, 449
 Disinfection methods, in soilless greenhouses 259-260
 Disinfection unit 78
 Dissolved organic carbon (DOC) 97
 Dissolved organic matter (DOM) 97
 Diurnal energy storage systems 451
 DLI. *see* Daily light integral (DLI)
 DOC. *see* Dissolved organic carbon (DOC)
 DOM. *see* Dissolved organic matter (DOM)
 Double-span CSG 40
 Drainage water 78
 Drip irrigation 248
 subsurface 249
 DSS. *see* Decision support systems (DSS)
 DWC. *see* Deep-water culture (DWC)
 DynaLight approach 397

 Ecuador 5
 Eddy-covariance technique 67
 Electricity-delivering greenhouses 474
 Energy sustainability 445-447, 465-466
 case studies 466-475
 efficiency maximization by climate control 458
 energy efficient cooling 461-462
 energy efficient dehumidification 462-464
 energy efficient heating 460-461
 humidity strategies 462
 next-generation cultivation strategies 464-465
 temperature strategies 459
 future trends 475-476
 insulation maximization 455-458
 of coverings 455-456
 natural solar energy use, maximizing 447-451
 solar energy conversion 451-454
 Energy use efficiency (EUE) 188-189
 Entomopathogens 312
 Environmental factors impact assessment, on greenhouse produce quality 413-414
 air humidity impact assessment 426-428
 CO₂ enrichment impact assessment 428-430
 future trends 434-436
 greenhouse production and produce quality 417-419
 growing techniques and cultural practices impact assessment 433
 intrinsic and extrinsic quality characteristics 417
 light impact assessment 419-423
 maturity and ripeness stage at harvest impact assessment 433-434
 product quality definition 414-416
 root environment impact 430-432
 temperature impact assessment 423-426
 Environmental impact assessment, of greenhouse cultivation 493-498, 503-507
 future trends 507-510
 goal and scope of study 494
 greenhouse climate systems 501-502
 greenhouse irrigation systems 499-501
 greenhouse structures 498-499
 substrates use 502-503
 Ethiopia 5
 EUE. *see* Energy use efficiency (EUE)
 EU Framework Directive 320
 European Commission Nitrates Directive 124
 Evaporative cooling systems 461
 Evapotranspiration 64-67, 265-269
 Excessive humidity 34
 External movable screens 27

 Far-infrared radiation (FIR) 26, 455
 losses, reducing 26-28
 Fertilisation management 141, 503-504
 nutrient-crop demand 142
 nutrient supply 142-145
 soil nutrient balance 141-142
 soil organic amendments and fertilisers 145-154
 Finland 446, 453
 FIR. *see* Far-infrared radiation (FIR)
 Fish and horticultural crop production, combined systems for 86-89
 Fish compartment 78-80
 Fish tank effluent 78
 Flap roof vents 21
 Flooded systems 250-251
 Flux-variance technique 67

- Foliar fertilizers 289
Forced ventilation 461
France 446, 453
Free-drain systems, strategies to optimize 252-257
Fresnel lens greenhouse 474-475
Fully automatic in-row pesticide sprayers 365
Functional unit (FU) 494
Fungi 101
FU. *see* Functional unit (FU)
- Generalist predators 312
Gerbera evapotranspiration case study 270
Germany 453
Glass greenhouse 499
Grafting robot 365
Greenery Energy Audit Tool 391
Greenhouse design advances. *see* Chinese solar greenhouses (CSG); High-tech greenhouses; Low-tech greenhouses
Greenhouse Energy Auditing Tool 397
Greenhouse thermal inertia, increasing 28-29
Greenmod 391
Gripping technology, robotic 374
- Heat treatment 259
Herbivores 337
High-pressure sodium (HPS) lamps 454
High-tech aquaponics 88-89
High-tech greenhouses 18, 31-35
 research trends in 35-37
High-tunnel greenhouses 57
Horizontal light distribution 449
HORTEX expert system 390
HPS. *see* High-pressure sodium (HPS) lamps
Hydroponics 75, 81-82, 124
 organic 140
Hyperpredation 336
- IFOAM. *see* International Federation of Organic Agricultural Movements (IFOAM)
Impermeable screens 27
Importation BC 316
Infrared thermal cameras 273
Inoculative BC 316
Insect-proof screenhouses 25, 55, 56, 59, 62, 323-324
Insect screens. *see* Insect-proof screenhouses
- In situ* measurements 20
Integrated pest management (IPM) 311-313
 case study 338-339
 challenges in ecologically-based 317-318
 components and rationale of ecologically-based 318-321
 future trends 340-342
 history of ecologically-based 313-317
 see also Biological control agents (BCAs); Chemical control
Integrated rootzone management 234-235
Intercropping systems 94
International Federation of Organic Agricultural Movements (IFOAM) 122
International Organization for Biological Control (IOBC) 340
Intraguild predation 336
Inundative BC 316, 334-335
IOBC. *see* International Organization for Biological Control (IOBC)
Ion-selective electrodes (ISE) 292-293
Irrigation efficiency 246
Irrigation management, advances in 241-242
 crop management practices coupled with IE 273-275
 future trends 275-276
 scheduling 260-261
 crop evapotranspiration direct determination 265-269
 irrigation turn and irrigation frequency 264-265
 irrigation volume determination 261-264
 modelling in greenhouse 269-273
 strategies 252-260
 systems
 microirrigation 246-249
 reference characteristics 242-246
 subirrigation 249-251
ISE. *see* Ion-selective electrodes (ISE)
Iseki crop-monitoring robot 371
ISO Cutting and Planting 1800 365
- Japan 186, 187
Japan Plant Factory Association 187
KASPRO simulation model 390
Kenya 5

- Labour cost 192
- LCA. *see* Life cycle assessment (LCA)
- LCIA. *see* Life cycle impact assessment (LCIA)
- LCI. *see* Life cycle inventory (LCI)
- Leaching fraction control 256-257
- Leaf area index (LAI) 210-211, 272
- Leaf removal, in high-wire grown cucumbers and tomatoes 369-370
- Leaf thickness approach 272
- LED. *see* Light-emitting diodes (LED)
- Lennard approach 87
- Life cycle assessment (LCA) 493-494
- Life cycle impact assessment (LCIA) 496-498
- Life cycle inventory (LCI) 494-496
- Light-emitting diodes (LED) 8-9, 420, 421, 454
- Light transmission 447-449
of low-tech greenhouses 23-25
- Long wave radiation 58
- Low-emissivity glasses 27-28
- Low-tech aquaponics 88
- Low-tech greenhouses 18
advances in 18-29
future trends in research on 29-31
- Low-tunnel greenhouse 499
- Lycopene analysis, need for 432
- Mathematical-deterministic models 394
- Mat roller, types of 41-42
- Mat systems 251
- Mechanistic-deterministic crop models 394
- Mechanistic explanatory models 393
- Mexico 5, 125
- Microbial loops 99-101
beneficial microorganisms 103-104
fish pathogens 101-102
human pathogens 103
plant pathogens 102-103
- Microfiltration 245
- Mini- and microsprinklers 248
- Mobile growing systems 365
- Model-based decision support systems and sensors 379
applications 392-393
case studies 396
boundary layer and greenhouse microclimate model prediction 396-397, 398-399
model-based planning tools for energy management 397, 400
models for early detection and stress control 399, 401
decision-making process
decision support targets 384-385
decisions by climate controller 385
greenhouse management systems 382-384
future trends 401-402
greenhouses as controllable units for decision making
climate control 381-382
energy management 381
structures and equipment 380
growers' decision tools
greenhouse planning tools 390-392
tool types 385-386
types 394-396
- Moisture retention curve (MRC) 262
- Morocco 5
- MRC. *see* Moisture retention curve (MRC)
- Mulching 28
- Multitrophic water-based culture systems 76
- Multi-tunnel greenhouse 499
- Municipal organic waste materials, composting 227-228
- Nagoya Protocol 340
- Natural BC 316
- Natural ventilation 19-22
- Near-infrared radiation (NIR)
transmission 450-451
- The Netherlands 3, 6, 10, 31, 32, 35, 186, 360, 362, 402, 446, 449, 453, 461, 466, 472-474
- Next Generation Growing. *see* Plant empowerment
- NFT. *see* Nutrient film technique (NFT)
- NIR. *see* Near-infrared radiation (NIR)
transmission
- Nitrification 95
- Non-supervised optimal control algorithms 385
- N-S oriented greenhouses 24
- Nutrient amendments 150-152
- Nutrient film technique (NFT) 77, 109, 295
- Nutrient management 285-289, 292-293, 296-298
container-grown crops organic nutrient management 290-291
of crops, in soilless substrates 293-295
fertilizer leaching reduction strategies 299-300
future trends 302-303

- of hydroponic crops in water
 - culture 295-296
- to improve postharvest shelf life
 - 298-299
- monitoring and 300-302
- Nutrient solution 78
- Octinion company 370
- Omnivorous predators 312, 338-339
- One-loop aquaponics 76, 77
- One-step approach 269
- Open vs closed irrigation systems 292-293
- Operationalization Life Cycle Assessment of
 - Pesticide emissions 505
- Organic greenhouse cultivation 121-123, 134-159
 - environmental impact of 160-161
 - expansion, worldwide 124-125
 - future trends 162-163
 - greenhouse types and 125-127
 - productivity and profitability of 127-133
 - quality value of products 159
 - seeds and seedlings 133-134
 - species and variety selection 133
 - specifics of 123-124
- Organic N in soil solution and plant uptake,
 - for organic crops 152-153
- Ozone, addition of 259-260
- Parasites 101
- Parasitoids 312
- Parral* greenhouse 499
- PAR. *see* Photosynthetic active radiation (PAR)
- Partial root drying (PRD) 253, 256, 432
- Particulate organic matter (POM) 97
- Passive greenhouses, night-time climate
 - improvement in 25-29
- Passive solar energy systems 451
- Pen culture systems 78
- Penman-Monteith model 65-66
- PE. *see* Polyethylene (PE)
- Pest and disease management. *see*
 - Integrated pest management (IPM)
- Pest-in-first method 331
- PFALs. *see* Plant factories with artificial lighting (PFALs)
- PGPB. *see* Plant growth-promoting bacteria (PGPB)
- pH 153
- Pharmaceutical and personal care products
 - (PPCP) 106
- Phenotyping and machine learning,
 - combining 395
- Photo-selective cover films 423
- Photo-selective screens 57
- Photosynthetic active radiation (PAR) 206, 207, 209, 447
- Photosynthetic photon flux density (PPFD) 188, 190
- Physical sensors 387
- Phytotoxic substances, accumulation of 260
- PicknPack EU project 371, 372
- Planning tools 386
- Plant biostimulants 274-275
 - beneficial microbes and, in crop nutrient management 296-298
- Plant empowerment 9
- Plant factories with artificial lighting (PFALs) 177
 - algorithms for optimal set of set points for environmental factors 199
 - applications of 200
 - challenges and key technologies 194
 - characteristics
 - components of 180-181
 - potential and actualized benefits 181-184
 - risk management 185
 - core technology 195-196
 - cost performance
 - affecting factors and economic value of produce 191-194
 - definition of 191
 - expected improvement of 193-194
 - electricity consumption affecting factors and possible reduction 188-190
 - electricity cost affecting factors 190-191
 - future trends 200-201
 - phenotyping unit 196, 198
 - plant traits suited for production 198-199
 - production cost and components 187-188
 - recent advanced technologies 180
 - resource consumption by resource elements 185-186
 - smart LED lighting system 200
 - subsystems, to be developed 196, 197
- Plant grafting 154
- Plant growth-promoting bacteria (PGPB) 298
- Plant maintenance operations (PMOs) 362, 366
- Plant phenotyping 196

- Plant production systems, types of 178-179
- Plant protection 157-159
- Plant protection products (PPPs) 504-506
- Plant stress sensing 272
- Plant water status, methods based on 272-273
- PM model 270
- PMOs. *see* Plant maintenance operations (PMOs)
- Polyculture 77
- Polyethylene (PE) 33, 55
- POM. *see* Particulate organic matter (POM)
- Pond culture systems 78, 80
- Porous screens 54, 60
- Pour-through method 232, 301
- PPCP. *see* Pharmaceutical and personal care products (PPCP)
- PPFD. *see* Photosynthetic photon flux density (PPFD)
- PPPs. *see* Plant protection products (PPPs)
- PPS Smart materials project 36
- PRD. *see* Partial root drying (PRD)
- Predators 312
- Prediction accuracy and models 393
- Priva company 370
- Priva Kompano leaf removal robot 370
- Prophylactic calendar spraying 316
- Pruning and training, importance of 433
- PV modules, use of 465
- Raceway culture systems 80
- Radiation 58-60
- Radiation use efficiency (RUE) 23
- Rakocy feeding rate ratio 87
- RAYPRO ray-tracing model 466-467
- RDI. *see* Regulated deficit irrigation (RDI)
- Real-time support tools 386, 387-390
- Recirculating culture systems 80
- Regulated deficit irrigation (RDI) 253, 432
- Renewable energy sources 465-466
- Resource use efficiency 181-182, 183
- Rhizosphere microbiome 333
- RomboMatic 364-365
- Rooftop greenhouse (RTG) 23, 36-37
- Root ventilation 21
- Root cooling 426
- RTG. *see* Rooftop greenhouse (RTG)
- RUE. *see* Radiation use efficiency (RUE)
- Salinity management 153-154
- Salt tolerance 256, 258
- Sap flow system 273
- Saturated media extract method 232
- Scale model studies 20
- Screen cover 55
- Screenhouse design and practice advances, for protected cultivation 53-54, 64-68
- future trends 70-71
- microclimate under screens 58-64
- product quality 68-69
- structures 54-55
- types, colours, and screen textures 55-57
- Screen strips 54-55
- Semi-closed greenhouses 33-35
- Semi-closed system 257, 259
- Sensor and gravimetric-based method 264
- Settleable solids 80
- Shading, significance of 461
- Shading screens 56-57
- Side wall ventilation 21
- Single-factor experiments 9
- Slow-release system 332
- Slow sand filtration 259
- SmartGrid approach 397
- SmartPackr technology 372
- SMSs. *see* Soil moisture sensors (SMSs)
- Soft sensors 386, 387-390
- Soil anaerobic disinfection 158
- Soil biofumigation 158
- Soil disinfection 322
- Soil growing systems
- agroecological service crops 135-136, 137-138
- crop rotation 136
- organic system 134-135
- soil properties 135
- Soilless cultivation, developments in growing substrates for 225-226
- beneficial microorganisms to create resilient rootzone 233-234
- future trends 235
- materials used 226-230
- methods and technologies to assess 230-231
- biological tests 233
- chemical property measurement 231-233
- physical property measurement 231
- Soilless growing systems 431
- advantages of 136, 139
- aquaponics 141
- growing systems 139-140
- hydroponics 140-141

- Soil moisture sensors (SMSs) 267
 Soil saturated extract (SSE) 256-257
 Soil solarisation 158
 Soil steaming 158
 Solarization 322
 Solid hydroponics 81
 Sorting and packing 371-372
 Spain 10, 18-19
 Speaking plant method 264
 Specialist predators 312
 Sprinkler irrigation 330
 SSE. *see* Soil saturated extract (SSE)
 Standing army approach 331, 336
 Stationary cultivation systems 365
 Steam disinfection 322
 Strawberry harvesting 370
 Sub-irrigation 330
 Sunery Greenhouse 471-473
 Surface renewal 66-67
 Suspended solids 80
 Sustainable greenhouse production 1-4
 current and future trends in 6-11
 current greenhouse horticulture state 4-5
 sustainability 5-6
 Sustainable plant production systems, requirements of 177-178
 Sweden 186
 Sweet pepper harvesting and automation 368-369
 Synthetic biodegradable materials and recyclable materials, developing 230
 Tank culture systems 78
 Temperature integration 216
 Tensiometers 267
 TES. *see* Thermal energy storage (TES)
 Thermal energy storage (TES) 35
 Thermal management, by shading 208
 Thermal screens 26, 32, 457-458
 Thermal window 326
 Thorvald robot 371
 Threshold-based application 316
 timer-based method 264-265
 Tipburn 212-215
 intermittent night-time humidity in integration control to manage 217-219
 Trophic loops
 nitrogen 94-96
 nutrients 92-94
 Trough systems 251
 Turkey 5, 130
 Two-step approach 269
 UAE. *see* United Arab Emirates (UAE)
 Ultraviolet B (UV-B) radiation 422-423
 Unit economic value and sales, affecting factors 193
 United Arab Emirates (UAE) 186
 United Kingdom 130
 United States 125
 USEtox model 505
 US National Organic Program 290
 U-value 456, 457, 458
 UV-B. *see* Ultraviolet B (UV-B) radiation
 UV radiation 259
 Vapour pressure deficit (VPD) 63-64, 191, 426-427
 Vegetable grafting 273-274
 Venlo-type glasshouses 31-33, 35
 VenloEnergy Greenhouse 469-471
 Vertical light penetration 449
 Viral diseases 102
 The Virtual Greenhouse 391
 Virtual Grower 391
 VPD. *see* Vapour pressure deficit (VPD)
 Waste management 506-507
 Water available to the crop (AW) 261-262
 Water-filled polyethylene sleeves 29
 Water loop 89-90
 electrical conductivity 92
 oxygen 91-92
 temperature 90-91
 Water management 156-157
 Water reuse systems, strategies to optimize 257, 259-260
 Water-soluble fertilizers (WSF) 287-289, 299, 300
 Water treatment compartment 80-81
 Water use efficiency (WUE) 67-68, 70, 242, 274, 275, 431
 Weighing system 266
 Window ventilation 429
 Wind tunnel 20
 Windward ventilation 21
 Winterlight Greenhouse 466-469
 Winter light greenhouse prototype 32
 Wood fiber 229
 WSF. *see* Water-soluble fertilizers (WSF)
 WUE. *see* Water use efficiency (WUE)
 Yield gap 127-129