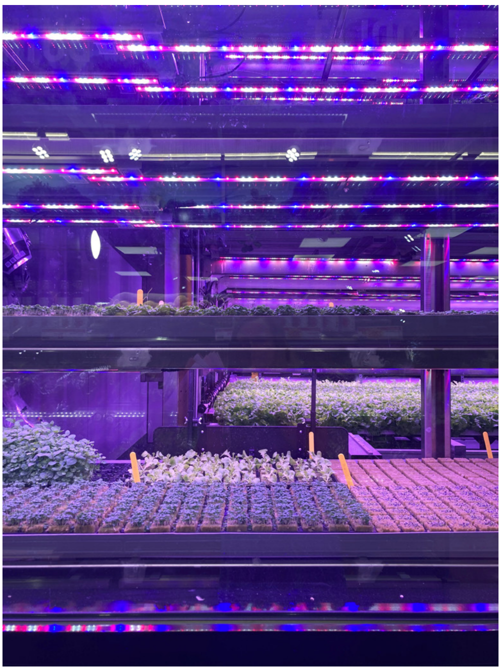
Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2023:95
Faculty of Landscape Architecture, Horticulture and Crop Production Science

Introduction and adoption of innovations in horticultural production systems

Annie Drottberger



Introduction and adoption of innovations in horticultural production systems

Annie Drottberger
Faculty of Landscape Architecture, Planning and Management
Department of Biosystems and Technology
Alnarp

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

DOCTORAL THESIS
Alnarp 2023

Acta Universitatis Agriculturae Sueciae
2023:95

Cover: Plant factory with artificial lighting
(photo: A. Drottberger)

ISSN 1652-6880
ISBN (print version) 978-91-8046-242-6
ISBN (electronic version) 978-91-8046-243-3
https://doi.org/10.54612/a.10669ph3uo

Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Alnarp, Sweden

Print: SLU Service/Repro, Alnarp 2023

Introduction and adoption of innovations in horticultural production systems

Abstract

Horticultural production occurs in various production systems, dominated by greenhouse and open-field production. During the last decade, alternative production systems with more advanced technologies, such as LED lighting and artificial intelligence, have started to appear, e.g., plant factories with artificial lighting. This opens up new opportunities where increased attention from venture capitalists and investors highlights food-tech as an innovative field of interest. Technological development can also accelerate possibilities, mainly for firms producing in greenhouses, if they can adopt relevant knowledge and innovations from other production systems. Another aspect is the increased interest in start-up initiatives and businesses in urban settings, e.g., urban farming, vertical farming, aquaponics, or rooftop greenhouses, to mention a few models. In parallel, low-tech initiatives are developing, e.g., market gardening and small-scale artisan production, which can also be important niches for the sustainable production of vegetables. The innovative production systems often use alternative food networks and different business models, e.g., Community Supported Agriculture or Product Service Systems, often with shorter supply chains. These different initiatives are also associated with positive movements influencing society and increasing consumers' awareness of sustainable food production. However, the fact that new actors are entering the market could also create tensions between urban and rural contexts due to the different backgrounds of business owners. This is further accelerated by the different conditions for the firms, e.g., depending on support and policies from the innovation system and society in general.

Keywords: greenhouse, horticulture, hydroponics, innovation, LED lighting, market gardening, plant factory with artificial lighting, rooftop greenhouse(s), urban agriculture, vertical farming

Introduktion och upptagande av innovationer i hortikulturella produktionssystem

Sammanfattning

Trädgårdsproduktion förekommer i olika produktionssystem, främst växthus- och frilandsproduktion. Under det senaste decenniet har alternativa produktionssystem med mer avancerad teknologi, såsom LED-belysning och artificiell intelligens, börjat dyka upp, t.ex. växtfabriker. Detta öppnar nya möjligheter där ökad uppmärksamhet från riskkapitalister och investerare lyfter fram foodtech som ett innovativt område. Den tekniska utvecklingen kan också påskynda möjligheterna, främst för företag som producerar i växthus, om de kan ta till sig relevant kunskap och innovationer från andra produktionssystem. En annan aspekt är det ökade intresset för nystartade initiativ och företag i urbana miljöer, t.ex. stadsodling, vertikalodling, akvaponik eller takväxthus, för att nämna några modeller. Parallellt utvecklas lågteknologiska satsningar, till exempel market gardening och småskalig hantverksproduktion, som också kan vara viktiga nischer för hållbar produktion av grönsaker. De innovativa produktionssystemen använder ofta alternativa livsmedelsnätverk och olika affärsmodeller, t.ex. Community Supported Agriculture eller produkttjänstsystem, ofta med kortare leveranskedjor. Dessa olika initiativ är också förknippade med positiva rörelser som påverkar samhället och ökar konsumenternas medvetenhet om hållbar livsmedelsproduktion. Samtidigt kan det faktum att nya aktörer kommer in på marknaden också skapa spänningar mellan stads- och landsbygdskontexter på grund av företagarnas olika bakgrund. Detta förstärks ytterligare av olika förutsättningarna för företagen, t.ex. beroende på stöd och policys från innovationssystemet och samhället i stort.

Nyckelord: hortikultur, hydroponik, innovation, LED-belysning, market gardening, stadsodling, takväxthus, vertikalodling, växtfabriker, växthus

Dedication

To Simon, Isaac and Anton

Ni stammisar på jorden. Lär oss hur ni gör. Från rötterna till kronan. Växer tills ni dör. 400 miljoner år av samlad erfarenhet. Ni stammisar på vår planet. Tack och förlåt. För allt vi människor ställt till med. Hur bar vi oss åt? Det här var aldrig vad vi ville. Som vi skövlar oss fram. Det tog aldrig stopp. Vi fick chans på chans. Aldrig att vi tog den. Finns det träd finns det hopp. Och än susar skogen. Än susar skogen.

Emil Jensen

Contents

List of publications 9

Other publications 11

List of tables 13

List of figures 15

Abbreviations 17

1. Introduction 19
   - 1.1 Background 19
   - 1.2 Horticultural production in a Swedish context 20
   - 1.3 Research objectives and questions 23
   - 1.4 Research positioning 24
   - 1.5 Overview of appended articles IV 25

2. Theoretical frameworks 27
   - 2.1 Diffusion and adoption of innovations 27
   - 2.2 Innovation decision process 28
   - 2.3 The firm and surrounding innovation ecosystem 29
   - 2.4 Innovations in horticultural production systems 30

3. Research approach and methodology 31
   - 3.1 Methodological and philosophical positioning 31
   - 3.2 Research strategy and design 33
   - 3.3 Methodological approaches in Articles I-IV 35
   - 3.4 Ethical considerations 37

4. Results 39
   - 4.1 Adoption of technological innovations in production of leafy vegetables in Sweden (I) 39
   - 4.2 Alternative food networks in food system transition—values, motivation, and capacity building among young Swedish Market (II) 41

4.3 Urban farming using rooftop greenhouse: A systematic literature review (III) 42
4.4 Farming as a service initiative in the making: insights from emerging proto-practices in Sweden (IV) 43

5. Discussion 45
5.1 Discussion of findings 45
5.2 Implications for practice and policy 46
5.3 Theoretical contribution 47
5.4 Future research 48

6. Conclusions 49

References 51

Popular science summary 56

Populärvetenskaplig sammanfattning 58

Acknowledgements 60

List of publications

This thesis is based on the work presented in the following articles, referred to by Roman numerals in the text:

I. Drottberger*, A., Bergstrand, K. J., Fernqvist, F., & Spendrup, S. (2022). Adoption of technological innovations in production of leafy vegetables in Sweden. EUROPEAN JOURNAL OF HORTICULTURAL SCIENCE, 87(4), 1-11.

II. Drottberger*, A., Melin, M., & Lundgren, L. (2021). Alternative food networks in food system transition—values, motivation, and capacity building among Young Swedish Market Gardeners. Sustainability, 13(8), 4502.

III. Drottberger*, A. Zhang*, Y. Yong, J.W.H., Dubois, M.C (2023). Urban farming with rooftop greenhouses: A systematic literature review. Renewable and Sustainable Energy Reviews, 188, 113884.

IV. Drottberger*, A. & Langendahl, P. A. Farming as a service initiative in the making: insights from emerging proto-practices in Sweden. Manuscript submitted to journal: Smart Agricultural Technology

Articles I-III are reproduced with the permission of the publishers.

The contribution of Annie Drottberger to the articles included in this thesis was as follows:

I. Planned the article with co-authors. Performed data collection, analysis, and study design, and wrote the article with the co-authors. Corresponding author.

II. Planned data collection and study design with co-authors. Supervised Lundgren together with Melin. Performed analysis in collaboration with Lundgren, and wrote the article together with co-authors. Corresponding author.

III. Planned and performed data collection and study design in collaboration with Zhang and Dubois. Analysed data and wrote the article together with co-authors. Shared first co-authorship with Zhang. Corresponding author.

IV. Planned and performed data collection and study design together with Langendahl. Analysed and wrote the article together with Langendahl. Corresponding author.

Other publications

Popular scientific articles

Bergstrand, K. J, Ekelund A.L., Drottberger, A., Fernqvist, F & Spendrup, S. (2020). Forskare: Odla mer i stora växtfabriker än bladgrönt och kryddor. In NyTeknik (https://www.nyteknik.se/ opinion/forskare-odla-mer-i-stora-vaxtfabriker-an-bladgront-och-kryddor-6990937) (accessed Aug. 21, 2021).

Drottberger, A., Bergstrand, K. J., Spendrup, S., & Fernqvist, F. (2023). Innovationer och kunskapsspridning vid produktion av bladgrönsaker. Viola, (1). (drottberger-a-et-al-20230412.pdf (slu.se) (accessed Apr. 12, 2023).

List of tables

Table 1. Production of leafy vegetables in various production systems based on statistics from the Swedish Board of Agriculture ……………….……..21

Table 2. Positioning the thesis within the research area……………………25

Table 3. Aims, research questions and purposes of Articles 1-IV…………26

Table 4. Empirical data used in articles I-IV………………………………32

Table 5. Methodological approaches used in articles 1-IV………………...37

Table 6**.** Characteristics of the different production systems studied…..…..40

Table 7. Thematic categories in the reviewed articles……………………..42

List of figures

Figure 1. Number of firms producing vegetables from 2008-2020 based on statistics from the Swedish Board of Agriculture...............................22

Figure 2. Trends in the production of leafy vegetables between 2008-2020, normalised yields based on statistics from the Swedish Board of Agriculture...22

Figure 3. Relationship between background, aim and research question....24

Figure 4. Relationship between the aim, research questions, and appended Articles I-IV...25

Figure 5. Photo from a larger PFAL...40

Abbreviations

FaaS	Farming-as-a-service
LED	Light emitting diode
RTG	Rooftop greenhouse
SDGs	Sustainable Development Goals
SLR	Systematic literature review
PFAL	Plant factory with artificial lighting

1. Introduction

This chapter begins by describing the background to the global sustainability challenges faced by humanity and our planet (section 1.1), followed by a description of horticultural production in a Swedish context (section 1.2), research objectives and questions (section 1.3). Finally, an overview of the appended articles I-IV is presented (section 1.4).

1.1 Background

Society is facing serious challenges, such as the destruction of natural ecosystems, loss of biodiversity, and climate change (OECD 2019; Shukla *et al.* 2019). This is occurring in combination with increased population and urbanisation, which puts pressure on improved food production and a transformation of the food system to more sustainable production (DESA 2019; Searchinger *et al.* 2019; Li *et al.* 2022). Agriculture is a significant driver of climate change and is also affected by its consequences (Rockström *et al.* 2017). One of the solutions to these challenges could be increased innovative approaches in firms producing agri-food (Ferraro *et al.* 2015). The OECD report (2019:107) highlights significant challenges in agri-food production, such as the absence of information on the farm level concerning the adoption of innovations. The report shows that many countries lack data on how farmers adopt and use innovative practices and technologies. This supports that there is a knowledge gap in understanding which innovations are being implemented and to what extent.

Vegetables constitute a significant part of the consumption (Saini *et al.* 2017) and have low climate impact (Garnett 2011). The firms that produce vegetables in different production systems, such as open-fields, greenhouses, PFAL (Plant Factories with Artificial Lighting) or rooftop greenhouses (RTGs), adopt innovations to a different extent. This occurs in combination with the rapid development of new technology in the indoor cultivation of leafy vegetables, leading to new production systems and firms (Orsini *et al.* 2020a). Unlike open-field and greenhouse firms, they are establishing themselves in urban environments close to consumers (Thomaier *et al.* 2015). RTG (rooftop greenhouse) technology is another interesting innovation with potential to increase sustainability, especially in urban contexts.

The Food and Agriculture Organization (FAO) has defined sustainable agricultural development as follows:

> "The management and conservation of the natural resource base, and the orientation of technological change in such a manner as to ensure the attainment of continued satisfaction of human needs for present and future generations. Sustainable agriculture conserves land, water, and plant and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" (FAO 1988).

The concept of sustainable agriculture involves three areas of concern: economic, environmental and public welfare (Weil, 1990). These factors rarely hold equal weight in agricultural decisions. The United Nations (UN) sees economic growth as imperative for sustainable development and believes it can enable social and economic goals to be met by trickle-down effects (United Nations, 2015). Since the UN's Sustainable Development Goals (SDGs) in the above-cited Agenda 2030 (Nations 2015) has become a working definition of sustainable development in political contexts, their perspective is very influential in practice. Meanwhile, sustainability depends on social, political and economic factors, which cannot be divorced from the definition of sustainable agriculture (Altieri, 1987). When evaluating the sustainability of a production system, it is easier to judge the direction in which a new technology or policy will move an agriculture system than it is to judge the absolute sustainability of a system the way it is (Weil 1990).

1.2 Horticultural production in a Swedish context

The horticultural industry includes the areas of horticulture, outdoor environment and recreational gardening (Ekelund & Nilsson 2017). The industry is the engine of a value chain, starting with companies that supply inputs and ending with the consumption of food, ornamental and nursery plants, outdoor environmental services and leisure consumption (Ekelund & Nilsson 2017).

The production of vegetables in Sweden represents high values in production and trade (Fernqvist & Göransson 2021). The total value of Sweden's fruit and vegetable production was SEK 6.7 billion in 2020, a 15% increase from 2019 and 25% higher than the previous five-year average (2015-2019) (Persson 2020). The cultivation of leafy vegetables in Sweden is increasing, and the production of iceberg lettuce (including leafy vegetables and baby leaves) has been around 25 000–30 000 tonnes during the last years, with yearly variations (Agriculture 2020). From 2014, production data for other lettuces (including large and small leaf lettuce) is available. In 2021, this production amounted to approximately 10,000 tonnes, an increase of almost 90 per cent since 2014 (Burman 2023). Table 1 shows the production of different crops and the number of firms producing leafy vegetables from 2011-2020 (Figure 1). Trends in the production of leafy vegetables between 2008-2020 based on normalised yields is shown in Figure 2. All numbers in Table 1 and Figure 1-2 are based on statistics from the Swedish Board of Agriculture (Agriculture 2023).

Table 1. Production of leafy vegetables in various production systems based on statistics from the Swedish Board of Agriculture.

System	**Crop**	**2011** Area (m^2)	**2014** Area (m^2)	**2017** Area (m^2)	**2020** Area (m^2)
Greenhouse/PFAL	Lettuce in pots	69 909	56 225	47 199	40 185
Greenhouse/PFAL	Other lettuce	47 455	57 216	46 185	57 475
Greenhouse/PFAL	Fresh herbs	77 075	95 479	99 405	123 944
Open-field	Iceberg lettuce	1 128 000	1 168 000	968 000	854 000
Open-field	Other lettuce	N/A	619 000	679 000	1 182 000
Open-field	Dill	156 000	194 000	176 000	173 000
Open-field	Spinach	167 000	114 000	39 000	74 000

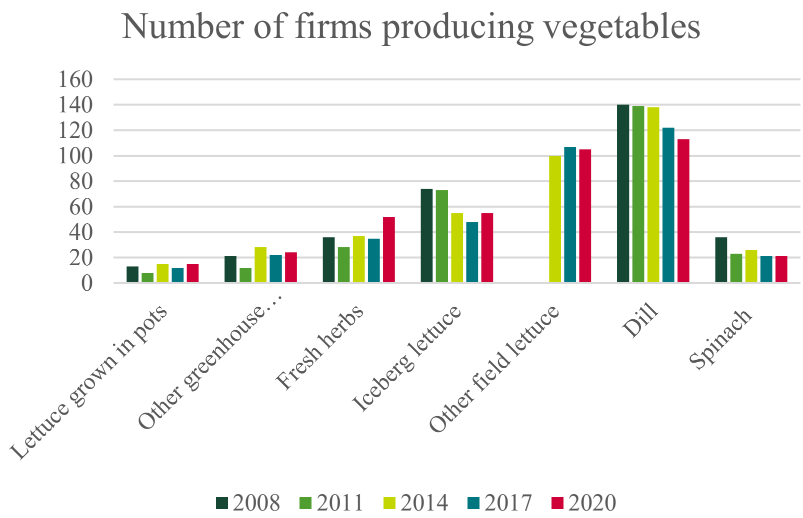


Figure 1. Number of firms producing vegetables from 2008-2020 based on statistics from the Swedish Board of Agriculture.

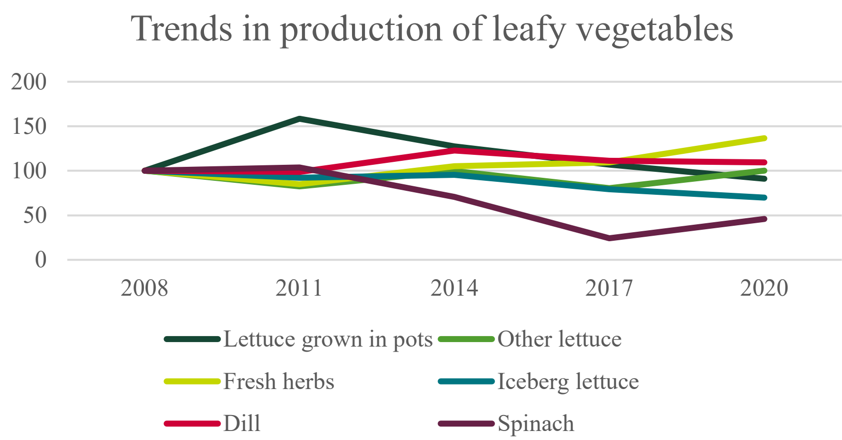


Figure 2. Trends in the production of leafy vegetables between 2008-2020, normalised yields based on statistics from the Swedish Board of Agriculture.

The market for leafy vegetables has been rapidly growing, and the consumption of leafy vegetables has increased and is expected to continue growing, according to trading operators (Fernqvist & Göransson 2021). The firms producing leafy vegetables in various production systems have adopted innovations to different degrees. The share of innovative firms is comparably high in the food industry, trade and restaurants (Agriculture 2020). However, a low level of education and ageing labour make primary production lag behind when adopting innovations (Agriculture 2020). Less than a third of the agricultural firms introduced a new or improved product or process between 2016 and 2018, considerably less than in other sectors (Agriculture 2020). Knowledge and innovation are central to the food chain's long-term development (Agriculture 2023). Over time, the level of education in the food chain needs to increase if the firms are to assimilate new technologies and research (Agriculture 2020).

The production of leafy vegetables is mainly taking place in open-field and greenhouse systems. Open-field production systems are relatively intensive, involving irrigation, fertigation and specialized machinery. Greenhouses include a wide range of structures, from simple plastic-covered unheated types with low technical standard (southern-type greenhouses) to high-technology, glass greenhouses with computerized climate control, artificial lighting, CO_2 supply etc. (northern-type greenhouses) (Castilla & Hernandez 2006; Stanghellini *et al.* 2019). During the past decade, production systems known as plant factories with artificial lightning (PFAL) have emerged, mainly driven by the introduction of LED technology. The PFAL system is a further advance of the high-technology greenhouse, where all climate factors can be controlled, including light, which is replaced by artificial light (Kozai 2013). Disadvantages with PFAL systems are the energy demand, which is higher compared to conventional food systems, and increased system resource use efficiency needs to be considered (Orsini *et al.* 2020b). The PFAL system can be comparable to greenhouse system when operating in cold climates and choosing high-efficiency LED light could improve the energy supply and enhance energy use in PFAL (Zhang *et al.* 2017). However, the energy demand can lead to difficulties in achieving economies of scale (Allegaert *et al.* 2020).

1.3 Research objectives and questions

This thesis aims to offer insight into the adoption of innovations in horticultural firms across various production systems. Studying the adoption of innovations will facilitate the anticipation of improvements in the horticultural sector. The following research questions (RQ) were formulated to address the overall aim of this thesis:

RQ: How does the adoption of innovations and technologies influence horticultural firms in different production systems?

The aim has been broken down further and resulted in the following sub-questions to be able to approach innovation in sustainable horticulture from different perspectives:

RQ1. Which innovations are adopted within different horticultural production systems?
RQ2. What drivers and barriers promote or inhibit the adoption of innovations by firms?
RQ3. What networks and/or practices do firms use in the innovation adoption process?

The relationship between the background of this thesis (described in section 1.1-1.2), the aim and RQs are presented in Figure 3.

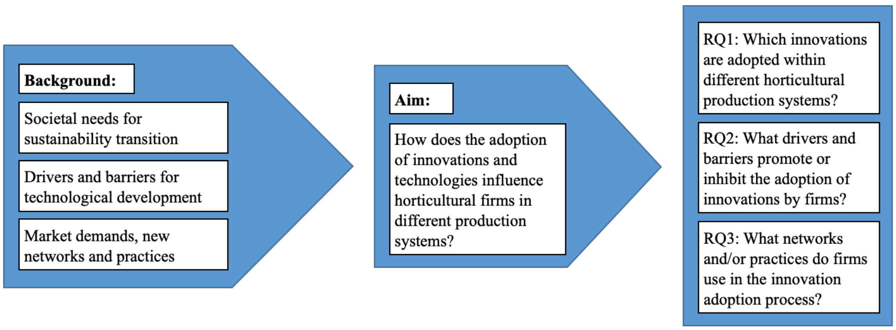


Figure 3. Relationship between background, aim and research questions.

The abovementioned research questions are addressed by the results in the studies described in appended Articles I-IV. This will be described further in section 1.4.

1.4 Research positioning

This thesis lies within horticultural science, with a specialisation in business administration. Horticulture is an interdisciplinary field, and research is conducted based on different scientific disciplines, as described by the American Society for Horticultural Science: “Horticultural science is the only plant science that incorporates both the science and aesthetics of plants. It is the science and art of producing edible fruits, vegetables, flowers, herbs, and ornamental plants, improving and commercialising them." (ASHS 2016). Horticulture includes several scientific subfields, such as biology, agriculture, plant physiology, plant chemistry, plant breeding, economics, etc. In addition, horticulture accounts for a large part of the world's food production. Added to that is the value of ornamental and nursery plants (Ekelund & Nilsson 2017).

Table 2. Positioning the thesis within the research area.

Discipline	Sub-discipline	Topics	Contexts
Horticulture	Horticultural economics	Innovation adoption Food system transition Rooftop greenhouses Product service system	Horticultural systems

1.5 Overview of appended articles IV

The work described in Articles I-IV strives to provide answers to the research questions in the following way:

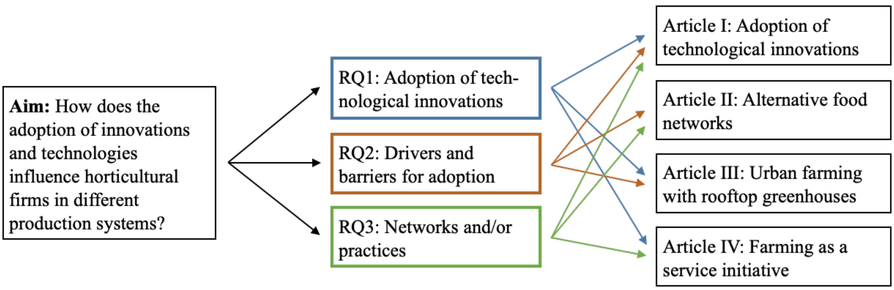


Figure 4. The relationship between the aim, research questions and appended Articles I-IV.

The research questions in relation to the purpose of Articles I-IV are summarised in Table 3.

Table 3. Aims, research questions and purposes of Articles 1-IV.

Title of paper	**Aim or research questions**	**Purpose**
I Adoption of technological innovations in production of leafy vegetables in Sweden	Investigate adoption of technological innovations in three different leafy vegetable production systems: i) open-field crop production, ii) greenhouse production iii) PFAL production.	Explorative study to map different technological innovations in different production systems of leafy vegetables.
II. Alternative Food Networks in Food System Transition Values, Motivation, and Capacity Building among Young Swedish Market Gardeners	(RQ1) What characterizes the businesses of young market gardeners in Sweden? RQ2) What motivates young people to become market gardeners? (RQ3) What barriers and opportunities are there for new entrants in market gardening?	To understand both the businesses as well as motivations of the owners of market gardens. Mainly focusing on competences and networks for next generation of market gardeners.
III. Urban farming with rooftop greenhouses: A systematic literature review	A systematic literature review about the rooftop greenhouse technology was carried out to examine benefits and challenges associated with this technology.	Review the literature related to rooftop greenhouses. Identify benefits and challenges associated with this technology.
IV. Farming as a service initiative in the making: insights from emerging proto-practices in Sweden	Examining early uptake of farming-as-a-service and contribute with in-depth insights on implementation: RQ1: What are the emerging practices of FaaS initiatives? RQ2: How are these developing in relation to the context in which they are implemented?	To understand the implementation of farming-as-a-service, which are developed modules for food production at the customer/consumer via a service. Focusing on practices in user contexts.

2. Theoretical frameworks

In this chapter, the theoretical frameworks that shaped the background to this thesis are presented: Diffusion and adoption of innovations (section 2.1), innovation decision process (section 2.2), the firm and surrounding innovation ecosystem (section 2.3), and finally, innovations in horticultural production systems (section 2.4).

2.1 Diffusion and adoption of innovations

The diffusion and adoption of innovations in agriculture is a topic in the literature, serving as the initial theoretical framework of this thesis, which is elaborated in Article I. The theory of diffusion of innovation was presented by Rogers in 1962, based on agriculture studies in the United States. It explains how an innovation spreads through a population or social system, resulting in the innovation being adopted (Rogers 2003). Four main elements are involved in the diffusion of innovations, which is defined as the process by which (1) an innovation (2) is communicated through specific channels, (3) over time, and (4) among the members of a social system (Rogers 2003). One of many definitions of an innovation is "an idea, practice or object that is perceived as new by an individual or other unit of adoption." (Rogers, 2003, page 12). Focusing on technological innovations, the definition of technology is a design for instrumental action reducing the uncertainty in the cause-effect relationships involved in achieving a desired outcome (Rogers 2003). The social system has structure or patterned arrangements of the units in the system and is engaged in joint problem-solving to accomplish a common goal. One aspect of social structure is norms, which are established behaviour patterns for the members of a social system (Rogers 2003).

However, it is also important that the actors of the innovation system possess the capabilities to translate this knowledge into practice to diffuse and adopt technologies that have economic value (Carlsson *et al.* 2002). This is described further down.

2.2 Innovation decision process

According to Rogers (2003), the innovation-decision process describes the process through which an individual passes from gaining initial knowledge of an innovation to forming an attitude toward the innovation, making a decision to adopt or reject, implementing the new idea, and confirming the decision. The firms implementing innovations also perform in a context affected by policy, social factors, market demands, environmental variables and technology (Sternberg & Arndt 2001; Verhees & Meulenberg 2004). Technology transfer is another phenomenon that is important to understand correctly, and there are three possible levels of technology transfer (Rogers 2003):

1. Knowledge, where the receptor knows about the technological innovation.
2. Use, where the receptor has used the technology in his or her organisation. This level of technology transfer is much more complex than just knowing about the technology. The difference is equivalent to the knowledge stage in the innovation-decision process.
3. Commercialisation, i.e., the receptor has commercialised the technology into a product sold in the marketplace.

Technology transfer often fails and is difficult because the effort required for such transfer to occur effectively is underestimated. For example, when it comes to commercialisation, the communication of research results needs to be ready to be adopted by users (Rogers 2003). Change agents or advisors can influence clients' innovation decisions in a desirable and importance way (Rogers 2003).

Worth mentioning is that the ”adoption and diffusion of innovations perspective” has been criticised theoretically for the intervention practices it has inspired (Leeuwis 2013). One example is the pro-innovation bias, which assumes that the innovations studied are considered worthwhile and that it would make sense for most farmers to adopt them (Röling 1988). In practice, however, many proposed innovations do not make sense for many farmers. The problem is that conventional adoption and diffusion research has tended not to correct for compatibility or relevance of the innovation to the specific firm when calculating adoption indexes (Leeuwis 2013).

2.3 The firm and surrounding innovation ecosystem

Innovation is driven by the capability to recognise opportunities, see connections from the firm-level perspective, and finally take advantage of them (Tidd & Bessant 2020). Management and support processes within the firm also affect the innovation process (Trienekens *et al.* 2008). This is important to the innovation process when turning ideas into reality and finally capturing the value from the adopted innovation (Tidd & Bessant 2020). A value network is the context where a firm competes and solves customers' problems (Christensen & Rosenbloom 1995; Katsamakas 2014). However, another alternative could be to focus on technological capabilities and organizational dynamics to become competitive (Lam 2005). The absorptive capacity is the ability of a firm to recognize the value of new, external information, assimilate it and apply it to commercial ends, which is critical to its innovative capabilities (Cohen & Levinthal 1990). Economic competence and the ability to business opportunities are also key in technological systems (Carlsson & Stankiewicz 1991). These skills and capabilities will affect the firms' strategies and innovation processes concerning decision-making about adoption of innovations. Another issue is lock-in effects, where larger investments in a particular technology hinder the adoption of new innovations involving further investments (Abernathy & Clark 1985; Augier & Teece 2021).

The Innovation Ecosystems thinking involves transitions to more sustainable agriculture and requires the formation of innovation niches (Elzen et al., 2012, Meynard et al., 2017). This conceptualises the need for cross-sector interactions to facilitate transboundary innovation (Walrave et al., 2018) and, therefore, may contribute to expanding the scope of traditional Agricultural Innovation System thinking (Pigford et al., 2018). For example, this is recognised in agroecology, which has sought to integrate multiple scales to advance innovation and scale novel agroecological systems (Dalgaard *et al.* 2003). The Agricultural Innovation Systems concept is anticipated to act as organising framework to strengthens the capacity to innovate and create novelty in agricultural production and marketing (Hall *et al.* 2006). Innovation Ecosystem thinking may offer a useful umbrella concept suitable for the broader multifunctionality of agricultural systems. This could offer the potential to better support the development of transboundary innovation niches designed to realise innovation in support of sustainability (Pigford et al., 2018).

2.4 Innovations in horticultural production systems

When it comes to the sustainable production of horticultural products in innovative ways, several pathways can be explored. Technology often plays a role in enabling new opportunities (Tidd & Bessant 2020). There could also be a possibility for improvements on old products using old technologies in new ways (Tidd & Bessant 2020). In the context of innovations in horticultural production, the connected studies to this thesis explored different technologies, including hydroponics, aquaponics, aeroponics, rooftop greenhouse technology, digitalisation, artificial intelligence, sensors, robotics, automation, and more. For a detailed description of the different technologies used in horticultural production systems, read the appended Article I-IV.

Except for product innovations, there are several examples of growth through service innovations (Bessant & Davies 2007; Tidd & Bessant 2020). In the horticultural sector, service-oriented farming, specifically farming-as-a-service, is an example of developed modules for food production for the customer or consumer via a service. In these business arrangements, firms are leasing out digitally augmented in-store farming units, which the customer uses, e.g. supermarket or restaurant, for vegetable production (Martin & Bustamante 2021). This is further explored and described in appended Article IV.

3. Research approach and methodology

This thesis focuses on qualitative research methods consisting of interviews, participant observations, and literature reviews. This chapter describes the research approach and methodology. The outline is as follows: Methodological positioning of the research (section 3.1), research strategy and design (section 3.2), methodological approaches in Articles I-IV (section 3.3), and finally, ethical considerations (3.4).

3.1 Methodological and philosophical positioning

The methodology was selected to gain deep knowledge and explore the phenomenon of innovations from several angles (Creswell & Poth 2016). Knowledge and empirical evidence have been gained by using qualitative research methods, e.g. direct and indirect observation (Cassell & Symon 2012), interviews or experience, as described by Guest et al. (2013). The analysis of the empirical data was implemented to answer pre-defined empirical questions (Okasha 2016). Adopting a multi-method approach means that the design of any research study is given to the different dimensions of a real situation, material, social, and personal (Mingers 2001). Table 4 presents an overview of the empirical data, which was used in articles I-IV.

Other relevant philosophical matters to this thesis were epistemology and ontology, which determine good social science, as Alvesson and Sköldberg (2017) argued. Epistemology studies the nature of knowledge, justification, and the rationality of belief (Kvale & Brinkman 2017). Ontology is the philosophical study of being. It studies concepts directly related to being, in particular, becoming, existence and reality (Kvale & Brinkman 2017). These matters encourage interpretative possibilities, allowing a clearer view of the researcher's construction of the explored subject (Alvesson & Sköldberg 2017).

Table 4. Empirical data used in articles I-IV.

Article	Empirical data
I	Fifteen business cases In-depth interviews with owners and managers
II	Fourteen business cases In-depth interviews with young market gardeners
III	Final dataset with 45 scientific articles
IV	One single business case Seven in-depth interviews Site visits with observations

Hermeneutics, the art of interpretation (Alvesson & Sköldberg 2017), is also highly relevant to this research. Hermeneutics can be described as a way to find the underlying meaning of the phenomenon of innovation and what the firms do when adopting new technologies or practices. This thesis is developed based on a combination of data from theory, conducting interviews, and finally observing to be able to interpret the results. Hermeneutics are more interested in phenomena that are complex and in interesting contexts, which has been an important motivation for the development of this thesis. This has been combined with an open and creative view, where the interview is seen as a method to create empirical materials that can be interpreted in several ways, as described by Alvesson and Kärreman (2012). This approach contrasts with positivism, which focuses on general laws to explain a phenomenon, where data or facts exist and are already there, and the researcher simply gathers and systematises them (Alvesson & Sköldberg 2017). The methodological approach of this thesis has been explorative, focusing on what happens when firms adopt innovations. Therefore, the emphasis has been on social constructionism, which is the idea that certain phenomena are social constructs instead of having an objective mind-independent existence (Alvesson & Sköldberg 2017). Social constructionism questions what humans and society define to be reality. Therefore, social constructs can be different based on the society and the events surrounding the time period in which they exist (Okasha 2016). It can be said that reality is precisely socially constructed for social constructionism, in contrast to positivism, as described by Alvesson and Sköldberg (2017).

Critical realism is another relevant theory to this thesis, as a more theoretical and realistic substitute for positivism and social constructionism, offering principles and ideas for science (Alvesson & Sköldberg 2017). This theory states that analysis of underlying mechanisms and structures behind phenomena is what it takes to create theories (Alvesson & Sköldberg 2017). Reflexivity, defined as a conscious and consistent effort to view the subject matter from different angles, strongly avoiding the a priori privileging of a favoured one (Alvesson 2011), was also present in the development of this thesis. A reflexive methodology with multiple interpretations would help avoid traps and enable the researcher to take the analysis a step further when producing relevant results as described by (Alvesson & Sandberg 2011). This is described as gaining an interpretive repertoire by Alvesson and Sköldberg (2017), "the more you know, the better you can put yourself and the data in and out of context".

When positioning this thesis in relation to philosophy of science, critical realism, reflexivity and social constructionism are the most relevant theories to the studies. It is central to reflections on the deep or non-subjective dimensions of knowledge and reality as an alternative to positivism and social constructionism (Alvesson & Sköldberg 2017). It is also important to be aware of the tradition of positivism in natural science and constantly reflect on the different approaches.

3.2 Research strategy and design

In order to answer the aim of the thesis, the following methodology and analytical perspectives were used:

- Article I: Qualitative method interview studies with semi-structured questions. Thematic analysis with NVivo. The Diffusion of innovations theory and innovation ecosystems thinking were used for analysing the results.
- Article II: Qualitative method interview studies with semi-structured questions. Thematic analysis with NVivo. The Agroecological framework and transition theory were used for analysis.
- Article III: Systematic literature review (SLR) with a literature search in databases for scientific articles. A non-exhaustive inventory of existing projects worldwide. SWOT analysis focusing

on Strengths, Weaknesses, Opportunities and Threats was used for evaluating the results.

- Article IV: A single case study involving qualitative interviews and site visits to firms and supermarkets using the innovation. Practice theory was employed to analyse the results.

The chosen research design of the appended articles was similar in Articles I and II, which focused on qualitative interviews. Article I had fifteen respondents, while Article II had fourteen. The point of departure for the interviews was different horticultural production systems, where three groups of managers were interviewed in Article I. In contrast, in Article II, the respondents comprised one group of growers identified as market gardeners. A case-based qualitative research model was used in Article II to understand better and interpret aspects that are difficult to measure quantitatively (Blättel-Mink *et al.* 2017). The interview results in Articles I, II and IV were recorded and transcribed (Lapadat & Lindsay 1999). The results from Articles I and II were also later coded in NVivo (Ltd. 2018) to facilitate the thematic analysis according to the model described by Braun and Clarke (2006). The empirical data was also combined with literature reviews in all four articles, focusing on relevant theories in relation to the explored phenomena and contexts where the participating business cases were operating.

Article III was a SLR and thus had a different character. The search was made on articles related to rooftop farming published in scientific journals from 1 January 2009 to 6 March 2023. A stepwise procedure was used, as described by James *et al.* (2016). The initial search generated 539 articles, and finally, 45 journal articles were included according to the stated inclusion and exclusion criteria, focusing on rooftop greenhouses in a cold or temperate climate. The search process is described in detail in the appended article III.

Article IV continued the work of Article I for an increased exploration and understanding of the development of PFAL firms. The point of departure focused on developing PFAL firms' practices in different contexts. This article's aim appeared more clearly as new commercial farming-as-a-service initiatives were developed as the industry was established in Sweden. Since the industry of PFAL firms was developing fast with firm initiatives taking different directions, it was considered most interesting to follow the initiatives using farming-as-a-service and their progress, as their business model seemed to be competitive. This appeared as a suitable path as the project proceeded, but it was not decided from the start. The analytical framework also changed over time, and the social constructionism view suited especially well with how the last article developed. The methodology focused on a longitudinal study of a single case using multiple methods, as described by Flyvbjerg (2006). The empirical data consisted of seven interviews with key informants over time. Site visits were also made to testbeds and supermarkets using the technology, and finally, the empirical data was combined with literature reviews.

3.3 Methodological approaches in Articles I-IV

Article I explored the adoption of technological innovations in production of leafy vegetables in different production systems; field crop production, conventional greenhouses, and novel vertical systems (including stacking cultivation). The study aimed to investigate the role of innovation and technology adoption in production of leafy vegetables in these growing systems. Purposive sampling was deemed suitable to ensure relevant respondents for the research question (Bryman 2016). Since there was only a limited number of firms producing crops in Sweden, the majority of firms were contacted. In addition, an Internet search for PFALs or "vertical farms" allowed identifying firms from this group, resulting in fifteen firms (five per system) agreeing to participate in the study. Telephone interviews were conducted to map the adoption of technological innovations in the different production systems. The data from semi-structured interviews were coded thematically (Boyatzis 1998) using NVivo (Ltd. 2018) and further analysed (Braun & Clarke 2006). The results were further processed in the light of other methodological sources in line with triangulation (Bryman 2016), i.e., theoretical data from the literature review connected to the research aim. Triangulation and using several methods or data sources when studying a social phenomenon aim to facilitate extra control and relevance of the results, as described by Bryman (2016). This offered a broader picture of technological development and increased insight into networks and the value chain for the different production systems.

Article II used a case-based qualitative research model (Johansson 2007) focusing on another production system with market gardening. This study targeted young growers to investigate their motivations for transitioning to a sustainable food system. Similar to the methodology in Article I, the method was qualitative interviews with semi-structured questions (Bryman 2016).

The data was thematically analysed in NVivo (Ltd. 2018) and subsequently integrated with theoretical data from the literature review. The sampling in Article II involved snowball sampling in which initial contact with respondents relevant to the study topic was used to identify other potential interviewees (Bryman 2016). Respondents were interviewed for 1–1.5 h using a semi-structured interview guide (Guest *et al.* 2013).

Article III was a Systematic Literature Review (SLR) focusing on production systems with rooftop greenhouses (RTG). This was the first study with a global focus in this thesis, and it contained a different methodology from the other articles (I, II and IV). The SLR was carried out based on articles published in scientific journals from 1 January 2009 to 6 March 2023. The search focused on rooftop farming but was later limited to only articles with rooftop greenhouses (RTGs) in a northern climate since this was the main interest. The choice to conduct a SLR was made since RTG technology is an emerging area and there are still no commercial establishments in Sweden. Therefore, the SLR method was suitable to contribute to an increased understanding of the research area, and future larger applications for projects on RTGs in northern Europe.

Article IV continued the work of Article I and focused on PFAL firms, specifically users of farming-as-a-service, which were studied in a Swedish context. This was motivated by the establishment of service-oriented farming initiatives observed during the final part of the PhD project. The longitudinal single case study methodology, as described by Flyvbjerg (2006), was deemed suitable since the development of the farming-as-a-service initiatives, generally, had been followed over time since 2018, and there have been well-documented data on the specific case since 2008. This data was available from respondents involved in the original business in combination with media reports. The exploratory qualitative research focused on implementing the farming-as-service initiative and followed case study research methods as described by (Flyvbjerg 2006). The method was useful for investigating FaaS and its development over time in different contexts. Table 5 describes the methods used to collect and analyse data in the empirical studies in articles I-IV.

Table 5. Methodological approaches used in articles 1-IV.

Title of article	Methodological approach	Treatment of data and analysis
I. Adoption of technological innovations in production of leafy vegetables in Sweden	Qualitative interviews of firms and literature review	Thematic analysis in NVivo
II. Alternative Food Networks in Food System Transition—Values, Motivation, and Capacity Building among Young Swedish Market Gardeners	Qualitative interviews of firms and literature review	Thematic analysis in NVivo
III. Urban farming with rooftop greenhouses: a systematic literature review	Systematic literature review	A SLR search was made on articles published in scientific journals.
IV. Farming as a service initiative in the making: insights from emerging proto-practices in Sweden	One single longitudinal case study with qualitative interviews, field visits and literature review	Interpretivist method to get a deeper understanding of FAAS with a reflexive methodology.

3.4 Ethical considerations

Several ethical aspects were considered when collecting data through interviews and participant observations in the empirical studies. Consent was obtained from the respondents. This also involved informing participants about the research project and that the data would be used in future scientific articles. Before participation, the respondents were also signing a consent form. The participants were always confidential when the results were reported, and the firms' names were left out in the articles for more generalisable results. It was important to investigate the need for Ethical review (Council 2017) for research with specific content. This was also explored thoroughly, but the research content was not classified as sensitive, and thus, an Ethical review was not necessary for the research connected to this thesis.

4. Results

The results will be concluded in this chapter, focusing on the main findings of the appended articles (sections 4.1-4.4). For a detailed description of the results, see the original articles, which are appended at the end of the thesis.

4.1 Adoption of technological innovations in production of leafy vegetables in Sweden (I)

The first study investigated the adoption of technological innovations in three different production systems with leafy vegetables: i) open-field crop production, ii) greenhouse production and iii) PFAL production. The empirical data came from fifteen qualitative interviews with semi-structured questions consisting of five growers from every group: i), ii) and iii). The thematic analysis from interviews resulted in five themes: (1) Production system and firm structure; (2) Technologies and innovations adopted; (3) The role of skills, knowledge and education capabilities; (4) The role of relations and networks; (5) The influence of actors within the food value chain. The empirical results were also combined with a literature review to connect the results to innovation theories described in sections 2.1-2.3.

The results showed that the adoption of technological innovations was mainly relying on what suited or was compatible with the specific production system. It also showed that firms in all three investigated production systems used several knowledge sources. The differences between the groups were that firms which employed different production systems worked in diversified social contexts, backgrounds and networks. Another finding was that PFAL systems often used shorter supply chains than more traditional production systems with open-field or greenhouse production. Table 6 presents the results from the conducted interviews.

Table 6. Characteristics of the different production systems studied

Production system	**Open-field**	**Greenhouse**	**PFAL**
Description	Open ground cultivation	Crops grown in substrate/soil	Indoor production
Number of firms	5	5	5
Start of firm (median year)	1998	1982	2014
Age interviewee (median year)	49	46	37
Crop production	Herbs, leafy vegetables, innovative vegetables (sweet potatoes, pak choi), etc.	Herbs, leafy vegetables (pot lettuce), vegetable plants, strawberry plants, etc.	Herbs, leafy vegetables, microgreens, ruccola, combined with fish, etc.

Figure 5. Photo from a larger PFAL. Photo: Annie Drottberger

4.2 Alternative food networks in food system transition—values, motivation, and capacity building among young Swedish Market (II)

The concept of sustainability in agriculture and horticulture and how economic, environmental and social concerns were aligned was briefly covered in Article II, focusing on theories connected to agroecology. This served as a departure for an improved understanding of the opportunities and challenges for firms in a transforming society and food system.

Article II focused on understanding the next generations of farmers by targeting a specific group called market gardeners. The study took an interest in both firm characteristics and the underlying motivations of the growers to contribute to a societal transition for more sustainable food production. The research questions of this second study were:

(RQ1) What characterizes the businesses of young market gardeners in Sweden?

(RQ2) What motivates young people to become market gardeners?

(RQ3) What barriers and opportunities exist for new entrants in market gardening?

The thematic analysis from interviews was categorised under 39 different codes. The codes were later connected to the following three themes: (1) general features of respondents' production systems, including firm structure and typical characteristics; (2) specific motives of young market gardeners and factors influencing their situation; and (3) barriers and opportunities for new entrants in market gardening.

The results showed that market gardeners strive for a food system change and sustainable horticulture. Market gardeners are social entrepreneurs, but economic sustainability is challenging for these firms after the start-up phase. Market gardeners face barriers due to the current political economy competing with industrial agriculture, including limited access to research-based knowledge, appropriate technology, extension services, and business support systems. They also lack certain skills necessary for daily work in the market garden, such as vegetable cultivation and financial management. However, these skills could be developed in the short term by increased focus on finance and entrepreneurship in existing adult education courses and by developing extension services that offer practical courses in small-scale vegetable cultivation techniques. In order to encourage more young people to pursue market gardening and contribute to the transformative agenda, extension workers, researchers, and policymakers must better understand the needs and characteristics of market gardeners.

4.3 Urban farming using rooftop greenhouse: A systematic literature review (III)

A systematic literature review (SLR) about the RTG technology was carried out to examine the benefits and challenges associated with this technology. The SLR was based on an extensive database search for scientific articles related to rooftop farming. The use of exclusion and inclusion criteria allowed for narrowing the search to 45 journal articles on rooftop greenhouses.

The thematic analysis of the included articles resulted in the following themes: (1) Effects of RTGs on yield; (2) Effects of RTGs on energy use; (3) Effects of RTGs on yield, water, energy use and global warming potential; (4) Environmental assessment and economic profitability of RTGs; (5) Life-cycle cost assessments of RTGs; (6) Intelligent rooftop greenhouses; (7) Potential area of implementation for RTGs; (8) Stakeholders' perceptions and social acceptance of RTGs; (9) Reviews of cases and systematic literature reviews focusing on RTGs. The categories and number of articles connected to the different themes are described in Table 8.

Table 7. Thematic categories in the reviewed articles

Thematic category	Number of articles
Effects of RTGs on yield	5
Effects of RTGs on energy use	9
Effects of RTGs on yield, water and energy use, and global warming potential	2
Environmental assessment and economic profitability of RTGs	9
Life-cycle cost assessments of RTGs	1
Intelligent rooftop greenhouses	4
Potential area of implementation for RTGs	2
Stakeholders' perceptions and social acceptance of RTGs	8
Reviews of cases and systematic literature reviews focusing on RTGs	5
Total	**45**

The findings showed that the symbiosis between RTGs and buildings improved energy use and efficiency. The RTG used heat and respired CO_2 from the host building and delivered electricity, heat, water, and food to the host building. Results also showed that RTGs reduced electricity use in comparison to PFALs. RTGs also optimised space while enhancing local food availability and job creation. The later advances of integrated and intelligent RTGs delivered even higher energy savings. The study also identified that streams of symbiotic heat, water, and CO_2 exchanges between the RTG and its host building were beneficial. Another advantage of RTGs was the potential for year-round crop production. Results highlighted that challenges with RTG technology were high investment costs and lack of flat roofs on potential host buildings. The problems connected to accessibility when cultivating on rooftops were also emphasised. In conclusion, RTG technology addresses numerous aspects of engineering design, regulatory compliance, energy efficiency, policy development and financial considerations. The study showed that RTG technology is considered a compelling option for both agriculture and sustainable urban development in the future.

4.4 Farming as a service initiative in the making: insights from emerging proto-practices in Sweden (IV)

The fourth article continued the work of article I, focusing on PFALs and service-oriented farming, specifically developing farming-as-a-service (FaaS) as a novel configuration of product service and system innovation using practice theory for the analysis. The article focused on the early uptake of digitally augmented and service-oriented farming practices. FaaS is conceptualised as emerging proto-practices where relations between elements of practices develop in contexts where other practices already exist. The results concerned; (1) Practices of prototyping FaaS; (2) Implementing FaaS in user context and (3); How proto-practices of FaaS develop in relation to context.

The results provided insights into service-oriented farming practices in user contexts and showed that implementing service-oriented farming follows a transformational process. It also revealed implications for the uptake of practices in user contexts. The meanings of these proto-practices were very different from more established horticulture since farming was made from a distance in controlled environments. Another finding was that technological competencies were needed to manage data about plants. The value claims of service-oriented farming initiatives make it important to reveal the instabilities that could limit the ability to control food production with technology and its transformative potential on market developments.

5. Discussion

This chapter discusses the research findings in relation to the background and the theoretical section (section 5.1), implications for practice and policy (section 5.2), theoretical contribution (section 5.3) and future research (section 5.4).

5.1 Discussion of findings

This thesis focuses on adoption of innovations specifically in horticulture and how firms adopt innovations, e.g. technologies or services in various production systems, where open-field, greenhouse and PFAL were explored first. In the next step, different developments of these systems were also investigated such as market gardening (open-field), rooftop greenhouse (greenhouse) and farming-as-a-service (PFAL). The systems used different innovations ranging from low-tech to high-tech and involved both product innovations/technologies and service innovations. The thesis also examined the role of knowledge and networks, as well as drivers and barriers for innovation adoption by firms or other adoption units such as organisations or networks.

The results showed that technological innovation adoption in firms depended on several variables and key elements: firm structure, technologies/innovations adopted, skills, knowledge and education capabilities, relations and networks, and influence of actors within the food chain. This was mainly explored in Article I and the results showed that at internal firm level, the adoption behaviour depended on firm/managerial characteristics in combination with the innovations' perceived benefits. This supports the diffusion of innovations theory as described by Rogers (2003). The diffusion of innovations theory has identified the decision process leading to adoption or rejection of the innovation. Rogers (2003) also mentions technology transfer, change agents, and innovation characteristics, which also goes in line with the results in Article I.

The phenomena of adoption of innovations and technologies are key to understanding the underlying processes related to innovations in horticulture. The capabilities and strategy of each firm affect how they decide to relate to sustainability and especially economic competence, as described by Carlsson and Stankiewicz (1991), was an often mentioned motivating force to maintain a competitive market position for the interviewed firms.

Adoption of innovations is an important means to solve sustainability challenges. This occurs when firms are implementing technologies and practices which are resource-efficient. At the same time, commercial horticultural businesses highlight increased competition and better profitability, which can sometimes be a complex equation to solve when considering all sustainability dimensions. Developing knowledge and information around the diffusion process regarding innovation adoption is key to understanding how horticultural firms can be a part of the sustainability transition.

The main results outlined the importance of technical innovations as a driver of the food system's transition towards higher levels of sustainability. The results also addressed how future technologies can be aligned with sustainability concerns, including economic, environmental and social aspects. It is clear that innovation in horticultural production is needed to address sustainability challenges.

5.2 Implications for practice and policy

Research on factors affecting the adoption of technological innovations in production of leafy vegetables can assist the sector in anticipating future improvements and thereby support stakeholders in future decisions. This implies that horticultural companies can gain advantages by adopting innovations faster through learning across different networks and business cultures, improving their competitiveness in the international market. Earlier adopters of innovations may be more likely to become competitive and show profitability in the long term, while late adopters may be too late to catch up and be competitive. This implies that horticultural companies can gain advantages by adopting innovations faster, thus improving their competitiveness in the international market. However, it also involves higher risks when adopting innovations. This work also provides insights into the kind of incitement needed in the future for the innovations to be adopted. Another interesting aspect is too further investigate the political climate's development and how this affects businesses over time. Implications for researchers and policymakers relate to better understanding of innovation governance in agri-food sectors, which has the potential to help society achieve sustainability goals.

5.3 Theoretical contribution

The ecosystems innovation approach (Walrave *et al.* 2018) was a suitable framework for describing the situation for the PFAL firms, which work in an environment not previously associated with horticultural production. Changing views may extend into conventional firms, broadening the view about "traditional" knowledge and innovation systems and facilitating the transition to more sustainable production systems requiring the formation of innovation niches (Elzen *et al.* 2012; Meynard *et al.* 2017). Innovation ecosystem thinking recognises a need for cross-sector interactions to facilitate transboundary innovation (Walrave *et al.* 2018) and may, therefore, contribute to expanding the scope of the AIS (Agricultural Innovation System) thinking described by Pigford *et al.* (2018). The findings fall well within innovation ecosystems thinking, especially that the wider multifunctionality of the horticultural systems can improve the potential to support transboundary innovation niches.

The production systems studied in this thesis are very different. For example, PFAL systems should not be regarded as a replacement for open-field or conventional greenhouse production but should be seen as an interesting new market and business opportunity and a contribution to existing production systems, according to Kozai *et al.* (2019). It could be expected that growers active within the horticultural industry would identify this possibility. However, the results showed that new actors primarily realised the presumed opportunities of PFAL. In contrast, established growers rarely adopted this new technology and, by extension, managed or developed PFAL firms.

Theoretically, this thesis also contributed to the literature on food systems transitioning by providing insights into the realities for a group of young vegetable growers who might represent future food entrepreneurs. The study also makes a practical contribution by suggesting focus areas for capacity building and policy development to support young people starting a market garden or similar horticultural business.

5.4 Future research

Future research of interest would involve additional interviews with firms producing vegetables in different production systems to understand the differences between greenhouse producers and other newly established initiatives, such as PFALs and RTGs. It would be interesting to get a deeper understanding of the firms’ decision processes and compare the adoption of innovations and knowledge. Another area of interest is to investigate firms’ and consumers’ attitudes to future technologies. Following the same firm over a longer time in a longitudinal case study would also provide a broader picture and show what happens after the start-up phase in the newly established firms. Another interesting aspect is to investigate the development of the political climate and how this will affect the businesses over time. Investigating the adoption of technological innovations in producing leafy vegetables can help the sector anticipate future improvements, thereby supporting stakeholders in their future decisions. Identifying barriers and needs can also contribute to informing policies to provide support.

6. Conclusions

The focus of this thesis has been on the introduction and adoption of innovations in various horticultural production systems. This chapter concludes the thesis (section 6):

- Adoption of innovations in producing leafy vegetables depends mostly on what suits the specific production system. The greenhouse and open-field firms are interested in new technologies but have limitations intrinsic to their current systems. The firms interested in new technologies are present in all investigated production systems, and the firms find knowledge in active search of best practices.

- Young market gardeners are social entrepreneurs devoted to generating income from their businesses, but they also seek a food system change with ecological production. The group faces political and economic barriers, e.g., access to research-based knowledge, suitable technology, advisory services, and financial support systems. Market gardeners lack skills related to daily work in the business, e.g., cultivation and financial management. This skill gap could be addressed by increasing focus on finance and entrepreneurship in existing education and developing advisory services for small-scale systems. Advisors, researchers, and policymakers need greater awareness of the group to support them and contribute to the transformative agenda.

- Benefits of RTG technology are the symbiotic heat, water, and CO_2 exchanges between the RTG and its host building and year-round crop production. Electric lighting of the RTG is reduced substantially compared to PFAL. RTGs use no additional land

and contribute to urban space optimisation. Intelligent rooftop greenhouses (iRTG) deliver even higher energy savings and benefits, e.g., enhanced photosynthesis by CO_2 recycling and additional water savings. Challenges with RTGs are additional investments, operational costs, limited availability of suitable flat roofs, and various urban or building regulations. RTG initiatives are exponentially increasing in number and scale, system diversity, societal acceptance and popularity among many commercial operations in large cities.

- Early uptake of service-oriented farming and digitally augmented hydroponic systems is examined in relation to the experimental practices of prototyping a product innovation in a test bed. The implementation in the user context follows a transformational process. Proto-practices analysed in relation to systems of practices show that proto-practices attach to and detach from established and stable practices. This offers limited but in-depth insights into practices of prototyping FaaS and implementing FaaS in specific user contexts.

References

Abernathy, W.J. & Clark, K.B. (1985). Innovation: Mapping the winds of creative destruction. *Research policy,* 14(1), 3-22.

Agriculture, S.B.o. (2020). *Utvärdering och uppföljning av livsmedelsstrategin - årsrapport 2020.* https://www2.jordbruksverket.se/download/18.5607cc461714d2007e77c8

Agriculture, S.b.o. (2023). Jordbruksverkets statistikdatabas. https://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets%20statistikdatabas/?rxid=5adf4929-f548-4f27-9bc9-78e127837625.

Allegaert, S., Wubben, E. & Hagelaar, G. (2020). Where is the business? A study into prominent items of the vertical farm business framework. *EUROPEAN JOURNAL OF HORTICULTURAL SCIENCE,* 85(5), 344-353.

Alvesson, M. & Kärreman, D. (2012). *Kreativ metod: skapa och lösa mysterier*. Liber.

Alvesson, M. & Sandberg, J. (2011). Generating research questions through problematization. *Academy of management review,* 36(2), 247-271.

Alvesson, M. & Sköldberg, K. (2017). *Reflexive methodology: New vistas for qualitative research*. sage.

ASHS (2016). *What is horticulture?* [2023-10-18]

Augier, M. & Teece, D.J. (2021). *The Palgrave encyclopedia of strategic management*. Palgrave Macmillan.

Bessant, J. & Davies, A. (2007). Managing service innovation. *Innovation in services,* 9, 61-96.

Blättel-Mink, B., Boddenberg, M., Gunkel, L., Schmitz, S. & Vaessen, F. (2017). Beyond the market—New practices of supply in times of crisis: The example community-supported agriculture. *International Journal of Consumer Studies,* 41(4), 415-421.

Boyatzis, R.E. (1998). *Transforming qualitative information: Thematic analysis and code development*. sage.

Braun, V. & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology,* 3(2), 77-101.

Bryman, A. (2016). *Social research methods*. Oxford university press.

Burman, C., Davelid, A., Edström, F., Lindström, S. (2023). *Uppföljning och utvärdering av livsmedelsstrategin - årsrapport 2023*. Jönköping. [2023-10-24]

Carlsson, B., Jacobsson, S., Holmén, M. & Rickne, A. (2002). Innovation systems: analytical and methodological issues. *Research policy,* 31(2), 233-245.

Carlsson, B. & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of evolutionary economics,* 1, 93-118.

Cassell, C. & Symon, G. (2012). Qualitative organizational research. *Qualitative Organizational Research*, 1-544.
Castilla, N. & Hernandez, J. (2006). Greenhouse technological packages for high-quality crop production. In: *XXVII International Horticultural Congress-IHC2006: International Symposium on Advances in Environmental Control, Automation 761*. 285-297.
Christensen, C.M. & Rosenbloom, R.S. (1995). Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network. *Research policy,* 24(2), 233-257.
Cohen, W.M. & Levinthal, D.A. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative science quarterly*, 128-152.
Council, S.R. (2017). *GOOD RESEARCH PRACTICE*. Stockholm.
Creswell, J.W. & Poth, C.N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications.
Dalgaard, T., Hutchings, N.J. & Porter, J.R. (2003). Agroecology, scaling and interdisciplinarity. *Agriculture, ecosystems & environment,* 100(1), 39-51.
DESA, U. (2019). World Urbanization Prospects 2018: Highlights (ST/ESA/SER. A/421. United Nations, Department of Economic and Social Affairs (UN DESA). *Population Division, New York, NY, USA*.
Ekelund, L.H., T.; Johnson, L.; Kristoffersson, A.; Lundqvist, S.; Malmström, F.; & Nilsson, U.P., B.; Persson, M.; Sandin, H. & Spendrup, S. (2017). *Branschbeskrivning Trädgård*. (ISBN 978-91-576-9536-9). Alnarp.
Elzen, B., Barbier, M., Cerf, M. & Grin, J. (2012). Stimulating transitions towards sustainable farming systems. In: *Farming Systems Research into the 21st century: The new dynamic*. Springer. 431-455.
FAO (1988). *Report of the FAO Council*. Rome.
Fernqvist, F. & Göransson, C. (2021). Future and recent developments in the retail vegetable category–a value chain and food systems approach. *International Food and Agribusiness Management Review,* 24(1), 27-49.
Ferraro, F., Etzion, D. & Gehman, J. (2015). Tackling grand challenges pragmatically: Robust action revisited. *Organization studies,* 36(3), 363-390.
Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative inquiry,* 12(2), 219-245.
Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food policy,* 36, S23-S32.
Guest, G., Namey, E.E. & Mitchell, M.L. (2013). Collecting Qualitative Data: A Field Manual for Applied Research. 55 City Road, London.
Hall, A., Janssen, W.G., Pehu, E. & Rajalahti, R. (2006). *Enhancing agricultural innovation: how to go beyond the strengthening of research systems*.
James, K.L., Randall, N.P. & Haddaway, N.R. (2016). A methodology for systematic mapping in environmental sciences. *Environmental evidence,* 5, 1-13.

Johansson, R. (2007). On case study methodology. *Open house international,* 32(3), 48-54.
Katsamakas, E. (2014). Value network competition and information technology. *Human Systems Management,* 33(1-2), 7-17.
Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: concept, estimation and application to plant factory. *Proc Jpn Acad Ser B Phys Biol Sci,* 89(10), 447-61. https://doi.org/10.2183/pjab.89.447
Kozai, T., Niu, G. & Takagaki, M. (2019). *Plant factory: an indoor vertical farming system for efficient quality food production*. Academic press.
Kvale, S. & Brinkman, S. (2017). Den kvalitativa forskningsintervjun (Vol., 3: 5). Studentlitteratur.
Lam, A. (2005). Organizational innovation. The Oxford handbook of innovation Oxford. Oxford University Press.
Lapadat, J.C. & Lindsay, A.C. (1999). Transcription in research and practice: From standardization of technique to interpretive positionings. *Qualitative inquiry,* 5(1), 64-86.
Leeuwis, C. (2013). *Communication for rural innovation: rethinking agricultural extension*. John Wiley & Sons.
Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y. & Raubenheimer, D. (2022). Global food-miles account for nearly 20% of total food-systems emissions. *Nature food,* 3(6), 445-453.
Ltd., Q. (2018). *NVivo Qualitative Data Analysis Software; 1.4 (4)*. [Programvara]. Melbourne, Australia.
Martin, M. & Bustamante, M.J. (2021). Growing-service systems: new business models for modular urban-vertical farming. *Frontiers in Sustainable Food Systems,* 5, 787281.
Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B. & Michon, C. (2017). Designing coupled innovations for the sustainability transition of agrifood systems. *Agricultural Systems,* 157, 330-339.
Mingers, J. (2001). Combining IS research methods: towards a pluralist methodology. *Information systems research,* 12(3), 240-259.
Nations, U. (2015). Transforming our world: The 2030 agenda for sustainable development. *New York: United Nations, Department of Economic and Social Affairs*.
OECD (2019). *Innovation, Productivity and Sustainability in Food and Agriculture*. https://doi.org/doi:https://doi.org/10.1787/c9c4ec1d-en
Okasha, S. (2016). *Philosophy of Science: A Very Short Introduction*. Oxford University Press. https://doi.org/10.1093/actrade/9780192802835.001.0001
Orsini, F., Pennisi, G., Michelon, N., Minelli, A., Bazzocchi, G., Sanye-Mengual, E. & Gianquinto, G. (2020a). Features and Functions of Multifunctional Urban Agriculture in the Global North: A Review. *Frontiers in Sustainable Food Systems,* 4, 27. https://doi.org/10.3389/fsufs.2020.562513

Orsini, F., Pennisi, G., Zulfiqar, F. & Gianquinto, G. (2020b). Sustainable use of resources in plant factories with artificial lighting (PFALs). *Eur.J.Hortic.Sci.,* 85(5), 297-309. https://doi.org/10.17660/eJHS.2020/85.5.1

Persson, J. (2020). *Trädgårds-undersökningen 2020. Kvantiteter och värden avseende 2020 års produktion*. (Sveriges Officiella Statistik). Jönköping: Jordbruksverket.

Pigford, A.-A.E., Hickey, G.M. & Klerkx, L. (2018). Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. *Agricultural Systems,* 164, 116-121.

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M. & Steduto, P. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio,* 46, 4-17.

Rogers, E.M. (2003). *Diffusion of innovations*. Simon and Schuster.

Röling, N. (1988). *Extension science: Information systems in agricultural development*. CUP Archive.

Saini, R.K., Ko, E.Y. & Keum, Y.-S. (2017). Minimally processed ready-to-eat baby-leaf vegetables: Production, processing, storage, microbial safety, and nutritional potential. *Food reviews international,* 33(6), 644-663.

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., Matthews, E. & Klirs, C. (2019). Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050. Final report. WRI.

Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.O., Roberts, D., Zhai, P., Slade, R., Connors, S. & Van Diemen, R. (2019). IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Stanghellini, C., Van't Ooster, B. & Heuvelink, E. (2019). Greenhouse horticulture: Technology for optimal crop production. In: *Greenhouse horticulture*. Wageningen Academic.

Sternberg, R. & Arndt, O. (2001). The firm or the region: what determines the innovation behavior of European firms? *Economic geography,* 77(4), 364-382.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B. & Sawicka, M. (2015). Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renewable Agriculture and Food Systems,* 30(1), 43-54. https://doi.org/10.1017/s1742170514000143

Tidd, J. & Bessant, J.R. (2020). *Managing innovation: integrating technological, market and organizational change*. John Wiley & Sons.

Trienekens, J., van Uffelen, R., Debaire, J. & Omta, O. (2008). Assessment of innovation and performance in the fruit chain: the innovation-performance matrix. *British Food Journal,* 110(1), 98-127.

Verhees, F.J. & Meulenberg, M.T. (2004). Market orientation, innovativeness, product innovation, and performance in small firms. *Journal of small business management,* 42(2), 134-154.

Walrave, B., Talmar, M., Podoynitsyna, K.S., Romme, A.G.L. & Verbong, G.P. (2018). A multi-level perspective on innovation ecosystems for path-breaking innovation. *Technological forecasting and social change,* 136, 103-113.

Weil, R.R. (1990). Defining and using the concept of sustainable agriculture. *Journal of Agronomic Education,* 19(2), 126-130.

Zhang, D.Q., Gersberg, R.M., Ng, W.J. & Tan, S.K. (2017). Conventional and decentralized urban stormwater management: A comparison through case studies of Singapore and Berlin, Germany. *Urban Water Journal,* 14(2), 113-124. https://doi.org/10.1080/1573062x.2015.1076488

Popular science summary

How can the adoption of sustainable innovations solve our future food needs? What different ways are there to develop a robust food system and simultaneously include all dimensions of sustainability? When it comes to vegetable production, there are various technological solutions and production systems, such as open-field cultivation, market gardening, greenhouse production and vertical cultivation in plant factories. Innovations are constantly being developed, but not all of them are adopted by the growers, depending on the different conditions between the production systems. This thesis aims to investigate how the adoption of innovations affects the horticulture sector. This is investigated by mapping which innovations are used in horticultural production systems. In addition, it examines which driving forces and obstacles promote or inhibit companies' adoption of innovations. Finally, which networks and the practices used in the companies are examined.

The companies studied in the thesis have different individual business characteristics and, based on that, have made different decisions regarding investing in innovations. Knowledge of innovations in the various systems comes from social or professional networks, the Internet, international contacts, fairs or universities, which varies between the various production systems. The uptake of innovations largely depends on what suits the production system.

One potentially surprising result of the study is the significant difference in the background of the entrepreneurs between the different production systems. Entrepreneurs with PFAL systems and market gardening more often have backgrounds unrelated to horticultural production than those with conventional systems (open-field and greenhouse production). This means that efforts to promote the uptake of technological innovations should be designed to suit target groups with very different backgrounds. PFAL companies have also started their operations in the last ten years, and the

interviewed company managers are younger than in already established companies. It is also apparent that communication and network relationships between conventional systems and PFAL are currently lacking. In addition, there is a lack of grower networks that cater to entrepreneurs with PFAL.

When it comes to system innovations, field growers have focused on packaging and automation, while greenhouse growers were more interested in energy-saving technology, irrigation water recirculation, and LED lighting. Growers with PFAL systems focused on knowledge and investments related to vertical growing, hydroponic growing techniques and LED lighting. In recent times, business models with farming-as-a-service have also been used, where cultivation takes place in the grocery trade but is controlled remotely by the cultivation company, which becomes a technology supplier. The systematic literature review regarding rooftop greenhouses also showed that the technology where the greenhouse used heat and CO_2 from the host building and delivered electricity, heat, water and food to the host building is interesting. The recent advances in integrated and intelligent rooftop greenhouses also provided even higher energy savings.

Studying how new technologies are adopted and integrated into conventional systems is important, as the volumes and range of crops they produce cannot be replaced by PFAL (at least in the near future). These systems can greatly benefit from technological developments. Greenhouse and field growers are interested in new technologies, but different innovations are more or less relevant and compatible with current systems. This should be recognised to a greater extent to support companies according to their specific situation. Companies interested in new technologies use different sources of knowledge depending on the internal and external business environment. Overall, the problems firms face in different production systems affect how these firms decide to adopt technological innovations. The results from the study could serve as support for the industry, decision-makers and actors within the innovation system to promote technical development in Swedish horticulture, regardless of the production system in which the companies operate.

Populärvetenskaplig sammanfattning

Hur kan upptagandet av hållbara innovationer lösa våra framtida behov av mat? Vilka olika vägar finns för att utveckla ett robust livsmedelssystem och samtidigt ha med alla hållbarhetsdimensioner? När det gäller grönsaksproduktion finns olika tekniska lösningar och produktionssystem såsom frilandsodling, market gardening (småskalig hantverksmässig odling), växthusproduktion och vertikalodling i växtfabriker (PFAL). Nya innovationer utvecklas ständigt men långt ifrån alla fångas upp av odlarna beroende på olika förutsättningar mellan produktionssystemen. Syftet med avhandlingen är att undersöka hur upptagandet av innovationer påverkar trädgårdssektorn. Detta utreds genom att kartlägga vilka innovationer som används inom trädgårdsproduktionssystem. Dessutom undersöks vilka drivkrafter och hinder som främjar eller hämmar företagens upptagande av innovationer. Slutligen granskas vilka nätverk och den praxis som används i företagen.

Företagen som studerats i avhandlingen har olika individuella affärsegenskaper och har med utgångspunkt i det tagit olika beslut rörande att investera i innovationer. Kunskap om innovationer i de olika systemen kommer från sociala eller professionella nätverk, internet, internationella kontakter, mässor eller universitet, vilket varierar mellan de olika produktionssystemen. Upptagande av innovationer beror till stor del på vad som passade produktionssystemet.

Ett kanske överraskande resultat i studien är den stora skillnaden i företagarnas bakgrund mellan de olika produktionssystemen. Företagare med PFAL-system och market gardening har oftare en bakgrund som inte haft koppling till trädgårdsproduktion jämfört med konventionella system (friland- och växthusproduktion). Detta innebär att insatser för att främja upptagandet av tekniska innovationer bör utformas för att passa målgrupper med mycket olika bakgrund. PFAL företag har dessutom startat sin verksamhet under de senaste tio åren och de intervjuade företagsledarna är yngre än i mer traditionella företag. Det är också påtagligt att kommunikations- och nätverksrelationer mellan konventionella system och PFAL för närvarande saknas. Dessutom saknas odlarnätverk som vänder sig till företagare med PFAL.

När det gäller innovationer inom systemen så har odlare med frilandsproduktion fokuserat på förpackningar och automatisering medan odlare med växthusproduktion var mer intresserade av energibesparande teknik, återcirkulation av bevattningsvatten och LED-belysning. Odlare med PFAL-system fokuserade på kunskap och investeringar relaterade till vertikalodling, hydroponiska odlingstekniker och LED-belysning. På senare tiden har även affärsmodeller med farming-as-a-service använts där odlingen sker i dagligvaruhandeln men styrs på distans av odlingsföretaget som blir en teknikleverantör. Den systematiska litteraturgenomgången som gjorts rörande takväxthus visade även att teknologin där växthuset använde värme och CO_2 från värdbyggnaden och samtidigt levererade el, värme, vatten och mat till värdbyggnaden är intressant. De senare framstegen med integrerade och intelligenta takväxthus gav dessutom ännu högre energibesparingar.

Att studera hur ny teknik tas upp och integreras i de konventionella systemen är viktigt, eftersom volymerna och utbudet av grödor de producerar inte kan ersättas med PFAL (åtminstone inom en snar framtid). Dessa system kan dra stor nytta av den tekniska utvecklingen. Växthus- och frilandsodlare är intresserade av ny teknik, men olika innovationer är mer eller mindre relevanta och kompatibla med nuvarande system. Detta bör erkännas i större utsträckning, för att stödja företagen i enlighet med deras specifika situation. Företag som är intresserade av ny teknik använder olika kunskapskällor, beroende på den interna och externa affärsmiljön. Sammantaget påverkar de olika problemen hos företag i olika produktionssystem det sätt på vilket dessa företag beslutar om upptagande av tekniska innovationer. Resultatet från studien kan vara ett stöd för branschen, beslutsfattare och aktörer inom innovationssystemet för att främja den tekniska utvecklingen inom svensk trädgårdsnäring oavsett vilket produktionssystem företagen verkar inom.

Acknowledgements

I would like to thank the participants in the studies for sharing their thoughts and views on adoption of innovations in horticulture. All these meetings have given me insights and positive energy to continue the journey and learn more about the different contexts where innovations are adopted. A special note of appreciation goes to the Federation of Swedish Farmers and SweGreen for their valuable industry insights, shedding light on what transpires beyond the confines of the academic world.

I also want to thank my main supervisor, Karl-Johan Bergstrand, for always being there with constructive answers. You were happy to solve whatever problem that came up along the way in a calm way. In addition, you have always believed in me and stayed positive about my work. I also want to thank my four assistant supervisors, who have all been highly involved in the process. Lena Ekelund Axelson; you were the biggest source of inspiration for me since I began my studies in horticultural science in the year 2000. When you came into the classroom and taught me about horticultural economics, I knew I was at the right place. I also want to thank Sara Spendrup, for constructive discussions and your positive attitude when we were digging deeper in to new innovative fields together. Fredrik Fernqvist, I want to thank you for your support and feedback especially during my first years as a PhD student when you introduced new concepts that broadened my understanding for innovation theories. I also want to thank Marie-Claude Dubois, who with your technical knowledge and sharp mind inspired me to get involved with rooftop greenhouse technology. In addition I want to thank my additional co-authors; Martin Melin, Lotten Lundgren, Yizhi Zhang, Jean Yong and Per-Anders Langendahl for interesting discussions and great teamwork in developing studies and writing articles together. I would also like to extend my gratitude to Per-Anders Langendahl for insightful comments and observations during the half-time seminar. I want to thank Fredrika Mårtensson for the preview of my final thesis with constructive much appreciated feedback. A special thanks to the funders of this study, the Faculty of Landscape Planning, Horticulture and Agricultural Science, the department of Biosystems and Technology and the NextFood project of the Horizon 2020 program. Your support has been highly necessary for this PhD project.

I want to thank my colleagues at the Department of Biosystems and Technology and the Department of People and Society, to be able to turn to you and be part of the positive atmosphere at the work place have filled me with energy to continue the work. This has been invaluable especially during challenging times. Especially Jean Yong, Lotta Nordmark, Andrus Kangro and Helene Larsson Jönsson; you have stood by my side and supported me whenever I needed someone to talk to or to solve world problems from my horizon. I also want to highlight fellow PhD students – thank you for a great community and the positive attitude. To the horticultural students I have thought when working as a teacher – you are a true inspiration and your insights inspire me and broaden my views. I also want to thank my dear friends for your support, especially my Lund gang and my Malmö gang.

The most important person for me to be able to finish this thesis is my husband Andreas. Your calm and loving energy and the care for our boys has been crucial for me to complete my journey and finish my PhD studies. In addition you were a positive influence and technician for me during the pandemic at home office to be able to finish my articles with a professional appearance. I also want to thank my family and relatives, especially my mum Ann who has been like an extra mum to my boys and always added positive adventures to their lives, while I was writing. I want to thank my brothers Axel with your insightful thoughts and Arvid, who is always with me in my heart. Last but not least – my boys Simon, Isaac and Anton, finally the hard work is over! Thank you for staying with me and bringing me back to reality during stressful periods. You, my sons are the biggest inspiration in my life and being your mother motivates me to make a difference for a better sustainable world.

Annie Drottberger, October 2023

I

Original article

Adoption of technological innovations in production of leafy vegetables in Sweden

A. Drottberger[1], K.-J. Bergstrand[1], F. Fernqvist[2] and S. Spendrup[2]

[1] Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Lomma, Sweden

[2] Swedish University of Agricultural Sciences, Department of People and Society, Lomma, Sweden

Summary

Leafy vegetable production represents high commodity and trade values. Consumption has increased, and will continue doing so according to trading operators. This study examined production of leafy vegetables in different systems and adoption of technological innovations from the firms' perspective. A qualitative approach was applied to investigate technological innovation adoption in three different production systems: open-field, greenhouse and plant factories with artificial lighting (PFAL). Fifteen owners/managers (five per production system) were interviewed, using semi-structured questions. The firms differed in individual business characteristics and in their decisions to adopt innovations and knowledge. Open-field growers focused on packaging and automation. Growers with closed production systems (greenhouses) were more interested in energy-saving technologies, recirculation of irrigation water and LED lighting. Growers with PFAL systems opted for vertical farming, hydroponic growing techniques and LED lighting. Sources of knowledge on innovations included networks, the internet, international contacts, trade shows, extension services and universities. Overall, adoption of innovations largely depended on what suited the production system. Open-field and greenhouse firms were more interested in new technologies, but certain characteristics in their current systems determined whether an innovation was appropriate. Firms interested in new technologies actively searched for best practice using knowledge inputs from multiple sources.

Keywords
greenhouse, horticulture, hydroponics, innovation, LED lighting, plant factory, urban agriculture, vertical farming

Significance of this study

What is already known on this subject?

- Studies often focus on environmental or technological aspects of one production system. Research on PFAL systems highlights efficient use of natural resources, but PFAL have higher energy needs and production costs.

What are the new findings?

- Comparison of different production systems showed that adoption of technological innovations is highly dependent on what suits the specific production system. Firms in all production systems use a wide range of sources to obtain knowledge, but operate in different social contexts, backgrounds and networks. PFAL systems often use shorter supply chains.

What is the expected impact on horticulture?

- Awareness of adoption of technological innovations and knowledge uptake in different leafy vegetable production systems can improve business strategy development and decision-making on acquisition of innovations and knowledge in horticultural firms.

Introduction

Society is facing serious challenges, *e.g.,* destruction of natural ecosystems, loss of biodiversity and climate change (IPCC, 2019). This is occurring in combination with increasing population and urbanisation, requiring increased food production and transformation of the food system to more sustainable production (World Resources Institute, 2019). One solution to these challenges could be increased adoption of knowledge and technical innovations in food-producing firms. Sustainability concerns, in combination with increased consumer demand for healthy and nutritious food, have led to a growing market for leafy vegetables (Fernqvist and Göransson, 2021; Saini et al., 2017). Horticultural products are seen as key in transitioning towards more sustainable food consumption, due to their high nutritional value (Saini et al., 2017) and low climate impact (Garnett, 2011). Adoption of technical innovations in Swedish leafy vegetable production is important to increase competitiveness on the European market. Apart from the economic perspective, there is also a need to consider environmental and social issues and find alternative technological innovations that move production systems in an efficient and sustainable direction.

Production of lettuce, other leafy vegetables and herbs currently mainly takes place in open-field and greenhouse systems. Open-field production systems for leafy vegetables are relatively intensive, involving irrigation (sometimes fertigation) and specialist machinery. Innovations over the last decade have mainly focused on further automations to facilitate the heavy workload for labour in the field whilst still focusing on maintaining a high-quality product. Precision agriculture is a further development in employing new technology, *e.g.,* multispectral cameras on drones and sensors on tractors to adapt seed, fertiliser and crop protection to the field. Greenhouses comprise a wide range of structures, from simple plastic-covered unheated types with low technical standard (southern-type greenhouses) to high-technology, glass greenhouses with computerised climate control, artificial lighting, CO_2 supply etc. (northern-type greenhouses) (Castilla and Hernandez, 2006; Stanghellini et al., 2019). Innovations in greenhouse production includes climatization, lighting, irrigation, mechanization in greenhouse and hydroponics. PFAL systems have emerged recently, mainly driven by the introduction of LED technology.

The PFAL is a refinement of the high-technology greenhouse in which all climate factors, including light, can be fully controlled and natural light can be replaced with artificial light (Kozai, 2013). Production of leafy vegetables in PFAL may add valuable improvements and underpin innovation and technological development of the food system, thus contributing to increased resilience and mitigating climate change. However, PFAL have higher energy demand than conventional food systems, in combination with increased system resource use efficiency (Orsini et al., 2020). When operating in a cold climate, the PFAL system is comparable to a greenhouse system. In terms of energy supply, choosing high-efficiency LED can improve and enhance energy use in PFAL (Zhang and Kacira, 2020). According to Orsini et al. (2020), the main advantages of PFAL are stable year-round production and improved quality (both achieved through a controlled environment), reduced distance to consumers and improved resource use efficiency. However, unless the energy equation is solved, there will be difficulties in achieving economies of scale (Allegaert et al., 2020).

Production in PFAL normally takes place in multiple layers, a system sometimes referred to as vertical farming (VF) or stacking horticulture. Production is always based on hydroponic principles, *i.e.,* the system is fed with nutrient solution (Butturini and Marcelis, 2020; Despommier, 2010; Kozai, 2013; Kozai et al., 2019). PFAL are often located in urban areas, *e.g.,* in basements, on rooftops or in abandoned industrial premises, and may be included in the concept of urban farming (Thomaier et al., 2015). In addition to high-tech smart farms such as PFAL, there are other niche initiatives for small-scale production of vegetables, *e.g.,* community-supported agriculture (CSA) or market gardening, focusing on sustainable production systems, but not employing technological innovations and solutions to the same extent (Drottberger et al., 2021). PFAL are thus technological systems that enable production in new settings, such as urban areas and indoor, closed systems. They also provide energy-saving alternatives for water and nutrient circularity and increased opportunities for control of production, and enable cultivation to be performed closer to consumers in urban areas. PFAL production is dominated by leafy vegetables and herbs, but rapid technological development creates opportunities to grow other crops, *e.g.,* peas, beans and kale (Bergstrand, 2020).

Wide-scale introduction of LED technology has extended to the horticulture sector, paving the way for commercial introduction of PFAL and for significant improvements in efficiency in conventional greenhouse production. PFAL are at the forefront of technology, but innovations such as renewable energy, climate control and LED are being implemented within existing systems, with, *e.g.,* use of renewable energy in greenhouse production increasing by 27% between 2014 and 2017 and only 18% of energy use in 2017 coming from fossil sources (Swedish Board of Agriculture, 2018). Important driving forces were introduction of a carbon dioxide tax on non-renewable fuels (Nilsson et al., 2015) and societal trends for reduced energy consumption and higher energy efficiency (Swedish Board of Agriculture, 2018).

Total Swedish horticultural output in 2019 was worth 570 million Euros, with open-ground cultivation accounting for 58% and greenhouse production for 42% of total production value (Swedish Board of Agriculture, 2020). In greenhouse production the value of potted lettuce decreased by 32%, between 2018 and 2019, while potted aromatic plants increased by 24% in value (Swedish Board of Agriculture, 2020). Other changes include decreased production of iceberg lettuce and increased production of other lettuces, often pre-packed in plastic bags (Fernqvist and Göransson, 2021). There are, however, difficulties when comparing output from different production systems. Official Swedish statistics on horticultural production, provided by the Swedish Board of Agriculture, do not include comparable numbers between production systems. Leafy vegetables from open-field production are typically recorded in tonnes, whereas lettuce and fresh herbs from greenhouse production are recorded in number of plants or pots (Swedish Board of Agriculture, 2021). Further, only production units (businesses) larger than 0.25 ha are represented in statistics, meaning that PFAL businesses with production area less than 0.25 ha are not included (*ibid.*). There are currently only nine initiatives (firms) in Sweden that can be categorised as being PFAL systems (Langendahl, 2020). Since there are no current data on production of leafy vegetables in PFAL (neither on yield or production area), sources such as online corporate media (firm websites and Facebook) must be used as a basis to describe the industry. Table 1 shows production of leafy vegetables and herbs in 2020.

Firms that have invested in a particular technology are generally less receptive to new technologies involving further capital investment. This leads to a lock-in effect whereby large investments in a particular technology hinder adoption of new innovations (Abernathy and Clark, 1985; Sherry, 2016). To prevent such firms falling behind in technological development and losing competitiveness, it is important to understand technological uptake and sources of knowledge used by firms with different production systems.

Table 1. Production of leafy vegetables in Sweden (based on data from Swedish Board of Agriculture, 2021).

Production system	Crop	No. of firms	Area (m^2)	Yield (tonnes)	Yield (× 1,000 plants)
Open-field	Iceberg lettuce	55	8,540,000	18,840	
Open-field	Lettuce (not iceberg)	105	11,820,000	9,949	
Open-field	Spinach	21	740,000	196	
Greenhouse	Lettuce in pot	15	40,185		11,423
Greenhouse	Lettuce (not in pot)	24	57,475		3,780
Greenhouse	Fresh herbs	52	123,944		47,115
PFAL	Leafy vegetables, herbs	9	–	–	–

Table 2. Firm characteristics and distribution channels.

Firm	System	Gender	Age	Start firm (yr)	Production area (m^2)	Employees (nr)	Educational background manager	Production	Distribution channels
O1	Open-field	Male	61	2002	850,000	20	Agriculturist, university	Strawberries, herbs, beetroots, fennel	Producer organisation, supermarkets
O2	Open-field	Female	49	1996	300,000	90	Economy, human resources	Salads, Chinese cabbage, cauliflower, leek, babyleaves	Producer organisation, supermarkets
O3	Open-field	Male	28	2018	70,000	1	Agriculture, polytechnic education	Savoy cabbage, pak choi, lettuce	Producer organisation, supermarkets
O4	Open-field	Male	57	1998	200,000	9	Agricultural technologist, university	Cauliflower, broccoli, lettuce, white cabbage	Producer organisation, supermarkets
O5	Open-field	Female	31	1984	900,000	4 + seasonal staff	Horticultural engineer, university	Salads, pumpkins, kale, leek, sweet potatoes, asparagus	Producer organisation, supermarkets
G6	Greenhouse	Male	61	1935	8,200	13	Gardener, polytechnic education	Herbs and pot lettuce	Producer organisation, supermarkets
G7	Greenhouse	Male	58	1953	5,000	29	Gardener, polytechnic education	Herbs, pot lettuce, vegetable plants, strawberry plants	Local supermarkets and restaurants
G8	Greenhouse	Female	46	1997	38,000	101	Economist, university	Herbs and pot lettuce	Producer organisation, supermarkets
G9	Greenhouse	Female	40	1982	50,000	80	Horticulture/agriculture, university	Herbs and pot lettuce	Supermarkets
G10	Greenhouse	Male	41	1988	20,000	59	Horticulture, university	Herbs and pot lettuce	Supermarkets and restaurants
P11	PFAL, integrated	Male	37	2012	Start-up stage	2	Horticultural engineer, university	Herbs, cale, babyleaves, fish	CSA (community supported agriculture)
P12	PFAL, own building	Male	72	2012	Start-up stage	0	Horticulturist, university	Vegetables, fish	None
P13	PFAL, container	Male	59	2018	200	2	Community planner, grocery trade	Babyleaves, herbs, etc.	Not relevant (showroom/supplier of tech)
P14	PFAL, integrated	Female	30	2014	100	9	IT, economist, university	Babyleaves, herbs, salads, cale, microgreens, etc.	Direct sale supermarkets and restaurants
P15	PFAL, integrated	Male	30	2016	300	10	IT, business developer, university	Ruccola	Direct sale supermarkets

This study examined adoption of technological innovations within horticultural production. The definition of innovation applied was that by Rogers (2003: p. 12) "…an idea, practice, or object that is perceived as new by an individual." The perceived newness of an idea determines the user's reaction, *i.e.,* if an idea seems new to an individual, it is defined as an innovation (Rogers, 2003).

The aim of this study was to describe production conditions and investigate adoption of technological innovations in three different leafy vegetable production systems at firm level: i) open-field crop production; ii) greenhouse production; and iii) PFAL production (including VF). This was done by describing and comparing the production systems, assessing main drivers for adopting technological innovations and exploring the main sources of knowledge in the adoption process.

The theory of adoption of innovations

According to Rogers (2003), a firm follows a process prior to deciding on adoption of innovations. The process starts with a person gaining knowledge of an innovation, then forming an attitude to the innovation and finally making a decision to adopt, leading to implementation of the innovation. However, there are individual differences in how quickly a firm decides to adopt an innovation. Firms categorised as early adopters of innovations often seek to exploit "first-mover advantages" (Christensen and Rosenbloom, 1995). First movers can make a technology or product difficult to replicate for later entrants by applying for patents to protect and establish their first-mover advantage (Lieberman and Montgomery, 1998).

Strategies and innovation decisions by firms, and their adoption processes, are influenced by internal skills and capabilities. Technological capabilities and organisational dynamics are seen as key for competitive ability (Lam, 2005) and for economic competence, described as the ability to develop and exploit new business opportunities (Carlsson and Stankiewicz, 1991). Absorptive capacity, *i.e.,* the ability to recognise the value of new, external information, assimilate it and apply it in a commercial setting, is also critical for firms' innovative capabilities (Cohen and Levinthal, 1990). Technology transfer to date has been shown to be difficult and prone to failure (Rogers, 2003), often due to underestimation of the effort required for transfer to occur effectively. This suggests that, for commercialisation of technology, research results must be packaged in a way that makes it easy for firms to implement and adopt the new findings. Change agents, defined as individuals who work to influence clients' innovation decisions in a direction deemed desirable by a change agency, can also be of critical importance for adoption of innovations (*ibid.*). Another aspect of great importance is sources of knowledge, *e.g.,* social networks, colleagues and relations with value-chain actors, which may influence knowledge uptake by the individual firm. This can be viewed as a value network, so a firm that formerly competed with other firms must shift to compete with other networks. When competition shifts to the network level, little is currently known about how value networks perform (Christensen and Rosenbloom, 1995; Katsamakas, 2014).

The agricultural innovation systems (AIS) concept is intended to act as an organising framework that strengthens the capacity to innovate and create novelty throughout agricultural production and marketing (Hall et al., 2007). The more recent concepts of innovation ecosystems thinking and transition to sustainable agriculture require the formation of innovation niches (Elzen et al., 2012; Meynard et al., 2017). Innovation ecosystems thinking conceptualises the need for cross-sector interactions to facilitate transboundary innova-

Table 3. Initial coding and final coding of the interviews.

Initial coding (themes)	Final coding (themes)
1. *Firm characteristics* 2. *Manager characteristics*	*1. Production system and firm structure* a. Production (crops, cultivars, standards) b. Firm/owner/manager characteristics c. Education d. Financing/Investments
3. *Adoption of innovation*	*2. Technologies/innovations adopted* a. Adoption process b. Type of technology/innovation c. Sustainability (economic, environmental, social) d. Crop quality e. Lock-in effects
4. *Knowledge uptake*	*3. The role of skills, knowledge and education* capabilities a. Sources of knowledge b. Decision-making *4. The role of relations and networks* a. Type of network b. Cooperation c. Knowledge input
5. *Sales and marketing*	*5. The influence of actors within the food value chain* a. Market demand b. Retail c. Consumers d. Producer organisations e. Distribution f. Suppliers (technological equipment) g. Initiating new crops/cultivars

tion (Walrave et al., 2018), which can contribute to expanding the scope of AIS thinking (Pigford, 2018). Formation of transboundary innovation niches involves modifying or redefining boundaries, for the purpose of solving social and planetary problems and achieving sustainable development. Innovation ecosystems thinking may offer a useful umbrella concept that is suitable for the wider multifunctionality of agricultural systems, with higher potential to support development of transboundary innovation niches designed to realise innovation in support of sustainability (*ibid.*).

Materials and methods

To investigate and assess main drivers for adoption of technological innovations at firm level, a qualitative approach (Guest et al., 2013) was deemed suitable. Data were collected in semi-structured interviews with respondents (producers of leafy vegetables) from the three different production systems; open-field, greenhouse and PFAL (including VF).

To ensure high relevance of respondents to the research question, purposive sampling of respondents (Bryman, 2012) was carried out. Potential respondents were identified in collaboration with the Federation of Swedish Farmers (LRF). The selection criterion set for interviewees was that they were either owners or employees with production responsibility. Potential respondents were initially contacted through email and provided with brief information about the aim and scope of the study. Due to low initial response rate, respondents were also contacted by telephone. Thus, relevant respondents were identified through a combination of internet searches and chain-referral (snowball) sampling (Bryman, 2012). The procedure continued until contact was established with 15 firms in total, five open-field (firms O1–O5), five greenhouse (firms G6–G10), and five PFAL (firms P11–P15). Twelve of the respondents were owners and three were managers. Ten respondents were male and five female, and the age range was 30–72 years. A majority of the respondents managed single or family/partner-run firms ($n=13$). One respondent represented a network and one a non-profit association. Pooled and averaged data on the respondents' firms (production system, year the company was founded, main production enterprise) and demographic data on the respondents (gender, age, educational background) are presented in Table 2. Each interview lasted 30–60 minutes. Three interviews were conducted face-to face, since the respondents were located nearby, while the remaining 12 interviews were conducted by telephone. All interviews were carried out between September 2019 and January 2020, using a semi-structured interview guide covering five major themes: 1) firm characteristics; 2) manager characteristics; 3) sales and marketing; 4) adoption of innovations; and 5) knowledge uptake. See Table 2 for further details concerning firm characteristics.

Interviews were recorded and transcribed (Lapadat and Lindsay, 1999), and supplementary notes were made during or immediately after each interview. The transcripts were analysed in depth using thematic coding, following the steps in Braun and Clarke (2006). Initially, the transcribed material was analyzed and coded in relation to themes 1–5 presented in Table 3 (initial coding). These themes are based on the theoretical framework presented in section 2 (adoption of innovation). Thereafter the coded material was further analysed, resulting in revised themes and several sub-themes, see Table 3, (final coding). NVivo qualitative data analysis software (QSR International Pty. Ltd., 2018) was used for coding the material and all respondents were anonymised.

Results

The results obtained in interviews are presented below following the thematic coding applied in text analysis, with: 1) general descriptions of the three production systems, including business structure; and 2) descriptions of typical technologies used in the systems and of categories of factors identified as influencing uptake of new knowledge and technology; *i.e.* 3) the special role of skills, knowledge, capabilities; 4) the role of networks; and 5) the influence of value-chain actors. Firm code numbers (open-field O1–O5, greenhouse G6–G10, PFAL P11–P15) are used to distinguish the different systems when presenting the results.

Description of the three production systems studied and firm structure

The three production systems have different conditions depending on the specific characteristics of their physical environment. Open-field production is affected by the outdoor climate, which is more difficult to control, *e.g.,* with fluctuating temperatures, droughts or heavy rain. These systems benefit from irrigation and specialist machinery. Greenhouse production has a more controlled indoor environment, but can still be affected by sun and the outdoor climate to some extent. Greenhouses have different designs, but are often high-technology glass greenhouses with computerised climate control, artificial lighting and CO_2 supply. PFAL systems are a refinement of high-technology greenhouses in which all climate factors, including light, are totally controlled. The controlled indoor environments in greenhouses and particularly in PFAL are generally more dependent on advanced technology.

A majority of the open-field production and greenhouse firms studied were family businesses, founded over a relatively long period (1930–2018). A dominant characteristic of these firms was a strong perceived historical anchoring in traditional horticultural production. As one respondent stated:

> *Here we are in an old part of the establishment; everything is old, actually, including the owners, and this summer we are entering our 35th year.* (Firm G6).

The PFAL firms consisted of more recently established firms, or start-ups, often financed by venture capital or private funding. Not all PFAL businesses were registered firms, but were instead member organisations, which was one difference identified between the more conventional and novel production systems.

The results also revealed a difference in educational background between owners/managers in the three systems. Open-field and greenhouse firms were mainly run by managers with conventional horticultural/agricultural education and experience, while PFAL owners and managers had a more diverse educational background and professional experience, *e.g.* within business management, engineering, physical planning and retail (Table 4). One PFAL respondent explained:

> *We started the firm in 2016, a friend and I. We are not growers ourselves. We were not growers from the start at least... Instead, I have a background as a community planner and my friend used to work in the grocery trade.* (Firm P13).

Choice of horticultural crops and cultivars aimed to focus on similar varieties but sometimes differed between

TABLE 4. Background and characteristics of the three different production systems studied.

Production system	Open-field	Greenhouse	Plant factory with artificial light (PFAL)
Description	Open-ground cultivation in natural soil	Greenhouse production. Crops grown in substrate/soil	Indoor production (incl. vertical farming)
Number of firms	5 (firms O1 – O5)	5 (firms G6 – G10)	5 (firms P11 – P15)
Start year of firm (median)	1998	1982	2014
Interviewee age (median, yr)	49	46	37
Crop production	Herbs, leafy vegetables, novel vegetables (sweet potatoes, pak choi), etc.	Herbs, leafy vegetables (pot lettuce), vegetable plants, strawberry plants, etc.	Herbs, leafy vegetables, microgreens, rocket, combined with fish, etc.
Educational/professional background of owner/s	Agriculture, horticulture	Agriculture, horticulture, business administration	Horticulture, social science, planning, supermarkets, business administration, IT, technology
Typical characteristics of firms/production	Partnerships with international firms to prolong the season/ year-round supply	Organic production in substrate/ soil. All year round supply of own produce	Start-up firms with venture capitalists involved, using vertical farming. All year round supply of own produce
Technology characteristics in adoption of innovations	Packaging, automation, specialist machinery, precision agriculture	Energy, LED lighting, packaging, automation, space saving (2 storeys), hydroponic water system	LED lighting, hydroponics, energy, data analysis (AI), aquaponic
Knowledge input	Advisors, international contacts, Internet, grower networks, producer organizations, suppliers	Advisors, articles, international contacts, Internet, trade shows, grower networks, supply chain actors	International contacts, Internet, suppliers, supermarkets, university contacts, social networks, venture capital networks

the three systems (Table 2). Open-field growers mainly produced herbs, lettuces and baby leaves, but also strawberries, beetroot, fennel, cabbage, cauliflower, leeks and pak choi. Greenhouse growers mainly produced herbs and pot lettuce, with a range of 20–76 different cultivars per grower. All greenhouse firms were certified organic producers, following the Swedish KRAV standards for organic production (KRAV, 2020). These systems are sometimes also referred to as “conventionalized” organic systems (Tittarelli, 2020) since this allows for a majority of Swedish growers to apply an organic labelling, even though Swedish greenhouse firms producing herbs, apply containerized production systems and hydroponics (Bergstrand, 2022). This type of system will however be phased out in Sweden before the year 2030 and be replaced by the EU organic regulation scheme. The PFAL growers produced around 20 cultivars, mainly baby leaves, microgreens, herbs, tomatoes and kale (Table 2). Depending on location (building) and access to cultivation area, production by some of the PFAL growers was largely controlled by availability of space. The PFAL firms use soilless cultivation and hydroponics without use of pesticides and are classified as conventional crops. A few firms with open-field production prolonged their season through imports of plants. The greenhouse and PFAL firms had all-year round supply of their own produce (Table 4).

Technologies/innovations adopted

The results revealed differences in adoption of technologies between the production systems (Table 4). In open-field production, the technologies adopted mainly related to crop quality and post-harvest handling, with several respondents having invested in packing houses or low-tech packing facilities in the field. One respondent said:

> *Yes, my lettuce box should be ready and go straight to the store, or cauliflower or whatever I grow, but I pack in the field. I’m thinking of packing a little bit more.* (Firm O4).

There were some prospects for increased robotisation of field practices, such as weeding, in the future. Fertigation was another area mentioned by some growers.

Greenhouse growers had mainly adopted technologies focusing on saving energy, such as blinds and temperature integration, and had invested in renewable energy sources, *e.g.,* wood chip heating and geothermal heating. Recirculation of water, hydroponics, automation and LED were other technologies adopted by greenhouse growers. When choosing to invest in technologies, such as LED, one opinion was that previous investments had generally been costly and showed poor performance, but as the technology is developing investment is becoming more rewarding. Some growers used VF or two storeys on parts of their greenhouses, *e.g.*, for young plant cultivation.

PFAL firms used novel technologies, such as VF, hydroponic growing techniques, automation, AI and LED. They also had a strong focus on energy-saving activities, mainly since energy was a critical factor in operating costs.

When adopting new technologies, techniques that reduce the need for manual labour were an important driver for all firms studied. However, some respondents mentioned switching to less labour-intensive crops as an alternative.

The role of skills, knowledge and education capabilities

A feature in common to all 15 firms was that they obtained relevant information and knowledge on uptake of technology through digital sources (*e.g.,* YouTube and company websites), in combination with published literature (articles/ newsletters/books) and networks (domestic, international, university contacts). Firms operating within open-field production also highlighted the importance of knowledge inputs from advisors, in particular relating to use of pesticides, fertilisation and crop varieties. International contacts and expertise from seed suppliers, mainly in the Netherlands and Denmark, were also seen as important sources of knowledge. Use of extension officers was often seen as positive, but one open-field grower mentioned a risk of information being leaked to competitors. The growers wanted to test different alternatives and make their own decisions, as pointed out by one manager:

I would like to use an extension officer. I want to plan and do everything in the field by myself, but I enjoy listening to a presentation from an advisor or researcher. They will maybe say ten things, but I may adopt one idea. One that really suits me. (Firm O4).

Knowledge sources mentioned by the greenhouse firms included trade fairs, specific grower networks, producer organisations and advisors. Employees, especially trained horticulturists and agronomists with specialist training and applied knowledge, were seen as key business resources when implementing new knowledge/technology. Greenhouse producers believed that on-going climate change, *e.g.,* longer periods with high temperatures, will lead to production challenges and create a need for technological development and improved production methods, *e.g.,* to cool greenhouses or deal with increased pest pressure.

Among PFAL firms, in-house knowledge and staff with technological skills were seen as key resources for knowledge uptake. One manager of a recently founded PFAL firm noted that external staff were an important source of knowledge:

We have one external board and two external advisory boards, one for production issues and one for market issues. […] We are 40 partners, the majority are entrepreneurs, and we cooperate with suppliers. […] Altogether, 50–100 people are involved in the company. (Firm P15).

Knowledge was thus acquired through key informants, in that case an advisory board, where participants not only focused on production but also market issues, in order to better prepare the business for new and emerging situations. For further details, see Table 3.

The role of relations and networks

Within all three production systems, use of networks was highlighted as an important area for knowledge input. However, depending on the system, there were differences in the type of networks the owner or managers used. For example, open-field and greenhouse growers tended to use more formal and conventional grower networks, primarily organised within the Federation of Swedish Farmers, but sometimes also within the advisory services (*e.g.,* Rural Economy and Agricultural Societies). University-organised network activities connecting research with growers were cited as other important network venues for knowledge exchange. Open-field owners/managers mentioned some informal networks and a regional cluster in North-Western Scania, an expansive and dynamic region within food production. Based on how the firms used and developed the networks, they functioned as both professional grower and social networks.

Contacts with domestic and international university researchers were mentioned as a source of knowledge by firms within all production systems. Open-field growers reported good experience of relevant communication with researchers regarding support and improvement of their production, *e.g.,* introduction of innovative varieties of vegetables. Greenhouse and open-field growers both mentioned domestic industry-related universities and agricultural (vocational) schools. They also mentioned collaboration units, *e.g.,* Partnership Alnarp, an organisation promoting cooperation between university and the business community, public authorities and industry organisations in southern Sweden.

Greenhouse and PFAL firms tended to have more international contacts with advisors and suppliers concerning technical equipment and technological development. These actors exerted a major influence on choices of new technologies by the respondents' firms and their investment in technology. Greenhouse growers also cited international influences, especially from the Netherlands, Germany and Finland. The PFAL firms mentioned social networks as an important source of knowledge:

In our network we have friends and acquaintances from which we take good advice, but we don't have any official advisors. We always have our ear to the ground in different ways. (Firm P14).

Owing to the different environments in which the firms operate and differences in educational background, the design of formal and informal networks differed between the systems.

The influence of actors within the food value chain

The results showed that value-chain actors greatly influenced firms within all three production systems as regards adopting new technologies. However, for the different systems, the push or pressure to adopt came from different types of actors within the food value chain, linked to the fact that the firms use different distribution channels depending on their production system (see Table 2). Open-field and greenhouse firms mentioned using producer organisations, typically a growers' co-operative, as a source of market knowledge, especially regarding the retail market. Close collaborations with suppliers and producer organisations were important in product development and selecting new/rare crop varieties, *e.g.,* sweet potatoes and pak choi, in open-field production. One grower stated:

Yes, I joined the producer organisation Sydgrönt, which handles contacts with customers, and they have asked customers (retail) what they demand and what they want. They have had these products before, but not Swedish-grown, and they wanted to find a Swedish grower who was willing to embark on the project, and I was interested. (Firm O3).

Greenhouse and open-field producers mentioned the importance of responding to market demand and consumers' opinions when deciding on which new technologies to adopt. Decisions on what cultivars to grow were often made in dialogue with retail stakeholders.

Areas of concern were negative effects of new technology, such as negative influences on taste when producing with hydroponics compared with conventional production. Another concern related to consumers' positive attitudes towards artisanal vegetable production and perceived resistance to increased technology in cultivation.

Among PFAL managers and owners, networks of industry representatives were mentioned as key contacts among actors within the food value system. Within PFAL, special emphasis was placed on suppliers of technological equipment, *e.g.,* Freight Farms (U.S.), a supplier of shipping containers for hydroponic farms. Contacts with supermarkets were also highlighted and many PFAL firms reported selling their products directly to supermarkets, bypassing the producer organisations. See Table 2 for further details about distribution channels.

Discussion

This study explored the role and main drivers for adoption of technological innovations within three different horticultural production systems (open-field, greenhouse, PFAL). It also examined the role of sources of knowledge and networks in relation to adoption of technological innovations within these systems. The results showed that adoption of technological innovations depended on a wide range of variables and key elements, which can be categorised as: firm structure, technologies/innovations adopted, skills, knowledge and education capabilities, relations and networks, and influence of actors within the food chain.

Internally, at firm level, adoption behaviour depended on firm/managerial characteristics, such as history, firm size, grower age and educational background. The internal adoption decision was also affected by perceived benefits of the particular innovation, such as compatibility with existing technology, sustainability or reliability. Previously, Rogers (2003) identified a business process leading to rejection or adoption of an innovation. However, norms and values per se were not investigated here, and need to be fully explored at a more profound level in future work. The firms reported an economic driving force, which affects their competitiveness and decisions on adoption of technological innovations. Higher investment costs will limit the possibility to adopt innovations, and thus firms adopting vertical farming practices are often start-up initiatives with access to external funding. This is in line with findings that economic competence and the ability to develop and exploit new business opportunities are equally important in technological systems (Carlsson and Stankiewicz, 1991).

The firms mainly adopted innovations suitable for their current production system, reflecting what Abernathy and Clarke (1985) and Sherry (2016) describe as the lock-in effect, where major technological investment may prevent adoption of newer technologies. Open-field firms adopted technologies suitable for outdoor cultivation, *e.g.,* fertigation, automation and post-harvest packing of crops. Greenhouse firms often made large investments in infrastructure and sometimes experienced lock-in effects. Some new technologies were viewed as incompatible with the current system, *e.g.,* a heating system may not be compatible with future changes to renewable energy or the current infrastructure may not be suitable for vertical farming. As noted by Sherry (2016) and Abernathy and Clark (1985), the initial decision by a firm to invest in a certain technology can limit future development of the firm and the business.

A number of parameters have driven the emergence of PFAL, but LED technology in particular has been crucial for the introduction and development of new innovative technological production systems. Another factor is financing, where PFAL firms are often in a better situation than conventional systems, mainly due to external funding from venture capital. To fully understand the outcome and consequences in a long-term perspective, longitudinal studies are needed on the economic development of innovative PFAL firms.

The open-field and greenhouse firms studied were usually family businesses that had been active for a long time (up to 85 years) and represented a more conventional horticultural or agricultural background. In contrast, PFAL firms were often start-up initiatives and their owners had, *e.g.,* a technological or business background. On comparing managers' skills and educational backgrounds, a need for technical knowledge was identified to a larger extent in the PFAL and greenhouse firms. Some open-field firms emphasised craftsmanship and focusing on different varieties and product development, instead of the latest technology. The firms in all three production systems often concentrated on economic issues when deciding on adoption or rejection of technological innovations, *i.e.,* an innovation perceived as expensive had limited possibility to be adopted. The main focus for the firms was thus to remain competitive and profitable, which clearly affected the investments made in new technologies such as LED, renewable energy, recirculation of water, automation, digitalisation and VF.

For the specific innovation of VF, the firms that adopted this technology were generally start-up initiatives backed by venture capitalists, which seemed to increase their possibilities to adopt new technologies, mainly due to external capital in combination with advanced technological capabilities. In the next step, this will affect the market situation and competition between firms in different production systems. It was found that PFAL firms were often organised as networks, a major difference compared with conventional growers. Competition on the market is generally shifting to a value network context (Christensen and Rosenbloom, 1995; Katsamakas, 2014), but it is difficult to predict how value networks will compete for firms. This creates further tension between different production systems, since they represent different networks and competences and thus operate rather independently from each other. However, increased knowledge exchange and collaboration between the systems would probably benefit individual actors within all three systems and promote implementation of sustainable technological production practices within the vegetable industry in general. All three production systems included managers with well-developed absorptive capacities (Cohen and Levinthal, 1990), constantly trying to find new opportunities and knowledge in an active search for best practice, with an open mind to new technologies.

Growers within all three production systems used a wide variety of sources for knowledge input, but there were differences between the systems. Open-field and greenhouse firms tended to use more formal grower networks and advisory services. These organisations were not mentioned by the PFAL firms, which instead emphasised other sources of knowledge such as social networks and international suppliers of technical equipment. A factor in common to all three systems was the influence of stakeholders (*e.g.,* producer organisation and retail) within the food value chain, but there were differences in the stakeholder/s that influenced the actual choice of produce. Open-field and greenhouse producers mentioned relations with producer organisations as an important source of new opportunities, which is in line with findings by Fernqvist and Göransson (2021). Open-field and greenhouse firms also used change agents, professionals with a technological background, *e.g.,* suppliers, actors in other parts of the value chain or possibly advisors/extension officers, as described by Rogers (2003). The PFAL firms reported selling directly to retailers or supplying retailer demand, and viewed relations with retailers as critically important for the business and the product range. Use of alternative networks and different business models in PFAL firms was reported previously by Allegaert et al. (2020), who also identified a focus on commercial development in VF, in contrast to more conventional production systems and their business models.

The results also showed the impact of contextual variables, such as policy, institutions, market and environmental conditions, in the setting in which the firm and surrounding system actors operate, and their influence on adoption of technological innovations within the horticultural industry.

The innovation ecosystems approach (Walrave et al., 2018) proved to be a suitable framework for describing the situation for PFAL firms, which work in an environment not previously associated with horticultural production. Changing views may extend into conventional firms, broadening the view on the "traditional" knowledge and innovation system, and facilitating transition to more sustainable production systems requiring the formation of innovation niches (Elzen et al., 2012; Meynard et al., 2017). Innovation ecosystems thinking also highlights cross-sector interactions to facilitate transboundary innovation (Walrave et al., 2018) and further developing the AIS thinking described by Pigford (2018). The findings in this study lay well within innovation ecosystems thinking, especially the finding that wider multifunctionality of horticultural systems can improve the potential to support transboundary innovation niches.

The three production systems studied are different. According to Kozai et al. (2019), PFAL systems should not be regarded as a replacement for open-field or conventional greenhouse production, but rather as an interesting new market and business opportunity and complement to existing production systems. Growers active within the horticultural industry might be expected to identify this possibility, but our results clearly showed that it was mainly new actors who had recognised the presumed opportunities of PFAL, with established growers rarely adopting this type of new technology and, by extension, managing or developing PFAL firms. Instead, the development of the different production systems reflected movement of the systems in different directions. PFAL are a special case of high-tech greenhouses where the greenhouse has been replaced to facilitate control of the environment, especially light. This represents a paradigm shift, providing the possibility to move production of vegetables into urban areas and for production to occur independent of sunlight. This involves new opportunities and branches in urban areas, but other production systems involving greenhouse and open-field production will still exist. There is also a new type of architecture in the PFAL, where the components are put together in a new constellation in which daylight and glass are replaced by a controlled environment with new components.

The limitations of the study are closely connected to differences between the production systems, which hampers comparability, *e.g.,* greenhouse production, which enables organic labelling, which is not possible for PFAL according to EU regulations. Firms within the three systems also operate under different regulations and funding opportunities which makes it difficult to compare the economic long-term perspective in the different production systems.

Practical implications and suggestions for future research

Research on factors affecting adoption of technological innovations in production of leafy vegetables can assist the sector in anticipating future improvements, and thereby support stakeholders in future decisions. This implies that horticultural companies can gain advantages by being faster in adoption of innovations through learning across different networks and business cultures, improving their competitiveness on the international market.

Future research should continue exploring the topic of adoption of innovations through conducting interviews and longitudinal case studies of firms growing vegetables in different production systems to be able to capture the expected developments within the different systems. Qualitative studies exploring adoption of innovations at firm level are less frequent than quantitative studies (Spendrup and Fernqvist, 2019). Future qualitative studies should seek to increase understanding of internal decision processes and strategic choices on adoption of knowledge and technological innovations. Another interesting research topic is how policy development will affect firms in different production systems over time compared with other niche players in vegetable production, *e.g.,* CSAs or market gardeners.

Conclusions

Adoption of technological innovations in leafy vegetable production appears to be largely dependent on their suitability for the existing production system. There are differences between conventional (open-field, greenhouse) and PFAL systems, suggesting that efforts to promote adoption of technological innovations should be designed to suit target groups with very different backgrounds. Communication and network links between conventional systems and PFAL currently seem to be lacking. Studying adoption of technology within the two more conventional systems is important, since the volumes and ranges of crops they produce cannot be replaced by PFAL (at least in the near future), and these systems may benefit from technological development. Greenhouse and open-field growers are interested in new technologies, but different innovations are more or less relevant and compatible with their current systems. This should be acknowledged more widely, to support the firms according to their specific situation in a fruitful way. Firms interested in new technologies actively search for best practice using different sources of knowledge, depending on the internal and external business environment. Overall, the differing concerns of firms in different production systems affect the way in which these firms decide on adoption of technological innovations.

Acknowledgments

Our thanks to the interviewees who participated in this study for sharing their thoughts and knowledge concerning adoption of innovations and knowledge. We also thank the Federation of Swedish Farmers for sharing their network and views concerning technological development of leafy vegetables.

References

Abernathy, W.J., and Clark, K.B. (1985). Innovation: Mapping the winds of creative destruction. Research Policy *14*, 3–22. https://doi.org/10.1016/0048-7333(85)90021-6.

Allegaert, S., Wubben, E., and Hagelaar, G. (2020). Where is the business? A study into prominent items of the Vertical Farm Business Framework. Eur. J. Hortic. Sci. *85*, 344–353. https://doi.org/10.17660/eJHS.2020/85.5.6.

Bergstrand, K.J. (2022). Organic fertilizers in greenhouse production systems-a review. Sci. Hortic. *295*, 110855. https://doi.org/10.1016/j.scienta.2021.110855.

Bergstrand, K.-J., Ekelund, A.L., Drottberger, A., Fernqvist, F., and Spendrup, S. (2020). Forskare: Odla mer i stora växtfabriker än bladgrönt och kryddor. In NyTeknik (https://www.nyteknik.se/opinion/forskare-odla-mer-i-stora-vaxtfabriker-an-bladgront-och-kryddor-6990937) (accessed Aug. 21, 2021).

Braun, V., and Clarke, V. (2006). Using thematic analysis in psychology. Qual. Research in Psychol. *3*, 77–101. https://doi.org/10.1191/1478088706qp063oa.

Bryman, A. (2012). Social Research Methods, 4th edn. (New York: Oxford University Press).

Butturini, M., and Marcelis, L.F. (2020). Vertical farming in Europe: Present status and outlook. In Plant Factory (Elsevier), p. 77–91. https://doi.org/10.1016/B978-0-12-816691-8.00004-2.

Carlsson, B., and Stankiewicz, R. (1991). On the nature, function and composition of technological systems. J. Evol. Economics *1*, 93–118. https://doi.org/10.1007/BF01224915.

Castilla, N., and Hernandez, J. (2006). Greenhouse technological packages for high-quality crop production. Acta Hortic. *761*, 285–297. https://doi.org/10.17660/ActaHortic.2007.761.38.

Christensen, C.M., and Rosenbloom, R.S. (1995). Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network. Research Policy *24*, 233–257. https://doi.org/10.1016/0048-7333(93)00764-K.

Cohen, W.M., and Levinthal, D.A. (1990). Absorptive capacity: A new perspective on learning and innovation. Admin. Sci. Quart. *35*(1), 128–152. https://doi.org/10.2307/2393553.

Despommier, D. (2010). The Vertical Farm: Feeding the World in the 21st Century (New York: MacMillan).

Drottberger, A., Melin, M., and Lundgren, L. (2021). Alternative food networks in food system transition-values, motivation, and capacity building among young Swedish market gardeners. Sustainability *13*. https://doi.org/10.3390/su13084502.

Elzen, B., Barbier, M., Cerf, M., and Grin, J. (2012). Stimulating transitions towards sustainable farming systems. In Farming Systems Research into the 21st Century: The New Dynamic (Springer), p. 431–455. https://doi.org/10.1007/978-94-007-4503-2_19.

Fernqvist, F., and Göransson, C. (2021). Future and recent developments in the retail vegetable category – A value chain and food systems approach. Intl. Food Agribusiness Mgt. Rev. *24*, 27–49. https://doi.org/10.22434/IFAMR2019.0176.

Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy *36*, S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010.

Guest, G., Namey, E.E., and Mitchell, M.L. (2013). Collecting Qualitative Data: A Field Manual for Applied Research (London, U.K.: Sage Publ., Ltd.). https://doi.org/10.4135/9781506374680.

Hall, A., Janssen, W., Pehu, E., and Rajalahti, R. (2007). Enhancing agricultural innovation: How to go beyond the strengthening of research systems. Washington DC, The World Bank, No. 36346, p. 13.

IPCC (2019). Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems (Rome, Italy: FAO).

Katsamakas, E. (2014). Value network competition and information technology. Human Systems Mgt. *33*, 7–17. https://doi.org/10.3233/HSM-140810.

Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proc. Japan Acad., Series B *89*, 447–461. https://doi.org/10.2183/pjab.89.447.

Kozai, T., Niu, G., and Takagaki, M. (2019). Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production (Cambridge: Academic Press).

KRAV (2020). Det här är KRAV. https://www.krav.se/krav-markt/det-har-ar-krav/ (accessed Aug. 26, 2021).

Lam, A. (2005). Organizational innovation. In The Oxford Handbook of Innovation, J.E.A. Fagerberg, ed. (London: Oxford Univ. Press), p. 209–239. https://doi.org/10.1093/oxfordhb/9780199286805.003.0005.

Langendahl, P.-A. (2020). Workshop on Smart Urban Food Production. Swedish Univ. of Agric. Sci. Personal message d.d. 2020-11-25.

Lapadat, J.C., and Lindsay, A.C. (1999). Transcription in research and practice: From standardization of technique to interpretive positionings. Qual. Inquiry *5*, 64–86. https://doi.org/10.1177/107780049900500104.

Lieberman, M.B., and Montgomery, D.B. (1998). First-mover (dis) advantages: Retrospective and link with the resource-based view. Strategic Mgt. J. *19*, 1111–1125. https://doi.org/10.1002/(SICI)1097-0266(1998120)19:12<1111::AID-SMJ21>3.0.CO;2-W.

Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., and Michon, C. (2017). Designing coupled innovations for the sustainability transition of agrifood systems. Agric. Syst. *157*, 330–339. https://doi.org/10.1016/j.agsy.2016.08.002.

Nilsson, U., Möller, N.J., Christensen, I., and Nimmermark, S. (2015). Renewable energy in Swedish greenhouse production – Knowledge base for education. https://pub.epsilon.slu.se/12740/7/nilsson_u_etal_151102.pdf (accessed Sept. 3, 2021).

Orsini, F., Pennisi, G., Zulfiqar, F., and Gianquinto, G. (2020). Sustainable use of resources in plant factories with artificial lighting (PFALs). Eur. J. Hortic. Sci. *85*, 297–309. https://doi.org/10.17660/eJHS.2020/85.5.1.

Pigford, A.A.E., Hickey, G.M., and Klerkx, L. (2018). Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. Agric. Syst. *164*, 116–121. https://doi.org/10.1016/j.agsy.2018.04.007.

QSR International Pty. Ltd. (2018). NVivo qualitative data analysis software.

Rogers, E.M. (2003). Diffusion of innovations. 5th edn. (New York, U.S.A.: Free Press).

Saini, R.K., Ko, E.Y., and Keum, Y.-S. (2017). Minimally processed ready-to-eat baby-leaf vegetables: Production, processing, storage, microbial safety, and nutritional potential. Food Rev. Intl. *33*, 644–663. https://doi.org/10.1080/87559129.2016.1204614.

Sherry, E.F. (2016). Lock-In Effects. In The Palgrave Encyclopedia of Strategic Management, M. Augier, and D. Teece, eds. (London, U.K.: Palgrave Macmillan). https://doi.org/10.1057/978-1-349-94848-2_425-1.

Spendrup, S., and Fernqvist, F. (2019). Innovation in agri-food systems – A systematic mapping of the literature. Intl. J. Food Syst. Dynamics *10*(5), 402–427. http://dx.doi.org/10.18461/ijfsd.v10i5.28.

Stanghellini, C., Oosfer, B., and Heuvelink, E. (2019). Greenhouse Horticulture: Technology for Optimal Crop Production (Wageningen, The Netherlands: Wageningen Acad. Publ.). https://doi.org/10.3920/978-90-8686-879-7.

Swedish Board of Agriculture (2018). Greenhouse energy use in 2017. https://jordbruksverket.se/download/18.341a6d7171e33d0f42d4985/1588860072873/201805.pdf (accessed Sept. 3, 2021).

Swedish Board of Agriculture (2020). Trädgårdsundersökningen 2019. Kvantiteter och värden avseende 2019 års produktion. https://jordbruksverket.se/2938.html (accessed Sept. 3, 2021).

Swedish Board of Agriculture (2021). Översikt trädgårdsodling efter odlingsform och odlingsinrik-tning. Antal företag, frilandsareal och växthusyta. Vart tredje år 1981–2020. Riket. Available at: https://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets%20statistikdatabas/Jordbruksverkets%20statistikdatabas__Tradgardsodling__Oversikt/JO0102K02.px/ (accessed Sept. 3, 2021).

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B., and Sawicka, M. (2015). Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). Renew. Agric. Food Syst. *30*, 43–54. https://doi.org/10.1017/S1742170514000143.

Tittarelli, F. (2020). Organic greenhouse production: Towards an agroecological approach in the framework of the new European regulation – A review. Agronomy *10*(1), 72. https://doi.org/10.3390/agronomy10010072.

Walrave, B., Talmar, M., Podoynitsyna, K.S., Romme, A.G.L., and Verbong, G.P. (2018). A multi-level perspective on innovation ecosystems for path-breaking innovation. Technol. Forecasting and Social Change *136*, 103–113. https://doi.org/10.1016/j.techfore.2017.04.011.

World Resources Institute (2019). Creating a sustainable world future – A menu of solutions to feed nearly 10 billion people by 2050. Final report. https://research.wri.org/sites/default/files/2019-07/WRR_Food_Full_Report_0.pdf (accessed Sept. 20, 2021).

Zhang, Y., and Kacira, M. (2020). Comparison of energy use efficiency of greenhouse and indoor plant factory system. Eur. J. Hortic. Sci. *85*, 310–320. https://doi.org/10.17660/eJHS.2020/85.5.2.

Received: May 18, 2021
Accepted: Mar. 31, 2022

Addresses of authors:
A. Drottberger[1], K.-J. Bergstrand[1], F. Fernqvist[2] and S. Spendrup[2]
[1] Swedish University of Agricultural Sciences, Department of Biosystems and Technology, 234 22 Lomma, Sweden
[2] Swedish University of Agricultural Sciences, Department of People and Society, 234 22 Lomma, Sweden
* Corresponding author; E-mail: annie.drottberger@slu.se

Appendix: Questions for interviews

Adoption of innovations and knowledge in production of leafy vegetables in Sweden

1. Name of interviewee and firm.
2. Can you tell me a bit more about the history of the firm and your involvement (age, size)?
3. How long have you been involved in the business and what is your educational background?
4. Which crops are grown by your firm?
5. Which technological innovations/investments in new technologies have been made in your firm?
   LED lighting and curtains;
   Renewable energy;
   Recirculation of water;
   Hydroponics;
   Climate control;
   Automation;
   Artificial intelligence;
   Vertical farming.
6. How do you find knowledge and information when it comes to deciding on investments in new technologies? For example advisors, internet, colleagues.
7. How do you see the market for leafy vegetables and herbs developing?
8. What do you see as advantages and disadvantages with technological development?
9. What do you think about the concept of vertical farming and start-up businesses?
10. How will vertical farming develop or change the horticultural market?
11. Do you see vertical farming as a complement or a threat to what you are doing?
12. Which technologies do you perceive as crucial for future development in your firm and the horticultural industry as a whole?
13. Do you have any other comments you want to add?

II

sustainability

Article

Alternative Food Networks in Food System Transition—Values, Motivation, and Capacity Building among Young Swedish Market Gardeners

Annie Drottberger [1,*], Martin Melin [2] and Lotten Lundgren [3]

[1] Department of Biosystems and Technology, Swedish University of Agricultural Sciences, 234 22 Lomma, Sweden
[2] Department of People and Society, Swedish University of Agricultural Sciences, 234 22 Lomma, Sweden; martin.melin@slu.se
[3] The Federation of Swedish Farmers, 243 30 Höör, Sweden; lotten.lundgren@lrf.se
* Correspondence: annie.drottberger@slu.se; Tel.: +46-76-000-1504

Abstract: This study sheds light on a new generation of Swedish food producers, market gardeners, who are attracting attention in terms of food system sustainability, prompted by increasing consumer awareness about the value of healthy and locally produced food. Market gardening is part of a global agroecological movement opposed to industrialized agriculture and its negative impacts on the environment and rural communities. These food producers challenge the incumbent agri-food regime through the building of alternative food networks. This case-based study involving 14 young vegetable producers showed that young people who engage in market gardening are strongly motivated by dual incentives, namely entrepreneurship and transformation to sustainability. Six main competences were identified as important for market gardeners: practical skills related to growing vegetables, business management, innovation and continuous learning, systems thinking, pioneering, and networking. Individuals develop their skills through continuous experiential learning and gain knowledge through peer-to-peer learning using social media. However, they need to acquire certain skills relating to their daily work in the field and to managing a business. Market gardeners currently face a number of barriers erected by the sociopolitical environment, in particular regarding access to research-based knowledge, extension services, and business support.

Keywords: agroecology; competencies; food system; lock-in; market gardening; skills; sustainability; transition; urban farming

Citation: Drottberger, A.; Melin, M.; Lundgren, L. Alternative Food Networks in Food System Transition—Values, Motivation, and Capacity Building among Young Swedish Market Gardeners. *Sustainability* **2021**, *13*, 4502. https://doi.org/10.3390/su13084502

Academic Editor: Francesco Caracciolo

Received: 29 March 2021
Accepted: 16 April 2021
Published: 18 April 2021

1. Introduction

The dominant regime in horticulture and agriculture is currently driven by global markets pushing for industrialized production systems based on high input of non-renewables, large-scale production, and specialization in crops or livestock. This undermines the possibility for alternative, less-intensive production system to compete, creating a productivity paradigm where high-input modern farming practices are key drivers in the destruction of natural ecosystems, loss of biodiversity, and climate change [1].

Outside the mainstream regime, social movements with links to agroecology support initiatives that promote ecological production practices, produce food for nearby markets, and support the local economy, including in urban and peri-urban areas [2]. Usually referred to as "alternative food networks" or "short food supply chains", these initiatives use various ways to build direct relationships with consumers, e.g., through farmers' markets, on-farm selling, box schemes, etc. This is boosting entrepreneurship in the agricultural and horticultural sector, not least among new entrants in market gardening and farming, resulting in development of alternative business models and diversification of farms. A European FP7 research project, "Food links: Short Food Supply Chains as Drivers for Sustainable Development", showed that short food supply chains in a range of forms contribute to increased food sovereignty, reductions in external inputs, and improved resilience of rural economies. Short chains represent an alternative to the globalized agri-food model and can act as drivers for change [3]. One such example in the food system is market gardening by small-scale organic fruit or vegetable producers who mainly rely on manual labor and sell their produce directly to consumers. These green activists can possible play a role in the transition of the current food system. The presence of niche players is suggested to be an important factor in technological and social transition processes [4,5]. Niches offer protected space where radical ideas can develop until they are ready for take-off [6]. The conventional food supply chain in Sweden is dominated by a few powerful food retailers [7], so market gardens operate in a niche distinctly separated from the mainstream food system regime. Partly for this reason and partly because of its recent emergence in Sweden, no previous study has examined market gardening in a Swedish context. Market gardeners and other grassroots innovators may already have the solution to some sustainability challenges, as they are managing to run businesses within a regime that has set up considerable barriers to their operation [8].

The overall aims of this study were to provide insights into the situation for young market gardeners in Sweden, identify barriers to development of new sustainable small-scale horticultural businesses, and propose ways in which this group of producers can be supported to overcome these barriers. An additional aim was to explore the potential of market gardeners to enact changes in the mainstream regime, which was done by identifying their values, attitudes, and motivations and relating these to the broader socioeconomic and institutional context for horticulture. The following research questions (RQ) were addressed:

(RQ1) What characterizes the businesses of young market gardeners in Sweden?

(RQ2) What motivates young people to become market gardeners?

(RQ3) What barriers and opportunities are there for new entrants in market gardening?

Theoretically, the study contributes to the literature on food systems transitioning by providing insights into the realities for a group of young vegetable growers who might represent future food entrepreneurs. The study also makes a practical contribution by suggesting focus areas for capacity building and policy development to support young people who want to start a market garden or similar horticultural business.

1.1. Transition of the Dominant Agri-Food Regime

Market gardening is related to the concept of agroecology, which was initially defined as the application of ecological principles in the design of sustainable farm systems [9]. The definition has since been broadened to include interdisciplinary perspectives on how food is produced, distributed, and consumed in an "ecology of food systems" [10]. Agroecology is today considered a scientific discipline, a set of agricultural practices, and a social movement, which in combination gives agroecology the potential to move the current food system regime onto a more sustainable path [11]. Food producers willing to engage in alternative production practices face many obstacles in the political economy of the industrialized horticultural sector. Current incentives to promote specialization, increased farm size, and mono-cultural cropping make it difficult for alternative production systems to compete [12]. It is increasingly recognized that a technology and policy "quick fix" approach will not be enough to address the lock-in of the current food systems and reverse the ongoing damage to eco-systems. Instead, a more fundamental systemic transition that also addresses dimensions of power and inequality in the system is needed [13,14]. In transition theory, experimentation in socio-technical niches plays an important role as a driver of change [6]. A niche is a protected space for testing new ideas and developing new practices, such as organic agriculture, renewable energy schemes, waste recycling, and community housing. These may be selected, protected, or marginalized by existing regimes supporting the dominant practices, structures, and institutions of a particular sector. A niche innovation may gain vitality through either a fit-and-conform empowerment process or a stretch-and-transform process [15]. In fit-and-conform, the niche innovation becomes competitive in terms of the narrower economic and technological criteria set by the selective environment of existing markets compared with the broader sustainability values that might originally have been the main drivers in development of the niche innovation. The stretch-and-transform approach aims to alter the selection environment in ways that favor evolution of niche initiatives and enact structural changes in the incumbent regime [15].

1.2. Market Gardening, Co-Learning, and Capacity Building

The need for capacity building among market gardeners has not been addressed in previous studies. Information about skills gaps could be important to educators and advisors aiming at supporting new entrants in small-scale horticultural businesses. Learning and knowledge exchange is key to supporting the development of sustainable farming systems [16]. The agroecological practitioner must obtain an understanding of a broad and complex set of biophysical and socioeconomic dimensions of food and agricultural systems. Transition towards more sustainable food systems will also require new forms of knowledge and new processes of learning [17]. However, the capacities needed to practice knowledge-intensive ecological farming are usually not covered in mainstream educational and extension programs, which has been identified as an obstacle to adoption and scaling-up of alternative and diversified farming systems [12]. Engaging in alternative ways of doing farming, like agroecology, means struggling against the subordination of alternative practices to industrial high-input farming and against the conventional understanding of how scientific knowledge emerges, where one side produces and the other side passively absorbs. Cognitive justice, a concept originating in decolonial thought, implies misrecognition due to the knowledge domain and, in effect, devaluation of practical and indigenous knowledge to other forms of institutionalized knowledge [18]. The importance of recognition and integration of different forms of knowledge domains was acknowledged by food system actors in a recent survey performed by the EU-funded Horizon 2020 project "NextFood". The survey identified an ability to integrate scientific and practical knowledge, and networking with other actors in the food system, as important competences for those seeking to enact change towards a more sustainable food system [19]. In a South American context, the food sovereignty movement La Vía Campesina exemplifies how learning and sharing of knowledge can take place in communities of practice, with active dialogue between different ways of knowing agriculture (*diálogo de saberes*) seen as an important lever to spur collective learning and joint action for change [16]. Mixing external and localized forms of knowledge can contribute to increased resilience in farming [20], but there are few examples of how this can be accomplished in a European context. One exception is a study on a participatory plant breeding network in France, which showed that agrobiodiversity learning is acquired in a process of collective knowledge production and mobilization of different knowledge domains [17].

1.3. Market Gardening in Sweden

In recent decades, structural change in the Swedish horticultural sector has moved towards fewer but larger farms, with the largest 10% of horticultural farms currently cultivating 65% of the total area of field-grown crops and 59% of the greenhouse area [21]. The average size of horticultural holdings is 8.2 hectares (ha) for open field crops [21] and the number of people employed in farming (including horticulture) has decreased to 2% of the economically active population. Further, farmers in Sweden are aging, with 68% of horticultural producers being older than 50 years [21]. Since the focus in the present study was on future challenges, horticultural producers below the age of 35 years, a group that represents 7% of all producers, were selected for interview [21].

Market gardening is a branch of horticultural production, and the term "market garden" has recently been popularized by publication of a specialist handbook and by the emerging "back to the land" movement in Fortier [22]. Family-run market gardens situated near cities were common in Sweden until the mid-1900s, when market competition increased and forced structural changes in the horticultural sector [23]. Contemporary market gardens are often smaller than one hectare, and a diversity of vegetables and fruit crops are cultivated. It is common to use organic inputs, grow in permanent raised beds, and rely on manual labor. However, the most distinctive trait is that the majority of the produce is sold directly to consumers via farmers' markets, community-supported agriculture (CSA), digital platforms such as online marketplaces on Facebook, or mobile applications such as Local Food Nodes [22]. As part of the "back to the land" movement, market gardening attracts people with no previous experience of professional horticulture. Thus market gardening can be regarded not only as a business model within horticulture, but also as a social movement for self-realization and food system transformation.

There are no official statistics on market gardening in Sweden. The Swedish Board of Agriculture, which is responsible for statistics within agriculture and horticulture, includes businesses with production units on a minimum of 0.25 ha [21]. This covers some of the businesses that identify as market gardens, but growers on production units <0.25 ha operate entirely "under the radar". The principal difference between market gardening and CSA is that market gardening refers to businesses whose main line of production is within horticulture, whereas CSA includes any agricultural or horticultural production [24]. Additionally, small scale is intrinsic to the concept of market gardening, and sales channels other than community-based channels may be used. However, there is significant overlap between the two concepts; a market garden can be a CSA, and vice versa. Many of the CSA farms described in the literature focus on vegetables [20,23], and thus the issues highlighted may also apply to market gardens.

Another indicator of advances in market gardening in Sweden is the recent emergence of courses in small-scale vegetable production. In May 2020, at least 13 courses in small-scale production of vegetables were available to students at Swedish adult education colleges. Several of these have appeared in the past few years. A handbook for aspiring market gardeners by Ringqvist [25], which in many regards is a Swedish counterpart to Fortier's handbook [21], is now available. The two works describe similar production methods, but publication in the Swedish language has facilitated expansion of the movement among grassroots operators in Sweden.

2. Materials and Methods

A case-based qualitative research model was used in the present study in order to better understand and interpret aspects that are difficult to measure quantitatively [24]. This is normally done by analyzing the views, behaviors, opinions, and experiences of people acting in a specific social context. Understanding the values, beliefs, and attitudes of the interviewees, and some characteristics of the complex food system in which they operate, was central to the present analysis. A case study design, which entails detailed and intensive analysis of a single case, for example a community or an organization [25], was applied. Fourteen cases were studied in order to improve emerging theory and gain a deeper understanding of the topic by comparing different cases [25]. Participants were recruited by snowball sampling, in which initial contact with a single food producer relevant to the study topic was used to identify others [25]. A total of 14 participants aged 18–37 years (8 female, 6 male) agreed to take part in the study.

Participants were interviewed for 1–1.5 h using a semi-structured interview guide (see Appendix A) in order to map the situation for young, small-scale vegetable producers in Sweden. This included a description of their businesses, the goals and values that motivate them, their skills and competences, their views on sustainability transition of the food system, and their perceived role in transition. The empirical data were recorded, transcribed, and analyzed using NVivo software [26] and Quirkos software [27]. The transcripts were coded using 39 different codes, of which 35 were decided beforehand and 4 emerged from the data as coding proceeded. Coding was done at the manifest level and at an underlying thematic level. While coding the transcripts, reflections about the coding process were added. The coding was repeated four times by two different researchers (two times each), so that all relevant statements were assigned a suitable code. The codes were then merged into three main themes. Some of the skills identified as important for market gardeners were explicitly mentioned by the respondents, whereas others were described indirectly and then concretized during data analysis. In all, 23 different important skills and competencies were highlighted by the respondents. These were then grouped into six themes: subject specific knowledge, business management, innovation and continuous learning, systems thinking, pioneering, and networking.

3. Results

The results from the interviews are presented below according to the thematization made in transcript analysis, in the form of (1) general features of respondents' production systems, including firm structure and typical characteristics; (2) specific motives of young market gardeners and factors influencing the situation for market gardeners; and (3) barriers and opportunities for new entrants in market gardening. Results from Section 3.1 is visualized in Table 1.

Table 1. Firm characteristics and demographics.

Component	Description
Respondents	Owners of newly started market gardens
Age	Ranging between 25 and 37 years
Gender	8 females and 6 males
Location	Southern and central Sweden
Settlement	10 rural and 4 urban farms
Educational background	University, business management, or other work experiences
Production	Vegetables with 20–50 cultivars/unit in open field or polytunnels
Farm size	Often less than 1 ha and ranging between 200 m^2 and 4 ha
Start of firm	1–10 years ago
Yearly revenue	Mean value €29,000, ranging between €1100 and €100,000
Business models	Alternative food networks; CSAs, farmers' markets, online, on-farm shops

3.1. Description of Production Systems and Business Structure

The respondents were owners of newly started market gardens and were aged 25–37 years (8 female, 6 male). The businesses were located in seven different counties in southern and central Sweden, and four were urban farms and 10 were located in rural areas. Most respondents had some training in farming or business management, often from an adult education college focusing on small-scale horticulture. Some respondents had studied at the university level, and at least three had a university degree, while a few had prior experience of business management. Previous occupations included chef, computer programmer, and international aid worker.

Most of the production systems were less than 1 ha in size (range 200 m^2 to 4 ha). Production mainly focused on vegetables, with a total of 20–50 different cultivars per production unit and was mainly carried out in open fields or polytunnels. Two respondents had greenhouse production and two had combined vegetable and animal production. One-third of the respondents farmed in systems designed for tractor-driven tools, while the remaining two-thirds farmed in permanent beds, mainly using handheld equipment such as wheel hoes, garden forks, and rakes. Some respondents had equipment designed for market gardening, e.g., quick-cut greens harvesters, rotavators, and two-wheeled tractors. The main source of plant nutrients used was animal manure, sometimes supplemented with compost, bone and blood meal, or different homemade biostimulants. None of the respondents used chemical pesticides or mineral fertilizers.

3.1.1. Financial Situation

All businesses were relatively newly started, with the past 1–10 years, and most were still in a start-up phase where the business was not yet making a profit. Yearly revenue ranged between €1100 and €100,000 (mean €29,000). Businesses with larger production units naturally had higher total revenues, but the profit per m^2 was lower than for those with smaller production units. Some of the smallest production units (around 200 m^2) managed to make €50 per m^2, compared with €1.5–3.0 per m^2 for businesses with production units >1 ha. This variation in revenue per unit area reflected a diversity of production systems with slightly different strategies to achieve a financial balance. Some respondents planned to diversify, some planned to rationalize, and some did not have a defined strategy for long-term financial stability. Some respondents deliberately applied a low-input strategy where revenues exceeded costs, instead of entering a loop of investment and a need for increasing returns:

> "We need to cut our costs so we don't need to make as much money." (Participant 6)

When asked about optimal business size for the chosen business model, most respondents replied in terms of employment rather than production area or revenue. All respondents aimed to support themselves and their families based on their market garden in the long run, but half the respondents were still financially dependent on incomes outside the business. Therefore, most respondents saw a need for the business to grow from a financial and social perspective, e.g., to be large enough to cope with setbacks.

3.1.2. Business Models

A feature shared by all businesses was that they had short value chains, with produce sold directly to end-consumers through different sale channels, e.g., CSAs, farmers' markets, online marketplace, and on-farm shops. Half the respondents also reported selling to restaurants and some sold to local supermarkets. One respondent noted:

> "So far, we have sold at farmers' markets and online and various forms of direct sales [...] The largest amount is sold directly to the consumer. Otherwise, the whole idea fails, I think. I like this relationship sale where you can look the customer in the eye." (Participant 11)

Despite having only slightly different approaches to the same value proposition, i.e., organic and locally produced vegetables, the 14 market gardeners interviewed often reported different experiences from using the same sales channels. Some respondents liked farmers' markets, while others preferred online marketplaces that allowed them to harvest only produce already sold. Some others disliked online marketplaces for their uncertainty, as quantities ordered can vary greatly between weeks. Marketing was done via social media and personal contact. The most frequently cited social media platforms were Instagram and Facebook. Direct sales were considered an important way of marketing, with the personal meeting seen as part of the value proposition. In general, the respondents reported good customer relationships, often highlighting customers as a key partner.

3.2. What Motivates Young Market Gardeners in Sweden?

The perceptions, values, and goals of the respondents reflected the inner driving forces that shape their everyday motivation and long-term lifestyle choices. One respondent said,

> "We started this farm partly because it is fun to work with the soil and grow vegetables, but also with an idea of transitioning in mind, that you can produce food in a different way and you can sell it in a different way." (Participant 1)

This statement clearly indicates the multidimensional nature of motivation and its interconnectedness with both personal identity and the surrounding food system. Market gardening allows the respondents to pursue a personal interest while also creating economic, ecological, and social value in their business and for the community. In a wider perspective, this contributes to what they see as the future sustainable food system, creating a sense of purpose that motivates them to continue developing their business.

3.2.1. Making a Living from Market Gardening

The prospect of generating an income acted as motivation to improve the production and business model. The market gardeners interviewed were determined to support themselves and their families on the income from their business. One respondent said:

> "We should be able to live off this and to put money aside, that is the goal of the business. It should be justifiable considering how much work one puts into it." (Participant 11)

Around 50% of the respondents did not have other sources of income and were instead living on low income and savings. In a long-term perspective, generating an income from their business will be essential to their livelihoods. Although income generation was an important incentive for the market gardeners, it was a business goal, not a personal goal. Many respondents saw making money as secondary to other goals, or simply as a prerequisite to continue with something they enjoy doing:

> "The financial part, it permeates it all because we want to support ourselves. But we don't feel the need to measure success financially, to put it that way." (Participant 5)

3.2.2. Personal Interest and Wellbeing

All respondents had a personal interest in cultivation. This provided their motivation to pursue an interest that they find creative, stimulating, fun, and challenging. Several respondents had started growing vegetables on a small scale to obtain a more balanced everyday life on a farm, with less stress. However, some respondents mentioned that they were rather stressed about their financial situation, in combination with not getting the necessary financial support from existing support systems that serve other types of businesses. It was common for the respondents to have income from other jobs outside their business to get by. One respondent said,

> "It is all about finding a balance in everything, the input/workload and the revenue, which provides for us [. . .] so that you have the strength in a long-term way." (Participant 10)

For some respondents, cultivating vegetables was therapy, curative as well as preventative. They had started market gardening to heal mentally, through returning to the land and the possibility to control their own workload. One respondent said,

> "It was also with a backdrop of a life crisis. [. . .] I thought I needed to have my 'fingers in the soil'. It's about being able to feel good." (Participant 6)

3.2.3. Sustainability Values and Leading the Sustainability Transition

All respondents explained their engagement in market gardening from an ideological standpoint, where they use agroecological production practices and/or organic farming. They saw market gardening as an act of opposing the globalized food system and seeking alternative sale channels to avoid the dominant players on the market. They were also concerned about industrialized agriculture and its negative impact on the environment, and saw market gardening as a means of more sustainable food production. Aspects mentioned were resource regeneration and recycling, soil health, reduced use of fossil fuels in production and transportation, carbon sequestration, biodiversity, avoiding use of pesticides or mineral fertilizers, and contributing to ecosystem health. The respondents viewed the basic premise of sustainability as being a long-term endeavor, expressed for example as stewardship of the soil. In addition, there was a strong emphasis on creating local systems, both in terms of recycling the means for production and in terms of distribution and consumption. The respondents viewed themselves from a holistic perspective and argued that they are part of the solution to more sustainable food production. One said,

> "I am thinking of changing society [. . .], but I also think that in order for it to be a real change, there must be some laws and rules about what to do." (Participant 1)

One respondent described trying to take responsibility for the whole system, from farm to fork, by implementing everything they knew about the soil microflora, plant requirements, compost techniques, and cooking. Another respondent had a practically oriented approach with a three-point bullet list for sustainability trade-offs: (1) to grow good quality products, (2) to be reasonably profitable, and (3) to be environmentally sustainable. One participant explained that their skills in permaculture design were important in reconciliation of competing sustainability objectives. These examples show that the participants negotiated between different dimensions of sustainability as part of their decision-making process.

Many market gardeners wanted to raise awareness among consumers about sustainable foods and to reach out to new customer segments by organizing courses and other events. For some, spreading the word about market gardening and engaging in public debate to influence policy makers was the single most important part of their business, while others saw it more as an added value or part of their activism:

> "[. . .] it is something else that attracts people. There is this view that there is something fundamentally wrong in society, and then you try to change it yourself in an active way. You could get involved in politics too, but if you want to [. . .] well, some of us are more attracted to try for ourselves, influencing from the inside so to speak." (Participant 3)

3.3. Barriers and Opportunities for New Entrants in Market Gardening

3.3.1. Barriers and Opportunities Related to Knowledge and Learning

The majority of the market gardeners interviewed had negative experiences of existing extension services, both official and private, since they did not receive the knowledge and support they needed. One respondent said,

> "We have tried, but we have not received help from anyone. Advice can be very theoretical and not so adaptable to our situation. People often think that it is bigger than it is. You only start from large-scale farms when you give advice, perhaps." (Participant 3)

Only one participant mentioned turning to academic research. The respondents preferred using websites or groups within social media, primarily domestic and international Facebook groups, when searching for knowledge. In the groups, members can ask questions about cultivation or market-related issues and receive knowledgeable replies. Thus, they work as effective platforms for sharing skills and knowledge. Social media was often multifunctional for the respondents, acting as a source of information, a platform for collaboration, and a marketplace. Use of knowledgeable personal contacts, e.g., neighbors or relatives, was also common. The respondents emerged as strikingly competent in continuous learning through experimentation, or "learning by doing". They reported that they constantly test new ways to solve problems, for example lack of appropriately scaled tools had required some to invent their own tools. One respondent said,

> "Well, something I think we had in the beginning is some kind of openness to try new things, we experimented a lot with different crops and so on. I believe we need to maintain that openness, but maybe shift the focus to what we are already producing, instead of trying to produce even more strange things." (Participant 1)

Lack of Skills in Business Management

Many of the respondents said that they lack training in business management. All of them had basic skills in accountancy in order to comply with legal requirements but wanted to develop their skills in accountancy, budgeting, economic forecasting, and marketing. Some respondents also mentioned a need for skills in providing leadership and in organizing daily work, as the projected growth of their business could require seasonal employees.

Technical Skills Are Learnt along the Way

Several respondents described a need for practical skills, such as mechanics, electrical work, constructing and fixing farm buildings and equipment, and practical skills to optimize their production systems. They also wanted to learn more about ecosystems to improve habitats for other organisms in the natural environment.

Pioneers Need to Be Good Communicators

Operating outside the established regime within a sector, with the aim of expanding a niche, requires a certain set of skills and competencies. Some relate to innovation to adapt and survive in a market environment. Participants also described a need to constantly justify their business model to both customers and policy makers, which requires skills in communication and teaching.

Networking Is an Important Skill

For many, digital platforms were central to their marketing, to learn new skills, and to communicate with market gardeners across the globe. Nevertheless, digital skills were not mentioned as a high priority by any of the respondents. Instead, they saw these as an obvious and unproblematic component of their daily work. They were members of various networks and initiated cooperation with other local businesses. The respondents demonstrated skills in participatory processes and stimulating local networks with a variety of stakeholders.

3.3.2. Barriers and Opportunities Related to the Political Economy

In general, many respondents felt strong support from their customers, some civil sectors, and each other, but they felt counteracted by the agricultural regime. Specifically, they emphasized a lack of financial support suitable for small-scale producers. Around one-third of the respondents had received start-up support for young farmers offered by the Swedish Board of Agriculture. Others reported that they could not apply because they did not own their own land, their production area was too small, or in one way or another they did not meet the requirements. One respondent had received a grant from a private foundation, and two respondents had received support through LEADER, part of the European Union rural development program that allocates financial support to local initiatives for innovation and cooperation [26]. Most participants were not aware of the different possibilities of applying for financial aid, meaning that the problem was not only scarce availability of financial support, but often also lack of awareness of the opportunities within the existing support system. One respondent said,

> "We haven't been able to squeeze ourselves into a regular program or standard form of any kind. It can be everything from the fact that we don't own our land so we can't go to the bank [. . .] or the Federation of Swedish Farmers or the Board of Agriculture think we are too small. And the municipality, they don't understand what we are up to." (Participant 8)

Respondents also pointed out that the current direct payment scheme favors large-scale agriculture with low labor intensity, to the disadvantage of small-scale producers. In other words, there was a certain level of distrust in the logic of existing support systems:

> "The authorities, and maybe also [the university], need to understand that there is a new generation of farmers, and in this generation, there are those, like me, who need to start from scratch. If we really want to achieve all those goals, we need to support them too and realize that they have different problems than those on a multigenerational farm." (Participant 4)

The reported difficulties in qualifying for venture capital show that market gardeners are operating in a niche locked outside a strong sociotechnical regime. In interview, the respondents were asked to look beyond the barriers and suggest reforms needed to improve their opportunities to run economically, environmentally, and socially sustainable businesses. Some economic reforms were suggested, such as raising the basic income tax threshold, lowering employer tax, or shifting to an employment-based system for direct payments, rather than the existing area-based system. As implied above, they also saw a need to change the requirements of, e.g., start-up support, to enable more market gardeners to benefit. Reforms relating to land access were also suggested, such as creating a program for collaboration between market gardeners and large-scale farmers. In all suggestions a general sense of urgency was conveyed, as reflected in the following quote:

> "A lot of young people come to us, they see the dream to contribute through farming. They really want to start up and they would do so in an instant if it were economically viable. Losing that resource is the saddest thing there is. There are thousands who want to participate, but we haven't figured out how to enable them to start. It's about access to land, it's about start-up support, it's about skills development—it's about society starting to value all aspects of small-scale vegetable production." (Participant 8)

4. Discussion

This study contributes to the literature by presenting market gardening as an example of food system redesign, and by providing empirical evidence for the link between alternative food networks and sustainability impacts. Market gardening is part of a growing system of alternative food networks producing food that is locally grown and produced with respect for the environment. It is also an example of the food sovereignty movement that has emerged as a consequence of citizens taking the initiative to produce food for their communities, and where responsible use of natural resources is embedded in the farming practices [28]. The results in this study confirmed that market gardeners are motivated by various personal, social, environmental, and economic factors. They strongly believe that market gardening can offer a grassroots alternative to the global agro-industrial food paradigm and that it is a step towards sustainable food systems by enacting a change at cultural and social levels.

Concern for the environment stimulates market gardeners to adopt agroecological farming practices with low levels of inputs and no mineral fertilizers or pesticides. They aim to grow a high variety of vegetables, fruits, and berries on their production units in order to contribute to high agrobiodiversity, while at the same time reducing food miles and supplying seasonal foods to their customers. It is well known that bio-intensive methods, including agroecological practices, have a higher yield output per area than conventional agriculture. Agro-ecological methods are often low-tech and labor-intensive, but are suitable for urban and peri-urban agriculture and horticulture, where farmland is a scarce resource [29]. A previous study on diversified farming systems as a social and economic basis to foster social–ecological conversion concluded that a diversity of knowledge and practices makes a promising alternative to the uniformity of industrialized agriculture when it comes sustaining and regenerating eco-system services, while comparing well with industrialized agriculture in terms of productivity (Marchetti et al. [30]).

Non-monetary rewards, such as meeting family needs, personal interests, and life satisfaction, were mentioned as important incentives by the market gardeners interviewed in this study, but economic aspects were also important for their commitment. The possibility to make a living out of market gardening must be ensured if the business is to survive in the long term. The respondents explained that they accept a low income because they are new entrants to gardening, and therefore inefficient. They believe profitability will increase when they have improved their practices and established a network of loyal customers. A striking characteristic of all market gardeners in this study was the entrepreneurial aspect of their motivation, i.e., they were determined to pursue ideals through entrepreneurial activities. In other words, given their ambition to find alternative ways to produce and distribute food and to contribute to food system transition, they can be described as typical "social" or "sustainability" entrepreneurs, striving for sustainability transformation while at the same time making a living from it [31].

There are clear links between the conditions and change of food systems and political ecology, because of the explicit considerations of relations of power [32]. Political ecology studies have uncovered social, environmental, and economic unfairness in the contemporary global food system and point out that finding solutions to the sustainability crisis will require a major rethink and political and social change, and not merely the addition of new technologies. According to De Molina, et al. [33], political agroecology is based on the fact that sustainability cannot be achieved using only agronomic and environmental innovations but needs a fundamental change in the institutional framework through collective action by social movements. In this respect, market gardeners can be seen as transformational change agents, since their business model questions the shortsighted neoliberal principles structuring and governing current food systems. By opposing mainstream food system actors, and sidestepping intermediary retailers and wholesalers, market gardening seeks to contribute to redistribution of power and fair income for farmers. The tendency to build strong lateral connections with other market gardeners, and not with representatives of the mainstream agricultural sector such as retailers and policy makers, is a result of their ambition to oppose industrialized agriculture and the globalized food system. It is obvious that they do not engage in farming to conform with the conventions and standards of mainstream agriculture, but rather apply a clear stretch-and-transform strategy [15]. They seek to build a tight relationship with their customers, whom they see as their closest business partners. The market gardeners interviewed in this study tried to stay independent of the current regime, but also expressed frustration at being marginalized by the existing framework for financial support to small-scale farmers. This locks out social innovation in the food system. The respondents wanted supportive public policies targeting alternative small-scale farmers that could help them develop persevering and thriving businesses. Our results are in line with Bruce and Castellano [34], who showed that the high degree of unpaid labor for producing foods prevents increased participation in alternative food networks. Strengthening market gardening management capability through "ecological entrepreneurship" skills training could be one way for advisors and educators to support the long-term sustainability of market gardening.

Competencies in horticulture and organic farming practices are of course very important, especially since market gardeners grow a diversity of crops. It is known that farmers usually make better choices for enhancing the sustainability of farming systems when they have access to various forms of knowledge [35]. All the market gardeners in this study obtained most of their information and knowledge from peers via virtual networks like Facebook. This was because they found it a reliable source of information, but also because they had experienced non-productive interactions with the mainstream extension services. Other examples of peer-to-peer learning can be found within the agroecological movement worldwide. In Latin America, the Campesino-a-Campesino (Farmer to Farmer) movement has promoted agroecological techniques for the past 35 years [16]. Conventional farmers transitioning towards organic agriculture use multiple sources of information in their personal network (family, neighbors, web forums) and more conventional sources (agricultural press, cooperatives, official and private extension services) [36].

Although the study was carried out in a national Swedish context, the results have been discussed in the perspective of published literature presenting empirical work from other parts of the world, which should make this study relevant also beyond the Nordic countries. Our study presents a snapshot of an emerging phenomenon in the food system and it would be interesting to perform a longitudinal study on how market gardens develop over time in relation to a changing socio-political environment. To support policy-making in the area of sustainable food systems, we suggest to contrast market gardeners with other transformational food producers, such as high-tech vertical farmers, in particular when it comes to the sustainability impact and the adoption of knowledge and innovations.

Market gardening is in line with the concept of "eco-economy" (Marchetti, Cattivelli, Cocozza, Salbitano and Marchetti [30]), a bottom-up strategy for the development of local food networks that represents an oppositional act to the global agri-industrial paradigm. Eco-economy is a model for food production that captures local and regional value between rural and urban spaces through a network of small and medium-sized businesses and economic activities. These utilize ecological resources in sustainable and ecologically efficient ways that do not result in net depletion of resources but instead add value to both rural and urban spaces. This model is already evolving in several places within and beyond Europe, working against the globalization of food systems and taking back control over how the food is produced. Importantly, these initiatives also re-establish connections between food production, the local environment, and local social conditions. Because of a variation in different types of alternative food networks, it is difficult to establish a clear link between the concept and sustainability outcomes [37]. In this study, we have shown that market gardeners directly contribute to environmental sustainability by the adoption of agroecological practices and by the reduction of food miles. Their businesses help them to fulfil personal social goals, but the amount of unpaid work poses a significant challenge to economic sustainability.

5. Conclusions

This study showed that young vegetable producers who engage in market gardening are social entrepreneurs, dedicated to make a living out of their businesses, while at the same time seeking food system change and more ecologically based, sustainable horticulture. These market gardeners face multiple barriers related to the existing political economy of industrialized agriculture, in particular regarding access to research-based knowledge, suitable technology, extension services, and business support systems. The skills they lack relate to daily work in the market garden, such as cultivation of vegetables and financial management. This skills gap could be overcome in a relatively short-term perspective by increasing the focus on finance and entrepreneurship in existing adult education courses and by developing extension services that can provide short and practically oriented courses in vegetable cultivation techniques for small-scale systems. To encourage more young people to start market gardening and contribute to the transformative agenda, there needs to be greater awareness of the characteristics and needs of market gardeners among extension workers, researchers, and policy makers.

Author Contributions: Conceptualization, A.D., M.M., and L.L.; methodology and software, A.D, M.M., and L.L.; validation, A.D., M.M., and L.L.; formal analysis, A.D. and L.L.; investigation, L.L.; resources, M.M.; writing—original draft preparation, A.D., M.M., and L.L.; writing—review and editing, A.D., M.M., and L.L.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partly funded by the European Union, through the Horizon 2020 project "NextFood", Grant agreement No. 771738. The APC was funded by the Horizon 2020 project "NextFood", Grant agreement No. 771738.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: The authors wish to thank the market gardeners who agreed to participate in this study. Your input provided the backbone of this study and it would not have come into being without you.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Introduction: Presentation of the interviewer and purpose of the study. Thank you for wanting to join. Ask about recording and guarantee anonymity. Are there any further questions?

Description of the owner and business characteristics

1. Which county are you active in?
2. How old are you?
3. Do you identify your gender (male, female, other)
4. Do you have any education in horticulture or business?
5. What area do you cultivate? (outdoor and greenhouse)

6. What is your production focus?

7. What do you grow?

8. What machines or technical aids do you use in cultivation? What are they used for?

9. What are your main sources of plant nutrition?

10. Do you use chemical pesticides?

11. How many people work in the company? All year? Season?

12. How long have you been working as a professional grower?

13. Did you start the company yourself or did you take over an existing company, such as a family business?

14. Do you have any other employment besides the farm?

15. Have you received grants or support, e.g., investment or start-up support?

16. How big is the company's turnover?

Theme 1: Motivation

1.1. What is the goal of your business? What is your vision?

1.2. What drives you to continue with the business?

1.3. What does the business model look like?

1.4. What is the right size for a company with your business model?

1.5. Who are your most important partners in the daily work?

1.6. What other actors do you have professional contact with? (suppliers, consultants, researchers, customers, other entrepreneurs in the same sector, authorities).

Theme 2: Skills and competences

Introduction: Skills can be learned in a relatively short time and are limited, for example technical skills, such as driving a tractor or wheel hoe, and digital skills, such as being able to use social media or Excel. Competences are linked to a specific context, in this case food systems, and are more complex. They often include both knowledge and skills, such as problem solving, critical thinking, business planning, leadership.

2.1. What are the most important skills and competencies in your daily work?

2.2. Compared with when you started cultivating, what new skills and competencies have you had to learn?

2.3. Are there any skills and competencies that you no longer use as much?

2.4. What skills to succeed better with your business do you feel you lack?

2.5. As you look into the future, what skills and competencies do you think you or your employees may need to develop?

2.6. When you think you need a new skill, competence or knowledge, where do you turn? (ask about the following actors: relatives, other entrepreneurs in the same sector, experts, local contacts, advisers, universities, market participants if the interviewee does not mention them voluntarily).

2.7. Which of your current knowledge and skills will become more important in the next 5–10 years? Why?

Theme 3: Sustainability and adaptation

3.1. What is sustainable food production for you? That is, what is included in your understanding of the concept? (ask about social sustainability, economic sustainability, and environmental sustainability if the interviewee does not mention them voluntarily)

3.2. What role does sustainability play in your daily work? Do sustainability goals shape your daily work? On which way?

3.3. Which of your skills or competencies contribute to making your food production and/or your business more sustainable? What are your most important skills and competencies when it comes to sustainability?

3.4. How does your company contribute to society as a whole achieving the global goals for sustainability development? (ask about Sustainable Development Goals such as Combating climate change, Reducing inequality, Sustainable consumption and production, Marine and marine resources and Ecosystems and biodiversity)

3.5. Which actors support you in your sustainability work? (ask about other companies in the same sector, advisers, educational institutions, associations if the interviewee does not mention them voluntarily)

3.6. What do you think about the concept of conversion?

Final question: Is there something we have not discussed that you think is important to better support young gardeners, bearing in mind that the societal goal is economic, social, and environmental sustainability?

References

1. IPCC. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; FAO: Rome, Italy, 2019.
2. Fernandez, M.; Goodall, K.; Olson, M.; Méndez, V.E. Agroecology and Alternative Agri-Food Movements in the United States: Toward a Sustainable Agri-Food System. *Agroecol. Sustain. Food Syst.* **2013**, *37*, 115–126. [CrossRef]
3. Galli, F.; Brunori, G. Short Food Supply Chains as Drivers of Sustainable Development. Evidence Document. 2013. Available online: https://orgprints.org/id/eprint/28858/1/evidence-document-sfsc-cop.pdf (accessed on 17 April 2021).
4. Schot, J.; Geels, F.W. Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy. *Technol. Anal. Strateg. Manag.* **2008**, *20*, 537–554. [CrossRef]
5. Witkamp, M.J.; Raven, R.P.; Royakkers, L.M. Strategic niche management of social innovations: The case of social entrepreneurship. *Technol. Anal. Strateg. Manag.* **2011**, *23*, 667–681. [CrossRef]
6. Kemp, R.; Schot, J.; Hoogma, R. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technol. Anal. Strateg. Manag.* **1998**, *10*, 175–198. [CrossRef]
7. Fernqvist, F.; Göransson, C. Future and recent developments in the retail vegetable category—A value chain and food systems approach. *Int. Food Agribus. Manag. Rev.* **2021**, *24*, 27–49 [CrossRef]
8. Seyfang, G.; Smith, A. Grassroots innovations for sustainable development: Towards a new research and policy agenda. *Environ. Politics* **2007**, *16*, 584–603. [CrossRef]
9. Altieri, M.A. *Agroecology: The Science of Sustainable Agriculture*, 2nd ed.; CRC Press Univ. Of California: Berkeley, CA, USA, 2018.
10. Francis, C.; Lieblein, G.; Gliessman, S.; Breland, T.A.; Creamer, N.; Harwood, R.; Salomonsson, L.; Helenius, J.; Rickerl, D.; Salvador, R.; et al. Agroecology: The Ecology of Food Systems. *J. Sustain. Agric.* **2003**, *22*, 99–118. [CrossRef]
11. Wezel, A.; Bellon, S.; Doré, T.; Francis, C.; Vallod, D.; David, C. Agroecology as a science, a movement and a practice. A review. *Agron. Sustain. Dev.* **2009**, *29*, 503–515. [CrossRef]
12. Iles, A.; Marsh, R. Nurturing diversified farming systems in industrialized countries: How public policy can contribute. *Ecol. Soc.* **2012**, *17*, 17. [CrossRef]
13. Gliessman, S. Agroecology and Food System Change. *J. Sustain. Agric.* **2011**, *35*, 347–349. [CrossRef]
14. Gonzalez de Molina, M. Agroecology and politics. How to get sustainability? About the necessity for a political agroecology. *Agroecol. Sustain. Food Syst.* **2013**, *37*, 45–59.
15. Smith, A.; Raven, R. What is protective space? Reconsidering niches in transitions to sustainability. *Res. Policy* **2012**, *41*, 1025–1036. [CrossRef]
16. Anderson, C.R.; Maughan, C.; Pimbert, M.P. Transformative agroecology learning in Europe: Building consciousness, skills and collective capacity for food sovereignty. *Agric. Hum. Values* **2019**, *36*, 531–547. [CrossRef]
17. Francis, C.; Breland, T.A.; Østergaard, E.; Lieblein, G.; Morse, S. Phenomenon-Based Learning in Agroecology: A Prerequisite for Transdisciplinarity and Responsible Action. *Agroecol. Sustain. Food Syst.* **2013**, *37*, 60–75. [CrossRef]
18. Coolsaet, B. Towards an agroecology of knowledges: Recognition, cognitive justice and farmers' autonomy in France. *J. Rural. Stud.* **2016**, *47*, 165–171. [CrossRef]
19. Hansen, S.R.; Sørensen, L.; Flynn, K.; Lindner, L.; Kristensen, N.H. *Inventory of Skills and Competencies*; NextFood: Alnarp, Sweden, 2019.
20. Jacobi, J.; Mathez-Stiefel, S.L.; Gambon, H.; Rist, S.; Altieri, M. Whose knowledge, whose development? Use and role of local and external knowledge in agroforestry projects in Bolivia. *Environ. Manag.* **2017**, *59*, 464–476. [CrossRef]
21. Agriculture, S.B.O. *The 2017 Horticultural Census*; Swedish Board of Agriculture: Jönköping, Sweden, 2018.
22. Fortier, J.-M. *The Market Gardener—A Successful Grower's Handbook for Small-Scale Organic Farming*; New Society Publishers: Gabriola Island, BC, Canada, 2014.
23. Olausson, I. *Competition on a Local Market—A Historical Study of Market Gardens in Stockholm*; International Society for Horticultural Science: Leuven, Belgium, 2016; pp. 135–140.
24. Blättel-Mink, B.; Boddenberg, M.; Gunkel, L.; Schmitz, S.; Vaessen, F. Beyond the market—New practices of supply in times of crisis: The example community-supported agriculture. *Int. J. Consum. Stud.* **2017**, *41*, 415–421. [CrossRef]
25. Ringqvist, J. *Odla Till Försäljning—Att Försörja sig på Småskalig Grönsaksproduktion*; Bossgården: Tidaholm, Sweden, 2018.
26. QIP Ltd. *NVivo Qualitative Data Analysis Software*; 1.4 (4); QSR International: Melbourne, Australia, 2018.
27. Limited, Q. *Quirkos 2.3.1*; Quirkos Software: Edinburgh, UK, 2020.
28. McMichael, P. Food system sustainability: Questions of environmental governance in the new world (dis)order. *Glob. Environ. Chang.* **2011**, *21*, 804–812. [CrossRef]

29. Kathryn, J.A.C.; Michael, W.H. Assessing the Local Food Supply Capacity of Detroit, Michigan. *J. Agric. Food Syst. Community Dev.* **2010**, *1*. [CrossRef]
30. Marchetti, L.; Cattivelli, V.; Cocozza, C.; Salbitano, F.; Marchetti, M. Beyond Sustainability in Food Systems: Perspectives from Agroecology and Social Innovation. *Sustainability* **2020**, *12*, 7524. [CrossRef]
31. Parrish, B.D.; Tilley, F. Sustainability entrepreneurship: Charting a field in emergence. *Mak. Ecopreneurs Dev. Sustain. Entrep.* **2010**, *2*, 21–41.
32. Galt, R.E. Placing Food Systems in First World Political Ecology: A Review and Research Agenda. *Geogr. Compass* **2013**, *7*, 637–658. [CrossRef]
33. De Molina, M.G.; Petersen, P.F.; Peña, F.G.; Caporal, F.R. *Political Agroecology: Advancing the Transition to Sustainable Food Systems*; CRC Press: Boca Raton, FL, USA, 2019.
34. Bruce, A.B.; Castellano, R.L.S. Labor and alternative food networks: Challenges for farmers and consumers. *Renew. Agric. Food Syst.* **2017**, *32*, 403–416. [CrossRef]
35. Darnhofer, I.; Fairweather, J.; Moller, H. Assessing a farm's sustainability: Insights from resilience thinking. *Int. J. Agric. Sustain.* **2010**, *8*, 186–198. [CrossRef]
36. Chantre, E.; Cardona, A. Trajectories of French Field Crop Farmers Moving Toward Sustainable Farming Practices: Change, Learning, and Links with the Advisory Services. *Agroecol. Sustain. Food Syst.* **2014**, *38*, 573–602. [CrossRef]
37. Forssell, S.; Lankoski, L. The sustainability promise of alternative food networks: An examination through "alternative" characteristics. *Agric. Hum. Values* **2015**, *32*, 63–75. [CrossRef]

III

Renewable and Sustainable Energy Reviews 188 (2023) 113884

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Urban farming with rooftop greenhouses: A systematic literature review

Annie Drottberger [a,1,*], Yizhi Zhang [b,c,1,**], Jean Wan Hong Yong [a], Marie-Claude Dubois [a,d]

[a] Swedish University of Agricultural Sciences, Department of Biosystems and Technology, 234 22, Lomma, Sweden
[b] School of Architecture and Planning, Hunan University, Changsha, 410082, China
[c] Hunan Key Laboratory of Sciences of Urban and Rural Human Settlements in Hilly Areas, Hunan University, Changsha 410082, China
[d] Lund University, Faculty of Engineering (LTH), Department of Building and Environmental Technology, Division of Energy and Building Design, Box 118, 221 00, Lund, Sweden

ARTICLE INFO

Keywords:
Energy conservation
Land optimisation
Rooftop farming
Rooftop greenhouse(s)
Urban agriculture
Urban population

ABSTRACT

The environmental impacts of food systems will increase in tandem with rapid urban population growth, which calls for alternative solutions, such as urban agriculture, to reach the United Nations Sustainable Development Goals. Among several urban agriculture systems, rooftop farming and its subset, rooftop greenhouses, are promising technologies. They optimize land use, increase profitability for building owners, deliver good yields per unit area, increase water use efficiency, and reduce the energy use of both greenhouse and host buildings while mitigating the urban heat island effect. A systematic literature review of the rooftop greenhouse technology was carried out to examine the benefits and challenges associated with this technology. This review was based on 45 articles, covering themes such as the impact of rooftop greenhouse technology on yields, energy use, water use, environmental impacts, and life-cycle costs; some benefits identified are the symbiotic heat, water, and CO_2 exchanges between the rooftop greenhouse and its host building, and the possibility of delivering year-round production. The additional investment, operational costs, limited availability of flat roofs, and various regulations were challenges to overcome. The relevance of symbiosis between rooftop greenhouses and buildings to enhancing sustainability, and meeting the SDGs was explored. This review also outlines that rooftop greenhouses are increasing in scale, system diversity, societal acceptance and popularity among commercial operations in large cities. The future of rooftop farming lies in customizing the right technology for selected building typologies globally, where food production is fully integrated into the urban landscape.

1. Introduction

The world's urban population is expected to grow to 6.7 billion by 2050 [1], representing an increase of 50 % or 2.5 billion people in 30 years. As more people move to cities, the demand for food increases, which exerts pressure on existing food systems. As a result, urban populations are increasingly reliant on food produced in rural areas or imported from other regions. Moreover, the distance between food production and consumption increases as cities develop. When considering the whole life cycle, transport-linked emissions of food systems represent a fifth of the total food system's emissions [2]. Note also that increasing the distance between the inhabitants and land that supports them alters ecosystem services [3]. The current food systems contribute to one-third of global greenhouse gas (GHG) emissions [4]. Clark et al. [5] demonstrated that even if fossil fuel emissions were eliminated immediately, emissions from the global food system alone would make it impossible to limit warming to 1.5 °C and pose difficulties in achieving the 2 °C target. Thus, major paradigm shifts in food production are urgently needed if humanity intends to meet the Paris Agreement's goals. Climate change impacts are also anticipated to increase the variability and the uncertainty of food production [6]. Several cities are developing urban agriculture (UA, also called urban farming) systems to reduce the reliance on imported food to address these challenges. However, it is worth mentioning that literature on UA includes peri-urban agriculture, which may exaggerate the expectation of inner-city farming. There is probably a higher potential for RTGs in peri-urban areas than in the inner city as the inner city is normally very dense.

Rooftop farming (RTF) is one of the promising futuristic solutions since rooftops constitute one-fourth of all urban surfaces [7]. Orsini et al.

* Corresponding author.
** Corresponding author.
E-mail addresses: annie.drottberger@slu.se (A. Drottberger), yizhizhang@hnu.edu.cn (Y. Zhang).

[1] These authors contributed to the work equally and should be regarded as co-first authors.

https://doi.org/10.1016/j.rser.2023.113884
Received 15 May 2023; Received in revised form 16 September 2023; Accepted 9 October 2023
Available online 16 October 2023
1364-0321/

Abbreviations

BIA	Building Integrated Agriculture
CEA	Controlled Environment Agriculture
ESG	Environmental, social, and governance
GHG	Greenhouse gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
IRTG	Integrated rooftop greenhouse
iRTG	Intelligent rooftop greenhouse
LCA	Life-cycle assessment
LCC	Life-cycle cost
LED	Light emitting diode
PV	Photovoltaics
PFAL	Plant factory with artificial lighting
RA	Rooftop agriculture
RTG	Rooftop greenhouse
RTF	Rooftop farming
SDGs	Sustainable Development Goals
SLR	Systematic literature review
STPV	Semi-transparent photovoltaics
UA	Urban agriculture
VF	Vertical farming or farm
ZFarming	Zero acreage farming

[8] estimated that not less than 77 % of Bologna's vegetable demand could be met by cultivating on flat roofs. This solution has several benefits: space optimisation and economic development, urban heat island (UHI) mitigation, energy savings, etc. Space optimisation is highly desirable in areas with little or no arable land. Many RTF projects are characterized by the non-use of land or acreage for farming activities, referred to as 'Zero-Acreage Farming' (ZFarming) [3]. This is an important development since projections indicated that arable land per person will have decreased to one-third of its 1970 value by 2050 [9].

Rooftop greenhouses (RTGs), a subset of RTF and building-integrated agriculture (BIA), are interesting in colder climates as they provide an optimal environment for plants by controlling temperature, humidity, and light (Fig. 1). RTGs are found on various building types (commercial, industrial, residential); they can be permanent or temporary structures involving different technologies e.g., hydroponics, aeroponics, aquaponics, vertical farming (VF), etc., allowing for efficient space and resource use. Hydroponic systems [10], and aeroponics are used in RTGs due to their lightweight. Note that these systems are highly efficient and one of the key reasons for reduced water use [11,12]. Some of the most recent RTGs (De Schilde [13] and Urban Farmers AG [14], in The Hague, Netherlands; Ferme Abattoir [15], in Brussels; Sky Greens in Singapore, etc.) even integrate aquaponics (use of fish waste to fertilise crops) with or without a rooftop garden [16].

RTGs also form a subset of the broader Controlled Environment Agriculture (CEA) category, offering localized urban production with biosecurity, pest and drought mitigation, and year-round profitable crop

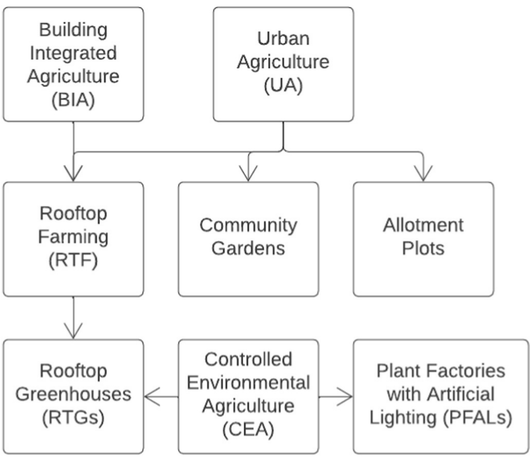


Fig. 1. Illustration showing the different urban agriculture concepts discussed in the introduction.

production [17]. CEA contributes indirectly to natural ecosystems by reclaiming the land lost to farming while providing jobs locally [18]. Other forms of CEA include ordinary greenhouses, VFs, and plant factories with artificial lighting (PFALs), sometimes called closed plant production systems. Most recent publications on CEA have focused on VFs [19], as these can increase crop yields by 10–100 times in a limited space compared to traditional farming [20]. Conversely, a drawback of PFALs is the energy cost associated with lighting.

To better harness energy transfer and optimisation [21,22], RTGs can be advantageously integrated with the host building, which involves exchanging energy, water and CO_2 (Fig. 2). The higher CO_2 concentration and moisture levels in the residual air act as enhancers that increase plant growth [23]. This integration is possible if the RTG and building can exchange residual air and collect rainwater or use treated grey water for irrigation [24,25]. Since significant amounts of non-renewable energy are used to operate greenhouses in Europe, an integrated method could decarbonise greenhouse-based production and promote efficient greenhouse heating [26,27]. The development of integrated rooftop greenhouses (IRTGs) allows local production and consumption ("zero km") of vegetables with negligible change in the energy use of buildings [23]. In recent publications, integrated RTGs were aptly called building-integrated rooftop greenhouses (BIRTGs) [28]. With further evolution, the concept of intelligent rooftop greenhouses (iRTGs) was enhanced and implemented [29]. Through an advanced controller, the iRTG optimises the resource symbiosis between the greenhouse and the host building. For example, the oxygen produced by the plants is recirculated into the host building, while the CO_2 produced during respiration by inhabitants is delivered to the plants.

From the operational perspective, RTGs entail some challenges, such as low solar transmission due to the poor transmissivity of coverings and additional structural elements needed to comply with the building code [25]. RTGs also require additional maintenance, ventilation, and structural stability against external perturbations [30]. In some scenarios, investments in equipment, such as lighting, heating, and cooling systems, may be needed, increasing energy requirements and costs [3]. UA stakeholders also highlighted that existing laws and regulations constrain cultivation on or in buildings [31,32]. Another limitation is the characteristics of existing buildings, including load capacity or fire safety regulations. Table 1 summarises the strengths, weaknesses, opportunities, and threats (SWOT) of RTG technology. Despite these challenges, RTGs have been widely implemented in cities like New York, Montreal, Berlin, etc. Table 2 shows a non-exhaustive global list of RTGs.

Several studies have investigated various aspects of RTG farming, including energy and water conservation, local job creation, economic profitability, global warming potential (GWP), etc. This article presents a systematic literature review (SLR) about RTGs to provide a better understanding and overview of the RTG technology. The method for searching, collecting, selecting, and summarising the articles is first presented, followed by categorising the main results under identified subthemes. The review includes only studies focusing on RTGs and does

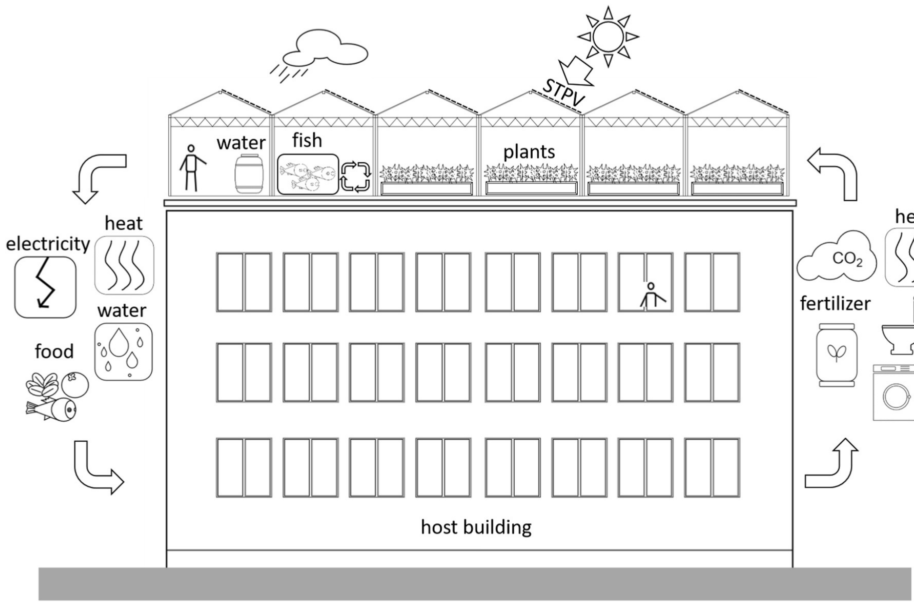


Fig. 2. Integrated rooftop greenhouse (IRTG), using heat and respired CO_2 from host building and delivering electricity, heat, water, and food to host building.

Table 1
SWOT analysis of RTGs.

Strengths	Weaknesses
- Higher energy efficiency of greenhouse and host building - Land optimisation - Low transport energy of products - Higher yield than conventional agriculture - Water conservation - Added social values - Local job creation - No pesticides - Less load capacity than edible green roofs	- High investment costs (equipment, heating, ventilation, lighting) - Need for extra structural elements - Low solar transmission of coverings due to structural elements - Limited availability of flat roofs (with slope $< 5°$) - Need for accessibility either through interior or exterior stairs and elevators - Limited habitat creation and biodiversity
Opportunities	**Threats**
- Growing urban population, increased need for food - Climate change uncertainty - Dietary changes (replacing meat with vegetables) - Climate emissions and costs of transport - Awareness of local food production	- Municipal laws and regulations - Fire regulations - Societal regulations - Stakeholder interests - Consumer acceptance - Scarcity of holistic studies on RTGs

not cover open-air rooftop farming. The United Nations Sustainable Development Goals (SDGs) are to be fulfilled by 2030 [33] and the implementation of RTG technology will have a positive impact related to several goals. RTGs in urban location will increase the availability of healthy food, contributing to both SDG 2 (zero hunger) and SDG 3 (good health and well-being). Several RTG projects are focusing on social sustainability, where greenhouses are located near schools fulfilling SDG 4 (quality education), when children and adults can learn practical aspects of cultivation. For environmental sustainability, the use of hydroponics and recirculation of water in RTGs will contribute to SDG 6 (clean water and sanitation), ensuring sustainable water management. In addition, the structural symbiosis between RTG and the host building, fulfils SDG 7 (affordable and clean energy) through efficient energy utilization. Adoption of innovations such as RTG technology and BIA will also contribute to SDG 9 (industry, innovation and infrastructure), with more sustainable production integrated in the city, this also enhances SDG 11 (sustainable cities and communities). Finally, the implementation of RTGs holistically contributes to SDG 12 (responsible production and consumption), where reduced transportation and decreased CO_2 emissions also fulfils SDG 13 (climate action).

2. Method

A systematic literature review (SLR) was carried out, based on articles published in scientific journals in the period January 1, 2009 to 6 March 2023. An extensive search was initiated focusing on rooftop farming. Subsequently, the search was limited to only include articles with rooftop greenhouses since this was the main interest. Production systems with RTGs are an emerging area involving new terminology (e.g., in abbreviation list) that appeared in these reviewed articles. The SLR was selected as research methodology, as it is the most valuable research method providing a strong basis for the next steps in a larger ongoing research on rooftop technologies in Northern Europe. The RTG technology was selected as one of the most promising technologies since it offers a higher potential for year-round cultivation, which is especially relevant to cold or temperate climates. A SLR provides a comprehensive and unbiased overview of the existing body of knowledge about a topic as it "aggregates, critically appraises, and synthesizes in a single source all available empirical evidence that meet a set of pre-specified eligibility criteria aiming to answer in depth a clearly formulated research question to support evidence-based decision-making" [34]. It also follows a rigorous methodology and a stepwise procedure [35], which helps minimize bias in the selection and analysis of studies. The SLR process is transparent and documented, facilitating replication of the study or verification of the findings, thus promoting scientific rigor. This reduces the risk of cherry-picking data that supports a particular viewpoint. By systematically reviewing the literature, this SLR allows to

Table 2
Non-exhaustive global list of RTGs.

Country	Company	City	Built	Size (m^2)	Website
USA	Gotham Greens	Chicago, Illinois	2015	6968	https://www.gothamgreens.com/
		Queens, New York	2015	5574	
		Brooklyn, New York	2013	1858	
		Brooklyn, New York	2011	1394	
	The Vinegar Factory	NYC, New York	1995	2043	https://www.elizabar.com/The-Vinegar-Factory.aspx
	Sky vegetables	Bronx, New York	2013	743	https://www.agritecture.com/sky-veg https://www.skyvegetables.com/
	The Urban Gardens, (Greenhouse Project lab)	Manhattan, New York	2010	130	https://www.urbangardensweb.com/2011/11/16/nyc-classroom-in-an-urban-rooftop-farm/
	Arbor House	Bronx, New York	2012	930	https://greenhomenyc.org/building/arbor-house/https://www.taxcreditcoalition.org/gallery/arbor-house/ https://www.architectmagazine.com/technology/developer-raises-the-bar-in-the-bronx_o
	Edenworks	Brooklyn	later than 2013	74/ unit	https://inhabitat.com/rooftop-aquaponic-farmlab-uses-tilapia-fish-to-grow-edible-plants/
	Loyola University	Chicago	n/a	288	https://stories.luc.edu/institute-for-environmental-sustainability https://schulershook.com/projects/loyola-university-institute-of-environmental-sustainability
Canada	Lufa Farms	Saint-Laurent	2020	15 218	https://montreal.lufa.com/en/about
		Anjou, Montreal	2017	5853	
		Laval, Montreal	2013	3995	
		Ahuntsic, Montreal	2011	2880	
	Maison Productive House	Montreal	2010	n/a	https://www.ecohabitation.com/guides/2079/la-maison-productive-house-mph-un-ecosysteme-dans-le-quartier-pointe-st-charles/
Germany	inFarming by Fraunhofer UMSICHT	Oberhausen	n/a	n/a	https://infarming.de/en/homepage/ https://divisare.com/projects/415461-kuehn-malvezzi-hiepler-brunier-administration-building-with-rooftop-greenhouse
	Dachfarm Berlin	Several projects in cities	n/a	n/a	http://www.dachfarmberlin.com/#referenzen-section https://partnerundpartner.com/en/projects/rooftop-farm-in-oberhausen-oberhausen-2016/ https://herne.we-house.life/ https://we-house.life/oeko-prinzip/
	Roof Water-Farm	Berlin	n/a	n/a	http://www.roofwaterfarm.com
	Rewe Green Farming	ErbenheimWiesbaden	2021	2000	https://www.rewe.de/nachhaltigkeit/nachhaltig-einkaufen/green-farming/?ecid=pos_nachhaltigkeit_greenfarming_direct-link_nn_nn_nn_nn_nn https://acme.ac/blogs/projects/rewe-green-farming
The Netherlands	UrbanFarmers AG	The Hague	2015	1200	https://www.urbanfarming-greenhouse.eu/the-new-farm-in-den-haag-operated-b
France	Sous les fraises	Paris	2018	400	https://www.souslesfraises.com/histoire/
Switzerland	UrbanFarmers AG	Basel	2012	260	https://digitalcollection.zhaw.ch/handle/11475/2471
	Rooftop Farm Ecco Jäger	Bad Ragaz	2015	1000	https://www.ecco-jaeger.ch/ https://www.ecf-farmsystems.com/referenzen?lang=en
Belgium	Ferme Abattoir BIGH	Bruxelles	2018	2000	https://bigh.farm/fr/ferme-abattoir/
	Agrotopia	Roeselare	2022	9500	https://www.dezeen.com/2022/02/04/rooftop-greenhouse-agrotopia-urban-agriculture-architecture-belgium/
Spain	University of Barcelona	Barcelona	2014	512	https://inhabitat.com/responsive-bioclimatic-skin-wraps-around-leed-gold-icta-icp-building-in-barcelona/icta-icp-by-h-arquitectes-14/ https://www.uab.cat/web/sala-de-premsa-icta-uab/detall-noticia/building-integrated-rooftop-greenhouses-an-energy-and-environmental-assessment-in-the-mediterranean-context-1345819915004.html?detid=1345815808101
Singapore	Sky Greens	Singapore	2012	670	https://www.skygreens.com/about-skygreens/
	Comcrop	Singapore	2011	2800	http://comcrop.com https://www.sfa.gov.sg/fromSGtoSG/farms/farm/Detail/comcrop

identify gaps in the current body of knowledge leading to the formulation of research questions and directions for the continuation of research on RTGs. In addition, this SLR is solely based on peer-reviewed publications, which ensures that research findings are based on high-quality studies. Conducting a SLR is time-consuming, but it is more time-efficient than repeating existing studies, which avoids duplication of effort and resources by consolidating the existing knowledge base. Finally, this SLR allows for the synthesis of data from studies with different methodologies, sample sizes, and geographical locations, which deliver a holistic understanding of this topic.

While the SLR is a powerful research method, it also contains intrinsic boundaries and limitations, which are briefly discussed below. Firstly, the SLR may be susceptible to publication bias since it typically includes only published studies. It was evident that studies with statistically significant or positive results are more likely to be published, which may lead to an overrepresentation of such findings [36]. Secondly, most articles reviewed in this SLR were published in English, which introduces a language bias. Note that the SLR cannot either consider contextual factors that could influence the results of individual studies, which in turn affects the generalizability of findings. Thirdly, the comprehensiveness of this SLR depends on the databases and sources searched. Relevant studies may not be indexed in the selected databases, potentially leading to the omission of important research. Fourthly, while defining clear inclusion and exclusion criteria is essential, this process introduces a degree of subjectivity, potentially affecting the review's outcomes. Fifthly, the authors found that studies included in this SLR vary broadly in terms of quality, methodologies, systems, technologies, and outcomes measured. This heterogeneity has made it challenging to analyse the data in a consistent manner. Finally, this SLR is based on existing literature, and therefore, it does not include the recent research developments in this field. This review is thus intrinsically limited as it cannot provide recent empirical data. In rapidly evolving fields, such as is the case for urban agriculture, the SLR may become rapidly outdated as new research constantly emerges. Also, in the context of private businesses, commercial or legal restrictions on data sharing and access may have limited the inclusion of certain studies, which is also one important limitation of this SLR.

The assessment method involved at least ten steps (Fig. 3).

Step 1 included searches in Web of Science Core Collection, Scopus and EBSCO (Garden, Landscape & Horticulture Index). The full search was (rooftop OR "roof top") near/2 (garden* or farm* or agriculture* or greenhouse*), with W instead of near for the search in Scopus. The broader search queries served to reduce the risk of excluding relevant papers. The final search was made on March 6, 2023, to allow database indexing, which would lag behind the last publication year. Subsequently, keyword search with (" … " AND " … *") AND " … " in the databases: Web of Science core collection, Scopus and EBSCO (Garden, Landscape & Horticulture Index) resulted in retrieving 686 records. Step 2 involved removing duplicates (n = 147), which left 539 records. Step 3 involved setting up exclusion criteria, which resulted in the removal of 101 articles and 438 kept for further analysis. The exclusion criteria were determined by the authors, and focused on selecting studies that would be relevant to cold or temperate climates; thus, an inevitable element of subjectivity in the methodology may be present. The exclusion criteria were: RTF = rooftop farming without a greenhouse, RG = rooftop garden without a greenhouse, GR = green roof, and C = excluded due to climate (and country); included articles from European, North American or South Korean climate. The inclusion criteria were: RTG = rooftop greenhouse in a European, North American or South Korean climate. Step 4 involved reading all titles and excluding articles that were not relevant. Step 5 involved reading the abstract and classifying it individually according to a code ranging from 1 (highly relevant) to 4 (not relevant). The relevance was again, attributed based on judgement of the authors, which also introduces an element of subjectivity. Step 6 consisted of reading all articles with code 1 or 2 and excluding all articles that were assessed to be irrelevant. In step 7, a final selection was made (n = 45), while step 8 entailed preparing notes for each article. Besides bibliographical information, the reading notes included information about the aim of the study, methodology, significant results, main conclusions, and limitations (according to the reader). These notes were shared between all co-authors. Step 9 consisted of grouping and classifying each reviewed article according to a set of identified subthemes. Finally, step 10 consisted of writing a first draft of the literature review based on the reading notes.

3. Results

Table 2 presents a non-exhaustive overview of the RTGs with the

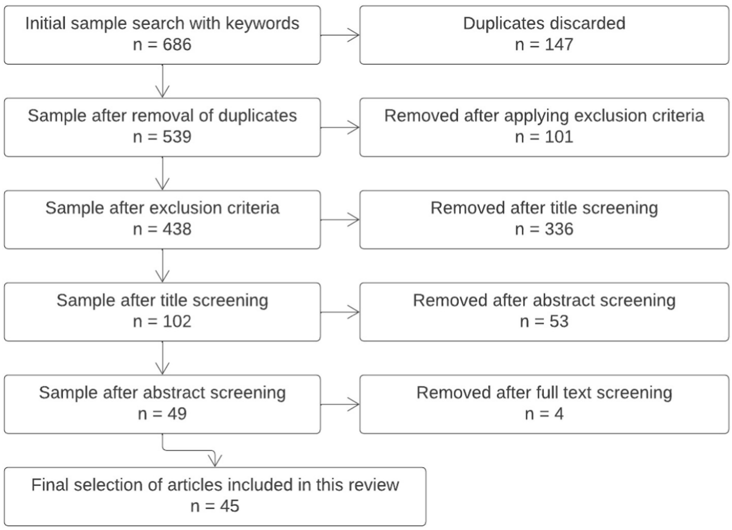


Fig. 3. Schematic diagram showing the procedure for searching, selecting, and summarising the articles.

examples dating from 1995 (The Vinegar Factory). It also shows that the largest RTG, covering 15 218 m^2, is in Montreal, Canada. Interestingly, some large companies have built several RTGs, starting with smaller ones and increasing in size with each new installation (i.e., modular approach), highlighting the importance of scale to ensure economic profitability. The following sections present a brief review of relevant articles grouped according to a few subthemes. Moreover, each of the 45 included publications was coded in a summary in Table 3 with details available in the Appendix section concerning year, type of RTG, country, salient features, notable output or learnings and author.

3.1. Effects of RTGs on yield

Five articles were reviewed regarding yield in RTGs. In three articles [25,37,38], it was found that RTG technology increased yields often in combination with other technologies i.e., VF [37] or light emitting diode (LED) [38]. Cerón-Palma et al. [39] also highlighted the potential for yield enhancement. Rufí-Salís et al. [40] focused on comparisons between different crops in RTGs and highlighted that greater species diversity leads to better performance. Cerón-Palma et al. [39] investigated barriers and opportunities of RTGs in the Mediterranean climate. The issues were analysed across three scenarios: residential, educational or cultural, and industrial buildings. The structural interconnection of the building and RTG optimized the usage of water, energy, and CO_2 flows in combination with reducing food transport. They found that urban horticulture has the potential to supply the city's needs. Depending on crop type, urban greenhouses may yield from 10 to 50 kg/m^2 per year of fresh fruits and leafy vegetables.

Montero et al. [25] investigated the climate and productivity of an integrated rooftop greenhouse (IRTG) in Barcelona, Spain. They found that while the IRTG had a poor transmission of radiation, it had a high natural ventilation capacity due to its size and large ventilator/ground ratio, low humidity regime, and suitable night-time temperature. This study used the KASPRO greenhouse climate model to simulate an IRTG model and compare its yield to a conventional soil-based greenhouse. They showed that an increase in light, CO_2 enrichment, and a longer growing cycle by cultivating during the winter months led to more than double the yield compared to the measured crop yield. Rufí-Salís et al. [40] also studied vegetable production in an IRTG in Barcelona over four years using life-cycle assessment (LCA) on 25 different crop cycles and seven species. Results showed that spring tomato cycles created the lowest impacts (CO_2 eq./kg), due to high yields. Conversely, spinach and arugula cultivation were associated with high impacts. Growing two serial tomato cycles is the best approach with a functional unit of yield (0.49 kg CO_2 eq./kg), although a long spring tomato cycle combined with bean and lettuce in autumn/winter is the best scenario when using market (0.70 kg CO_2 eq./€) and nutritional value ($3.18 \cdot 10^{-3}$ kg CO_2/kcal). This study showed that greater species diversity in a production system leads to a better environmental performance when suitable crops are selected for different seasons.

Investigating the yield of UA systems compared to conventional on-soil agriculture, through a meta-analysis of 200 articles, Payen et al. [37] found that UA yields (per unit area) were similar to or greater than global average yields of conventional agriculture. Although their study did not allow for differentiating between open-air rooftops and RTG, they reported yields for rooftops in the range of 2–3 kg/m^2, depending on the species. They discovered that hydroponic systems delivered higher average yields than soil-based systems while VF also led to higher yields than horizontal farming.

Appolloni et al. [38] recently evaluated supplemental LED light in IRTG for tomato production. They showed that LED light increased yield by 17 % compared to natural illumination (CK). Fruit ripening was also affected, with an increase of 35 % red proximal fruit in LED-treated plants.

3.2. Effects of RTGs on energy use

Nine articles examined the effects of RTGs on energy use, highlighting that RTGs can lead to energy savings in heating and cooling demands compared to conventional greenhouses [23,28,30,41–46]. Combining thermal exchange, high-performance glazing, and shading solutions in RTGs can improve energy efficiency. Additionally, integrating RTGs with host buildings and employing ventilation systems can yield further energy co-benefits. Bambara and Athienitis [41] conducted a study in Montreal, Canada, to validate a Transient System Simulation energy model of a semi-transparent photovoltaic (STPV) greenhouse. They compared the energy performance of a greenhouse (4000 m^2) and a vertically stacked VF (four floors, 1000 m^2 each) illuminated by LED lights, both using STPV. The simulations tested single- and double-glazed STPV cladding and showed that the VF used 31 % and 18 % less heating energy annually than the greenhouse for single and double-glazed STPV, respectively. Cooling energy use was almost equal for both glazing solutions. Double-glazing reduced the heating demand by 76 % for the greenhouse and 72 % for the VF, but increased cooling requirements by 35 % and 26 %, respectively. Nadal et al. [23] studied energy use of the first IRTG in Spain, which exchanged heat, CO_2, and rainwater with the host building. They compared the IRTG energy use to that of a freestanding greenhouse using the EnergyPlus computer simulation software. This research exemplified the significant energy, carbon, and financial savings achieved by coupling the thermal exchange between the IRTG and the host building.

A similar study using the same building (ICTA) as Nadal et al. [23] was conducted based on simulations. Muñoz-Liesa et al. [42] obtained heating-related savings of 31.9 kWh/m^2yr due to the additional thermal buffering effect of the IRTG. However, the authors did not observe the cooling-driven effects of the IRTG via plant transpiration in winter (Nov–Mar). Transpirational cooling was only observed during spring and summer under the Mediterranean climate. They concluded that more research on the dynamic microclimatic causes was needed to better estimate the potential cooling impact by plants.

Jans-Singh et al. [43] created a combined simulation model of an archetype school building with a greenhouse zone to analyse the heat and mass transfer between the classroom and the IRTG. The simulation results showed that air with low CO_2 levels and temperatures from the IRTG can reduce ventilation demand in the classroom for heating and cooling by 33 %–57 % annually. Conversely, the reuse of waste streams, such as warm air with enriched CO_2 from the IRTG to the host building, was beneficial for plant growth.

Gholami et al. [44] evaluated three roofing technologies using a two-dimensional hygrothermal simulation. The study analysed the impact of water on the roof thermal behaviour and the feasibility of designing a building with little cooling needs. The study used a precise localised microclimate model of a neighbourhood in Bologna, Italy, to estimate buildings' cooling and heating loads. The three solutions analysed were insulated roof, green roof, and RTG, and their thermal performance was evaluated in four aspects (energy calculation, the impact of moisture on energy performance, thermal performance of passive-designed RTG, and zero-cooling need building). The performance of the RTG was effective with a 50 % reduction in cooling loads. The insulated roofs and RTG scenarios showed improvements of 20 % and 15 % in annual heating and cooling loads, while the green roof yielded a 7 % improvement compared to the baseline. Additionally, the impact of moisture on green roofs was considered a negative factor for thermal and energy performance in this climate. The results thus highlighted the potential of passively designed RTG to create a building with little cooling needs.

In Sweden, Zhang et al. [45] investigated energy use for an existing warehouse fitted with an RTG in Malmö, using the dynamic energy simulation program IDA-ICE. The effects on energy use by combining RTG and warehouse were analysed by altering the parameters of RTG (glazing materials and shading devices). The results showed that the warehouse had a lower heating and cooling demand by 11 % and 7 % respectively when fitted with an RTG. Interestingly, the RTG had a 10 % lower heating demand and a 12 % lower cooling demand than the soil-based greenhouse. Overall, this study showed that the combination of RTG and warehouse is mutually beneficial for overall energy efficiency. Furthermore, the results showed that the glazing and shading solutions are important aspects affecting the energy efficiency of the whole system. Combining high thermal resistance glazed envelopes and an external shading system for the RTG can substantially improve energy performance. The study also showed that the energy use for electric lighting in a RTG can be reduced by 60 % compared to an indoor horizontal farm of the same size illuminated by LED lamps.

Muñoz-Liesa et al. [46] examined the energy co-benefits between a host building and an IRTG using integrated active ventilation systems. The results indicated that the IRTG harvested 198 kWh/m^2yr of waste heat from the host building for its own thermal and ventilation needs while delivering 205.2 kWh/m^2yr of solar energy to the host building as sensible heating gains in the ventilation system. The authors noted that when ventilation needs are higher, as in, for example, educational buildings, the magnitude of potential solar energy recovery from IRTG could increase to 61 % compared to an office building. Furthermore, the total energy savings were equivalent to 8 % of the host building's annual energy demand.

Yeo et al. [28] designed and validated a building energy simulation model for a naturally ventilated greenhouse with tomatoes in South Korea. Their study, involving time-dependent measurements, was achieved using full-scale assessments. The greenhouse BES model was validated by comparing the simulation results for air temperature and relative humidity to the ones obtained by direct measurements in the greenhouse.

In another study, Yeo et al. [30] analysed energy savings from installing an RTG using the building energy simulation and CFD software TRNSYS and ANSYS. Interestingly, the annual energy demand of a greenhouse for tomatoes was reduced by 5 % by using the RTG and this saving was attributed to thermal energy transmitted from the host building to the greenhouse. After integrating air temperature management, a technology for reducing energy loads by changing the set temperature over time, the heating energy savings reached 12 %. They also discovered that by installing a single-span greenhouse without tomato crops on the roof, the annual energy demand of the office building could be reduced by 11 %. The energy use reduction was lowered when the tomato crop was included in the calculations. This multi-disciplinary research is one of the thorough studies involving the effects of crops on the energy use of buildings and RTG.

3.3. Effect of RTGs on yield, water and energy use, and global warming potential

Two publications indicated that RTGs have the potential to significantly reduce water consumption, greenhouse gas emissions, and reliance on food imports [47,48]. High-tech farms, including RTGs, demonstrate improved efficiency and sustainability compared to conventional farming, especially when incorporating soilless cultivation techniques and utilizing natural resources such as rainwater. Additionally, integrating RTGs with building heating systems and solar power can further reduce CO_2 emissions.

Gould and Caplow [48] outlined that 1 ha of rooftop vegetable farm has the potential to save 20 ha of rural land in the USA, where each ha can save 74 000 tons/yr of fresh water on average. In their survey of environmental impacts of growing tomatoes, they found that the freshwater consumption of RTGs was 16 % that of conventional farms, while avoiding pesticides and reducing GHG emissions by 60 %. Furthermore, they estimated that when the RTGs are integrated with the building heating systems and onsite solar power; further reductions of 1000 tons of CO_2 emissions are obtained annually compared with conventional greenhouses. They showed that a single acre of BrightFarms greenhouse in Chicago could yield approximately 230 000 kg of produce, capturing 20 million litres of rainwater, mitigating 740 tons of CO_2, and avoiding 195 kg of pesticides annually, based on estimates by Gould and Caplow [49].

Benis et al. [47] conducted an exhaustive study to assess the resource use of several BIA solutions in urban areas. They used a performance-based simulation workflow to compare the environmental impacts of three hi-tech urban farms located in Lisbon, Portugal, with different designs and growing technologies:

1) a polycarbonate RTG, 2) an indoor VF with windows and skylights on the top floor of a building, and 3) a completely opaque artificially illuminated VF on the building's ground floor. The type of urban farm significantly affected emissions and water usage, with the RTG and top floor VF yielding lower GWP than the current supply chain for tomatoes. The high-tech farms' year-round production and higher plant density of soilless cultivation resulted in a factor of four efficiency gains. The study also found that high-tech farms with no daylight penetration performed poorly, requiring 205 % more energy than the greenhouse, mostly for electric lighting (91 %). Importantly, the year-round production in the metropolitan area reduced the need for food imports and the transportation burden, thus making high-tech farms more sustainable than conventional farms.

3.4. Environmental assessment and economic profitability of RTGs

Various studies and their findings related to the environmental assessment and economic profitability of RTGs in different locations are discussed [12,49–60]. It is noteworthy that while RTGs may have higher initial costs associated with the greenhouse structure, they can offer lower environmental impacts, reduced transportation and distribution losses, increased food security, and potential productivity gains. The economic viability of RTGs can vary depending on factors such as yields, prices, and specific local conditions. Therefore, a comprehensive assessment of environmental and economic aspects is necessary when evaluating the feasibility and profitability of RTGs in different locations.

In a case study located in Barcelona, Sanyé-Mengual et al. [50] quantified the environmental benefits of RTGs. They found that switching from a linear to an RTG system for tomato cultivation resulted in significant environmental impact reductions of 44–76 % per kg in various categories. The main reductions were achieved through changes in packaging, transportation, and retail stages to minimize produce losses. The IRTG system also allowed for year-round crop production, potentially reaching productivity rates of 56.5 kg/m^2, which is twice the productivity of RTGs (25 kg/m^2) [59].

Sanyé-Mengual et al. [12] analysed RTGs' environmental and economic performance using LCA and life-cycle cost (LCC) analysis for a real project in Barcelona. The results showed that the greenhouse structure of an RTG has an environmental impact 17–75 % higher and an economic cost 2.8 times bigger than a multi-tunnel greenhouse. At the consumption point, environmental savings were up to 42 % for local RTG-produced tomatoes, which were also 21 % cheaper than conventional tomatoes from multi-tunnel greenhouses in Almeria. The study concluded that RTGs face law-related limitations that make the greenhouse structure less environmentally friendly and economically competitive than current industrial greenhouses.

Pons et al. [51] used a technological and sustainability approach to analyse a new agricultural production system by integrating RTGs in Mediterranean urban areas — the IRTG energy, water, and CO_2 flow in the metabolism of the building. The project used multiple methods such as LCA and the Integrated Value Model for Sustainable Assessment. In the case of IRTG, the authors concluded that the LCA demonstrated that from a cradle-to-consumer point of view, locally cultivated tomatoes in RTG-Lab are cheaper and have lower environmental impacts.

Sanyé-Mengual et al. [52] conducted a multi-national environmental assessment focusing on urban horticulture in retail parks. They performed an LCA on the implementation of RTG in eight sites in seven different cities in Europe and South America with specific requirements. The evaluation focused on geographical contrasts and compared differences between isolated and integrated RTGs by evaluating symbiotic metabolism. Their results showed that retail parks have the potential to implement RTGs, where between 53 % and 98 % of the buildings had rooftops that are technically and economically feasible. Interestingly, retail parks performed better than industrial parks and logistic parks.

Sanjuan-Delmás et al. [53] performed an LCA on VF consisting of a RTG connected to a university building in Barcelona. The goal was to determine the feasibility of producing food, while examining potential issues. This included an evaluation of the system's environmental performance to analyse both the crop and its association with the building with respect to rainwater, residual heat (energy), residual air (CO_2) and food from an industrial ecology perspective. They concluded that this system could be an alternative to conventional production and an opportunity to improve food security and self-sufficiency in cities.

Benis et al. [54] compared different rooftop systems by examining the economic sustainability and net social welfare of a set of options over a 50-year life cycle. A Cost-Benefit Analysis approach was applied to compare the conventional unused flat roofs: (1) Rooftop farms for open-air production, (2) "Low-tech" Rooftop Greenhouse (RTG) farms, (3) "High-tech" RTG farms with controlled-environment production, (4) Building Integrated Photovoltaics energy systems. The economic sustainability of alternative rooftop systems was dependent on yields and prices. The authors concluded that food production to be more beneficial than energy generation for both the owner of the system and the local community when considering financial return and local job creation. Conversely, Corcelli et al. [55] conducted an LCA to assess the environmental impacts of urban rooftops with building-applied solar photovoltaic systems and RTG systems in Mediterranean regions. Their results indicated that building applied photovoltaic systems were more environmentally friendly due to lower impacts on climate and fossil depletion (-430 kg CO_2 eq./m^2 and -110 kg oil eq./m^2) compared to RTG systems (-22 kg CO_2 eq./m^2 and -4.7 kg oil eq./m^2).

Muñoz-Liesa et al. [56] reported the energy benefits of BIA through (i) a calibrated energy model and (ii) a thermal analysis of a selected building with IRTG in a Mediterranean region. The case study was previously assessed with a calibrated energy model that quantified the recovered heat from the building and the IRTG. The authors demonstrated the potential effectiveness of bidirectional energy symbiosis of IRTG to improve their efficiency. Simulation results indicated that the IRTG passively recovered an equivalent annual heating energy of 98 kWh/m^2yr from the building (especially during night-time) if heated with the same heating, ventilation, and air conditioning (HVAC) system as the host building. Simulation work also revealed that the IRTG provided an added insulation value especially in winter, which resulted in an annual energy saving of 35 kWh/m^2yr. In the humid continental temperate climate of South Korea, Torres Pineda et al. [57] performed an LCA on tomato production, comparing conventional greenhouse and RTG. Their results showed that RTGs required 19 % less energy for heating and 38 % more for cooling than greenhouses. Interestingly, RTGs total energy load reduction was 13 % due to smaller heat losses during colder months.

Parada et al. [49] performed an LCA-based analysis on three fertigation practices used in an RTG for tomatoes in Barcelona: 1) open management, 2) recirculation, where 30 % of drained, unused water was used to irrigate the crops, and 3) same recirculated management of recirculation with a further reduction in freshwater input of 15 % leachate recirculation. Interestingly, all three irrigation practices delivered similar yields. Concerning environmental benefits, recirculation delivered the best performance in almost all impact categories.

Subsequently, Muñoz-Liesa et al. [58] discovered that through structural improvements, the environmental impact of IRTG systems decreased by 24 %. Furthermore, their findings [59] also demonstrated that an optimized steel structure utilizing tensioned cables offered a potential reduction of up to 36 % of the IRTG steel provision, thereby cutting 16 % of environmental impacts due to GHG emissions. In addition, Muñoz-Liesa et al. [60] used experimental data integrated with a modelling approach to compare tomato yields and the environmental impacts in an IRTG using different covering materials in Barcelona, Spain.

From the analyses of various aspects of the structural RTG-building symbiosis (3.1, 3.2, 3.3, 3.4), increasing food production was possible while decreasing resource usage and input costs could contribute to the achievement of many SDGs: SDG 1, 2, 6, 7, 9, 11, 12 and 13.

3.5. Life-cycle cost assessments of RTGs

Using the LCC methodology, Peña et al. [61] examined the economic viability of tomato production in an innovative building with an IRTG located in Barcelona. Data was collected from two stages: i) infrastructure and ii) production. Production costs entailed labour, external services, and various materials. The calculations included fixed and variable costs. The main cost drivers for tomato production in IRTG representing 61 % of total costs, were labour (25 %), the IRTG infrastructure (15 %), external pest control services (13 %), and the rainwater harvesting system (10 %). The sensitivity analysis indicated that the infrastructure costs could be reduced further to ensure economic viability, while rainwater harvesting costs could be reduced by optimising the rainwater tank size as a function of the productive area.

3.6. Intelligent rooftop greenhouses

With the availability of intelligent and sophisticated control systems, the challenge to deliver successful rooftop greenhouses with integrated food production management, renewable energy utilization, water resources, and atmospheric gas composition, is achievable [29,62–64].

These successful studies revealed that implementing iRTGs with sophisticated control systems could contribute to the creation of environmentally friendly cities with low carbon footprints, high carbon offsets, and a strong human-plant symbiosis.

Balas et al. [62] and Balas et al. [63] developed the concept of iRTG, which is similar to IRTG but with a more sophisticated control system to manage the energy, CO_2–O_2, and water exchanges between RTG and host building. The iRTG typically has a two-way ventilation system conveying O_2-enriched air from the RTG to the building and CO_2-enriched air from the building to the RTG. In conclusion, they anticipated that the iRTG can deliver an integrated management of food production, renewable energies, water resources, and atmospheric gas composition. With optimized iRTGs and implemented widely throughout a city, it is possible to create a "Green-Skyline City" i.e., a city having all buildings covered by passive greenhouses, with low carbon footprint, high carbon offset, local production, and a tight human-plant symbiosis.

Balas et al. [64] proposed a Simulink model for an iRTG focusing on gas exchange control. Better measurements regarding iRTG air composition could be achieved by using a fuzzy-interpolative expert system with self-adaptive capabilities and receiving accurate geometric variables, implemented by harnessing the look-up tables with linear interpolation. They would develop the iRTG model for further research by incorporating gas (CO_2, O_2, water vapours) and heat exchanges from humans and plants.

Recently, Popa et al. [29] developed fuzzy self-adaptive interpolative controllers based on an earlier model of iRTG with distributed ventilation fans, for different environmental conditions. They proposed that a locally adapted flexible and distributed fans network, working under the control of temperature self-adaptive interpolative controllers, could assist the iRTG to operate effectively over a broader range of conditions.

3.7. Potential area of implementation for RTGs

Two review articles focused on implementing RTGs in industrial and logistics parks. These areas appeared to be ideal locations for commercial RTG implementation due to their roof ownership, larger size, homogeneous shape and stronger structural materials, and potential reduction of heating and cooling requirements compared to residential buildings [39,65]. Sanye-Mengual et al. [65] also designed a guide using a geographic information system and LCA tool to assess RTG implementation potential in industrial and logistics parks. The case study at Zona Franca Park (Barcelona, Spain) revealed a high potential, with 87 % of rooftops deemed feasible for long-term or mid-term RTG implementation. The estimated annual tomato production could reach nearly 2000 tons, meeting the demand of 150 000 people and potentially replacing imported tomatoes.

3.8. Stakeholders' perceptions and social acceptance of RTGs

Five review articles focused on the social science perspective, while the other three articles [31,66,67] evaluated stakeholder perceptions and examined potential benefits and challenges, related to societal risks and policy making. From these articles, RTG was generally recognized as a promising model. The other two articles focused on sustainability assessment [68] and consumer perception [69]. The articles generally noted high acceptance of RTGs among stakeholders and consumers.

Specht et al. [66] investigated stakeholders' perception of buildings with agricultural production and focused on resolving various issues associated with introducing ZFarming in Berlin. Stakeholders perceived potential benefits and challenges related to ZFarming in all dimensions (economic, social, environmental, and political). The stakeholders also identified RTGs as the most promising farming model for Berlin. Specht et al. [31] reported further on the participatory approach, aptly termed Regional Open Innovation Roadmapping, which focused on bringing together different actors. In later studies, Specht and Sanyé-Mengual [67] examined the stakeholder perspectives on understanding risks and policy making associated with urban horticulture. Nadal et al. [68] also investigated RTG focusing on social science sustainability assessment. Ercilla-Montserrat et al. [69] studied consumers' perception of the soilless system in RTG; they observed that 94 % of people approved of the quality of rooftop agriculture (RA) products and perceived them to be local and fresh.

3.9. Reviews of cases and systematic literature reviews focusing on RTGs

Five review articles focused on comparing multiple cases or presenting a SLR [70,71]. Generally, RTGs could deliver sustainable food production with efficient use of resources, although the RTG sector is still relatively small and often not orientated towards commercial interests. The other three articles were about SLRs and examined different systems including RTGs such as CEA [20,72] and BIA [73].

Harada and Whitlow [70] discussed the concept of urban green infrastructure, with a focus on rooftop agriculture. They highlighted the opportunities and challenges associated with advancing the science and technology of these constructed ecosystems, with a specific focus on rooftop agriculture. They outlined that RTG has the potential to achieve increased yield, water use efficiency, and stormwater retention, making it a promising approach for sustainable food production. However, they emphasized that while RTGs offer benefits for food production, they do not provide habitat creation opportunities.

Appolloni et al. [71] presented the status of RA through a database of 185 cases. Their study showed that 84 % of practices are open-air farms and gardens and the growing sector of RTGs is still relatively small. Results also indicated a greater emphasis on RA in North America (44 % of the cases). Most RA cases in their database targeted social and educational goals or seeking improvement in urban living quality, with less emphasis on commercial cases. There are untapped business opportunities that can contribute to developing more sustainable and resilient urban food systems providing fresh products from the inner urban areas. The study revealed a rising global interest in RA and stronger policy intervention is crucial to upscale RA practices to achieve self-sufficiency in urban food production.

A critical review of CEA by Engler and Krarti [20] provided key information relevant to greenhouses and RTGs. They identified the high operating costs and unfavourable carbon footprint as major constraints affecting CEA operations. Lowering energy use by the CEA facilities was essential to attract urban users. They reviewed energy efficiency measures, covering building envelope improvements, distributed generation technologies, low-energy HVAC systems, and energy-efficient lighting. The addition of thermal insulation was found to reduce the cooling demand by 19–30 %, depending on the climatic zones. Using thermal mass could reduce heating demand by 32 %, while shading devices could reduce cooling by 30 %. Natural ventilation in dry climates and other passive heating and cooling strategies could reduce HVAC loads and energy use by up to 31 %. As electricity usage for lighting needs for plant growth is usually the largest in CEA (up to 70 % of total energy use), their review suggested that incorporating LED lights could reduce electricity use by up to 76 %.

More recently, Orsini et al. [73] presented a review of BIA focusing on food production in cities. The development of building-integrated technologies has led to an evolution of traditional UA systems (e.g., community gardens) to include the built landscape (e.g., VF and RTGs). BIA often uses soilless production methods and the production is known as CEA (including greenhouses and indoor growing facilities). The main difference between greenhouses and indoor facilities is that the greenhouse is a semi-controlled environment with a transparent design influenced by exterior climates. Solar energy is harnessed naturally for plant growth via photosynthesis, while passive ventilation in greenhouses is provided through evaporative cooling during plant transpiration. Indoor facilities (e.g., PFALs) do not permit any interaction with the outdoor climate during plant growth. The study also highlighted the different dimensions of sustainability and the strengths and weaknesses of the different production systems.

The future of BIA lies in customizing the right production methods for selected building typologies. A successful BIA is achieved when a novel and circular food economy is developed, where food production is fully integrated into the architectural landscape while delivering excellent human liveability and food self-sufficiency amidst natural biodiversity.

Glaros et al. [72] presented another review comparing the impacts of five food production models ("frontiers") for the global food system in 2050. One suggested frontier CEA included novel designs such as RTGs. The novel building designs were often profitable and had greater water use efficiency, but they also reported higher energy use than conventionally grown produce. Results confirmed that CEA-grown plants have dietary benefits. CEA was ranked as the most feasible frontier to be implemented by 2050 compared to the other systems. Interestingly, compared to others, CEA was considered the most feasible and compatible technology to implement globally. To attain these sustainable goals during food production, future work is needed to decarbonise energy sources and integrate various operations that enhance circular resource with minimal environmental impacts. Further social and scientific engagements are needed to better understand the often complex political and institutional frameworks hindering the implementation of the food frontiers.

4. Discussion

This article presented a systematic literature review (SLR) of rooftop greenhouse (RTG) systems. The salient information is as follows:

The urban population is expected to represent more than two-thirds of the global population by 2050, putting unprecedented pressure on food systems. As cities increase in size, the distance between food production and consumption increases, which increases transport energy. Conventional cultivation is currently responsible for one-third of global GHG emissions, and 70 % of global freshwater use. Transport emissions of food systems represent one-fifth of the total food system's GHG emissions. UA may involve a combination of several cultivation systems. RTG is a plausible solution as it provides several benefits such as higher yield, decreased transportation energy and costs, community enhancement, increased urban resilience and food security, nutrient cycling, local availability of fresh products, and mitigation of the UHI effect.

Some cities have indicated a potential for self-sufficiency of up to 70–80 % in fruits and vegetables by exploiting a combination of UA systems. However, electric lighting requirements and GHG are major issues of PFALs. Within the realm of UA, rooftop farming, which includes both open-air and RTGs is one of several approaches with a large potential as rooftops constitute one-fourth of all urban surfaces, and recent research indicates that RTGs have several benefits.

Several studies showed that IRTGs could reduce the cooling and heating loads of the host building by reducing the exposure of building surfaces to heat gains and losses through the roof. When crops are grown on a roof, the roof temperatures and internal air temperatures of the greenhouse can be decreased through shading and evapotranspiration of crops, which concomitantly reduce the host building's cooling demand. The heating demand of the RTG is also reduced compared to that of a soil-based greenhouse since the RTG uses low-grade heat losses from the host building. Electric lighting of the RTG is reduced substantially (up to 60 %) compared to the case of PFALs. As they normally fall under CEA, RTGs generally do not use pesticides. Since they are normally based on hydroponics-related cultivation techniques, RTGs save more water ($>$ 70 %) than conventional soil systems. Rooftop technologies use no additional land and thus contribute to space optimisation (ZFarming) through roof space utilization. RTGs generally can provide increased revenue for the owner of the host building through the leasing of the roof space.

Recent developments in RTG technology such as IRTG and iRTG have delivered higher energy savings, while providing other benefits such as enhanced photosynthesis by CO_2 enrichment and additional water savings. The more advanced control systems used in iRTG can also allow better temperature mitigation for the RTG and host building. One study indicated that high-tech conditioned RTGs could be more sustainable than conventional unconditioned greenhouses for crop production. The same study indicated that high-tech RTGs generate more jobs and less GWP than conventional rooftop photovoltaics.

The tradeoff between renewable energy (e.g., PV) and agricultural production on urban rooftops involves considerations such as energy efficiency, economic viability, spatial conflicts, and environmental benefits. PV systems are more energy-efficient and financially lucrative, while high-value rooftop farming can provide economic benefits and local food production. Spatial conflicts may arise when allocating limited rooftop space. Both options have environmental benefits. A single article comparing PV with RTG was found by Benis et al. [54] and showed that when considering financial returns and local job creation, food production proved to be more advantageous than energy generation for both the system owner and the local community. Technological advances, like integrating transparent solar panels, can minimize the tradeoff. Balancing these factors is crucial to developing comprehensive strategies promoting sustainable energy generation and urban agriculture. Some RTG projects are integrating VF with plants arranged on A-frames to maximize irradiance and photosynthesis. Others integrate aquaponics, to allow for concomitant aquatic (mainly protein) production.

Despite these benefits, the challenges associated with RTG technology are high infrastructure investment and energy costs (equipment, HVAC, lighting), since constructing and maintaining a RTG can be expensive. The initial investment for building and equipping the greenhouse, can be significant. Additionally, ongoing expenses for maintenance, energy consumption, and staffing can be substantial. The need for additional structural elements and special indoor environmental management, water, and resource management may be substantial. These microclimatic variations can impact plant productivity, requiring careful management within the greenhouse to maintain optimal growth. Efficient water management is crucial for RTGs, as they may have limited access to water sources and face constraints on water availability. Additionally, managing other resources, such as energy consumption and waste disposal, should be considered for a comprehensive sustainability approach. Low solar transmission of coverings due to the additional structural elements, limited availability of flat roofs, need for accessibility through staircases and/or elevators are some of the key challenges. Transporting supplies to the rooftops can be more labour-intensive and time-consuming than traditional ground-level agriculture. This includes structural limitations, where RTGs impose additional weight and structural demands (flat roofs) on buildings. Not all rooftops are designed to support the extra load of a greenhouse, which may require costly structural modifications or reinforcement. Also, ensuring the building's structural integrity is essential to prevent potential risks or damage. Considering limited space and scalability, RTGs have limited available space, which can restrict the scale of agricultural production. The design of the rooftop may pose challenges in meeting commercial-scale demands. Scaling up the production to make it economically viable may not always be feasible due to space limitations. Also, regarding safety and security, RTGs may introduce safety risks during construction, operation, and maintenance. Additionally, RTGs might be more susceptible to vandalism or theft due to their urban location, requiring appropriate security measures.

While RTGs offer benefits for food production, they do not provide opportunities for natural habitat creation and conserving biodiversity. Moreover, several authors mentioned that municipal laws and regulations and fire regulations could also represent a major hindrance to implementing RTG technology in many cities. A suggestion to overcome barriers to implementing RTG technologies was to involve stakeholders to increase understanding of the potential of RTGs in cities. Greater stakeholders' involvement and ownership are likely to affect policy makers. Overall, a limited number of holistic studies on RTG technology were found, which is a restraint for their widespread social acceptance. Another mentioned area was consumer perceptions, which could benefit from further studies especially pilot-scale demonstration projects. Nevertheless, this review suggests that RTG technology is increasing in popularity with many full-scale implementations in the last ten years and witnessing commercially profitable operations in major cities. Several companies are also increasing the size of each new RTG project, probably due to the economy of scale provided by running larger operations. The adoption of the RTG technology is relatively recent, hence, more research is needed for customization in different climates to better understand the potential of this technology to provide fresh food in urban environments at reasonable environmental and economic costs. Future research should focus on matching appropriate technology with different climates and contexts to ensure economic profitability. The future of RTG lies in customizing the right technology for selected building typologies globally. A successful RTG is achieved when food production is fully integrated into the architectural landscape.

5. Conclusions

In conclusion, the study aimed to conduct a systematic literature review of the RTG technology to examine the benefits and challenges associated with this technology. Boundaries and limitations of this SLR have been identified e.g., publication bias (significant or positive findings more often published), language bias (English), etc. Limitations intrinsic to the selected methodology and character of the technology (new) are also discussed in the method section.

This SLR was based on 45 journal articles, covering key subthemes that were described in detail. The study identified that the symbiotic heat, water, and CO_2 exchanges between the RTG and its host building combined with the potential for year-round crop production, are some of the main benefits of RTGs. For example, RTGs can reduce the cooling and heating loads of both greenhouses and host buildings. The roof temperatures and air temperatures of the greenhouse are decreased through shading and evapotranspiration of crops, which concomitantly reduce the host building's cooling demand. The heating demand of the RTG is also reduced compared to that of a soil-based greenhouse since the RTG uses low-grade heat losses from the host building. Electric lighting of the RTG is reduced substantially compared to the case of PFAL. RTGs use no additional land and thus contribute to urban space optimisation. IRTG and iRTG deliver higher energy savings, while providing other benefits such as enhanced photosynthesis by CO_2 enrichment and water savings. The additional investment, operational costs, limited availability of flat roofs, and various regulations are some key challenges to overcome. This review also noted that RTGs are increasing in scale, system diversity, societal acceptance, and popularity among many commercial operations in large cities.

Holistically, RTG technology relates to various aspects of engineering design, building and urban regulations, energy systems, policy, finance, and environmental, social, and governance (ESG) aspects. Concerning engineering design, RTGs require careful consideration of the building's structural integrity to support the added weight of the RTG structure, its soil or water system, as well as plants. Engineering rules and guidelines need to be developed to include rooftop structures that can be safely accounted for in structural calculations. Proper ventilation, heating, and cooling systems are also crucial for maintaining an optimal indoor climate inside the RTG. Engineers need to design efficient HVAC systems that optimize temperature and humidity control of both RTG and host building, taking advantage of the potential symbiosis between the two systems as seen in iRTGs. The design of effective irrigation and drainage systems to minimize water usage and prevent leakage into the building is also required.

In terms of building and urban regulations, RTGs need to comply with local building codes and regulations related to structural stability, fire safety, accessibility, etc. Each city or country needs to develop building regulations to accommodate RTG structures. Urban regulations need to be rewritten taking into consideration the potential addition of an extra floor height for the rooftop structure. In the future, these policies may provide incentives, tax benefits, or zoning accommodations for RTG projects. Government policies and initiatives aimed at reducing carbon emissions and promoting sustainable agriculture should encourage the adoption of RTGs as part of urban planning.

RTGs also require additional electric lighting, ventilation, heating, and cooling, which demands additional energy systems and power supply. Engineers should design energy-efficient systems integrating e.g., solid-state lighting and renewable energy sources such as integrated PV systems, to reduce energy use and GHG emissions.

RTGs can be attractive investments, offering potential revenue from agricultural products and potentially increased property values, while also providing an additional revenue from rent of the host building's roof space. Financial structures and calculation methods need to be developed to assess the feasibility and return on investment for such projects. RTGs align with ESG principles, making them eligible for green financing options and investments from organizations committed to sustainability. RTGs contribute to environmental sustainability by reducing food transportation distances and minimizing the carbon footprint of agriculture, which is in line with ESG criteria related to environmental responsibility. The provision of fresh, locally grown produce, contributing to food security and community well-being is also aligned with ESG as well as many SDGs.

In summary, RTGs address several aspects of engineering design, regulatory compliance, energy efficiency, policy development, financial considerations, ESG and SDGs initiatives, making them a compelling option for sustainable urban development and agriculture in the future global urban realm.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank the Faculty of Landscape Architecture, Horticulture and Crop Production Science (LTV faculty) at the Swedish University of Agriculture Sciences (SLU), Sweden, for funding this article. The authors also thank Agneta Lindsten, librarian at the SLU University Library, for performing the database search and providing invaluable support throughout the process.

Appendix A

Table 3
Articles reviewed with rooftop farming using rooftop greenhouses.

Year	Type of RTG	Country	Main output/learnings	Authors
2012	RTG	Barcelona, Spain	Barriers and opportunities regarding RTGs were investigated focusing on social, economic, environmental and technological aspects. Interconnection of building and RTG improved interactions among water, energy, and CO_2 flows. RTGs yield from 10 to 50 kg/m^2 per year of vegetables.	Cerón-Palma et al. [39]
2012	RTG, IRTG	Chicago, USA	A hectare of rooftop farm could save 20 ha of rural land. The freshwater consumption of RTGs was 16 % that of conventional farms. RTGs reduced GHG emissions by 60 % and avoided pesticides.	Gould and Caplow [48]
2013	RTG	Barcelona, Spain	Switching from a linear system to an RTG system may cut environmental impact by 44–76 % per kg tomatoes, with up to 74 % energy savings. RTG could be key in designing low-carbon Mediterranean cities.	Sanyé-Mengual et al. [50]
2015	RTG, IRTG, multi-tunnel greenhouse, industrial greenhouse	Barcelona, Spain	LCA and LCC on RTG projects show RTG has an environmental impact 17–75 % higher and an economic cost 2.8 times higher than multi-tunnel greenhouse. RTGs face law limitations making greenhouse structures less friendly and less economically competitive than current industrial greenhouses.	Sanyé-Mengual et al. [12]
2015	STPV RTG	Montreal, Canada	Double glazing decreases heating demand by 76 % for the RTG and 72 % for the VF but increases cooling by 35 % and 26 %,	Bambara and Athienitis [41]

(continued on next page)

Table 3 (*continued*)

Year	Type of RTG	Country	Main output/learnings	Authors
			respectively. Due to greater solar exposure, the RTG generated almost twice the solar electricity through STPV compared to VF.	
2015	RTG	Barcelona, Spain	Industrial and logistics parks are ideal for RTG implementation, with 87 % of rooftops deemed feasible for long-term or mid-term RTG implementation in the case study of Zona Franca Park (Barcelona, Spain).	Sanyé-Mengual et al. [65]
2015	IRTG, RTG-Lab	Barcelona, Spain	LCA and Integrated Value Model for Sustainable Assessment were used. LCA shows that locally cultivated tomatoes in RTG-Lab are cheaper and have lower environmental impact. RTG-Lab temperatures are higher at night compared with conventional greenhouses.	Pons et al. [51]
2015	RTG	Berlin, Germany	Stakeholders' perception of benefits and challenges for the introduction of ZFarming. Potential benefits and challenges related to all sustainability dimensions. Stakeholders identified RTGs as the most promising farming model for Berlin.	Specht et al. [66]
2016	RTG	Berlin, Germany	Presentation/evaluation of participatory approach called Regional Open Innovation Roadmapping, focused on bringing together stakeholders. The Regional Open Innovation Roadmapping process simulated new networks, contributed to knowledge and created a common understanding for future implementation of ZFarming.	Specht et al. [31]
2017	IRTG	Barcelona, Spain	An increase in light, CO_2 enrichment, and extension of the growing cycle by cultivating during winter can double the yield compared to measured crop yield.	Montero et al. [25]
2017	IRTG	Barcelona, Spain	IRTG has a higher average hourly temperature in winter and a lower average in summer. It yields significant energy, carbon, and financial savings compared to a freestanding greenhouse.	Nadal et al. [23]
2017	RTG	Lisbon, Portugal	RTG and top-floor VF yield lower GWP than the current supply chain for tomatoes with conventional farming. High-tech farms' year-round production and higher plant density of soilless agriculture result in a factor of four efficiency gains.	Benis et al. [47]
2017	RTG	Berlin, Germany; Barcelona, Spain	Explored stakeholder perspective focusing more on risks in urban horticulture as well as policymaking.	Specht and Sanye-Mengual [67]
2018	RTG in retail parks	Barcelona, Spain; Lisbon, Portugal; Utrecht and Rotterdam, The Netherlands; Berlin, Germany; Manizales, Colombia; Sao Carlos, Brazil	Assessment revealed that 58–98 % retail parks have the potential to implement RTGs. Retail parks also performed better than industrial- and logistic parks. Production was directly sold avoiding distribution costs. IRTGs yielded large production values (31–234 tonnes of tomato per ha), CO_2 savings (16–112 tonnes of CO_2 eq./ha) and self-sufficiency in food.	Sanyé-Mengual et al. [52]
2018	RTG with VF	Barcelona, Spain	System produced 30 kg of tomato per m^2 over 15.5 months, providing 2540 kg of food. The system could grow approximately 1660 kg of tomatoes per year. Synergy with the building afforded significant resource savings, e.g., 80–90 % of the water	Sanjuan-Delmás et al. [53]
2018	RTG	Lisbon, Portugal	Food production by high-tech RTG is more beneficial than energy generation by PV on roof for owner and the local community.	Benis et al. [54]
2018	RTG	Barcelona, Spain	Investigated RTG focusing on social science sustainability assessment.	Nadal et al. [68]
2019	IRTG	Barcelona, Spain	Heating-related savings of the host building can reach 32 kWh/m^2yr due to the additional thermal buffering effect of the IRTG. However, the cooling-driven benefits of IRTG via transpiration are not observed in winter (Nov–Mar) and have positive impact only during spring and summer in the Mediterranean climate.	Muñoz-Liesa et al. [42]
2019	IRTG	London, UK	Using the air with low CO_2 levels and temperatures from the RTG can reduce ventilation demand in classrooms for heating and cooling by 33 %–57 % annually. Conversely, reusing waste streams such as warm air with enriched CO_2 from the host building to the RTG is beneficial for crop growth.	Jans-Singh et al. [43]
2019	IRTG	Barcelona, Spain	Building-applied solar photovoltaic systems have favourable environmental impacts compared to RTG, with reductions of -430 kg CO_2 eq./m^2 and -110 kg oil eq./m^2 in climate change and fossil depletion categories, respectively (compared to -22 kg CO_2 eq./m^2 and -4.7 kg oil eq./m^2 in RTG).	Corcelli et al. [55]
2019	IRTG	Barcelona, Spain	The consumer's perception of a soilless system in RTG was analysed and results showed that 94 % of people approved of the quality of RA products and perceived them to be local and fresh.	Ercilla-Montserrat et al. [69]
2020	IRTG	Barcelona, Spain	LCA on 25 different crop cycles and 7 species over 4 years showed that spring tomato cycles exerted the lowest impacts due to high yields. Growing two serial tomato cycles was the best alternative with a good yield (0.49 kg CO_2 eq./kg). A long spring tomato cycle combined with bean and lettuce in autumn/	Rufí-Salís et al. [40]

(*continued on next page*)

Table 3 (*continued*)

Year	Type of RTG	Country	Main output/learnings	Authors
			winter was the best scenario in terms of market (0.70 kg CO_2 eq./€) and nutritional value ($3.18 \cdot 10^{-3}$ kg CO_2/kcal).	
2020	RTG	Bologna, Italy	Compared to insulated roofs and green roofs, the performance of RTG is best concerning energy and moisture. RTG produced a 50 % reduction in cooling demand.	Gholami et al. [44]
2020	IRTG	Barcelona, Spain	Integrating HVAC systems of building and IRTG offers large potential in energy savings by recovering and exchanging of heating and cooling energy flows. An overall 128 kWh/m^2 of net energy savings and 45.6 kg CO_2 eq./m^2 of savings can be obtained by integrating both systems.	Muñoz-Liesa et al. [56]
2020	RTG	South Korea	LCA on tomato production comparing conventional greenhouse and RTG revealed that RTG required 19 % less energy for heating and 38 % more for cooling than a greenhouse. Total energy load reduction for RTG was 13 % due to smaller heat losses of RTG during colder months. Decreased energy load, combined with shorter transports, storage and distribution stage losses, resulted in 43 % less GWP, 45 % less cumulative energy demand and abiotic depletion, 37 % less photochemical oxidation and acidification, and 27 % less eutrophication for the RTG.	Torres Pineda et al. [57]
2020	RTG, RTF	Several	RTG could achieve increased levels of yield, water use efficiency, and stormwater retention for sustainable food production. However, RTGs do not provide opportunities for natural habitat creation relevant to supporting biodiversity.	Harada and Whitlow [70]
2021	RTG	Barcelona, Spain	They examined the performance and environmental life cycle impacts and benefits of three fertigation management practices used in a RTG for tomato crop in Barcelona. Despite harnessing recirculation methodology and improving water- and nutrient-use efficiencies, all three irrigation management practices resulted in similar yields.	Parada et al. [49]
2021	IRTG	Barcelona, Spain	The environmental impact of IRTG systems decreased by up to 24 % through structural improvements, increased steel strength, and the utilization of lightweight tensioned cables.	Muñoz-Liesa et al. [58]
2021	Open-air farms, RTG	Several (database with 185 different cases)	An analysis of the current status of RA through database with 185 cases revealed that 84 % of practices are open-air farms and gardens. The RTG sector was small but growing steadily.	Appolloni et al. [71]
2021	greenhouses, RTG	Several	Energy efficiency measures, including building envelope improvements, distributed generation technologies, low-energy HVAC systems, and energy-efficient lighting, can reduce the energy use of CEA including greenhouses significantly.	Engler and Krarti [20]
2021	iRTG (intelligent rooftop greenhouses)	Barcelona, Spain	Self-adaptive Proportional Integral Derivative (PID) controller produced an additional performance, resulting in lower energy	Balas et al. [62]
2021	iRTG (intelligent rooftop greenhouses)		use due to robust performance and sharp transient regime avoiding overdrive.	Balas et al. [63]
2021	iRTG (intelligent rooftop greenhouses)	Barcelona, Spain	First simulations regarding iRTG air composition are not very precise, but multiple-input-multiple-output nonlinear system can be dealt with, at this early stage, only by a comprehensive expert system. Future work should focus on how humans and plants consume and exhale CO_2, O_2, water vapour and heat.	Balas et al. [64]
2022	UA general, open-air rooftops and RTG	Several	UA yields were on par with or greater than the global average yields of conventional agriculture. Yields for rooftops (open-air and RTG) were 2–3 kg/m^2, cycle on average depending on crop type.	Payen et al. [37]
2022	IRTG	Barcelona, Spain	Evaluation of supplemental LED light applications in IRTG with tomato production shows LED light increased overall yield by 17 % compared with naturally illuminated plants, which were 9.3 % lighter and 7.2 % fewer than tomatoes grown under LED treatments. Fruit ripening increased by 35 % in red proximal fruit in LED-treated plants.	Appolloni et al. [38]
2022	IRTG	Andong-Si, South Korea	Prediction of air temperatures and RH of naturally ventilated greenhouses with acceptable accuracy was demonstrated using BES and CFD.	Yeo et al. [28]
2022	IRTG	Yeongam–gun, South Korea	IRTG delivered energy savings for both greenhouse and host building.	Yeo et al. [30]
2022	RTG	Malmö, Sweden	Integrating RTG and the host building (a warehouse) was beneficial when assessing overall energy efficiency. The energy use for electric lighting in an RTG can be reduced by 60 % compared to an indoor horizontal farm of the same size illuminated by LED lamps.	Zhang et al. [45]
2022	IRTG	Barcelona, Spain	Integration of active ventilation strategies was 1.9 times more energy-efficient than passive ventilation configurations, which can utilize building assets to improve material and energy circularity, saving 8 % of the annual energy demand of buildings.	Muñoz-Liesa et al. [46]

(*continued on next page*)

Table 3 (*continued*)

Year	Type of RTG	Country	Main output/learnings	Authors
2022	IRTG	Barcelona, Spain	Optimized steel structure that uses tensioned cables showed a potential reduction of up to 36 % of the IRTG steel needs, cutting 16 % GHG emissions.	Muñoz-Liesa et al. [59]
2022	IRTG	Barcelona, Spain	AR-glass and ethylene tetrafluoroethylene film for tomato crops have the least environmental impacts while increasing average lifetime productivity (19.9 $\pm$ 2.3 kg/m^2 and 19.2 $\pm$ 2.2 kg/m^2 each).	Muñoz-Liesa et al. [60]
2022	IRTG	Barcelona, Spain	Cost drivers for tomato production in the IRTG were: 61.8 % of total costs, for labour 24.7 %, for the IRTG structure 15.0 %, external pest control services 12.6 %, and the rainwater harvesting system 9.5 %.	Peña et al. [61]
2022	IRTG, CEA, PFAL	Several	Development of BIA led to movement from traditional UA systems, including the built landscape (e.g., VF and RTGs). Designing the right treatments for resources from the buildings is crucial for high quality production in BIA developments.	Orsini et al. [73]
2022	iRTG (intelligent rooftop greenhouses)	Any climate	Developing a fuzzy-interpolative control system of temperatures for iRTG allows adaptation to a broader range of climates and better performance.	Popa et al. [29]
2022	Five food production models (frontiers), where one is CEA in general including RTG	Several	Scholarly agreement that CEA has dietary and ecological benefits. CEA is ranked as the most feasible frontier to be implemented by 2050. Future work is needed to decarbonise energy sources or integrate operations in circular resource-use systems to reduce ecological impacts.	Glaros et al. [72]

References

[1] Anonymous. World urbanization prospects 2018 highlights (ST/ESA/SER.A/421. New York: Department of Economic and Social Affairs, Population Division, United Nations; 2019.

[2] Li M, Jia N, Lenzen M, Malik A, Wei L, Jin Y, et al. Global food-miles account for nearly 20% of total food-systems emissions. Nat Food 2022;3:445–53. https://doi.org/10.1038/s43016-022-00531-w.

[3] Thomaier S, Specht K, Henckel D, Dierich A, Siebert R, Freisinger UB, et al. Farming in and on urban buildings: present practice and specific novelties of Zero-Acreage Farming (ZFarming). Renew Agric Food Syst 2015;30:43–54. https://doi.org/10.1017/S1742170514000143.

[4] Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food 2021;2:198–209. https://doi.org/10.1038/s43016-021-00225-9.

[5] Clark MA, Domingo NGG, Colgan K, Thakrar SK, Tilman D, Lynch J, et al. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 2020;370:705–8. https://doi.org/10.1126/science.aba7357.

[6] Mbow C, Rosenzweig C, Barioni LG, Benton TG, Herrero M, Krishnapillai M, et al. Chapter 5 : food security — special report on climate change and land. Cambridge University Press; 2019.

[7] Costanzo V, Evola G, Marletta L. Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. Energy Build 2016;114:247–55. https://doi.org/10.1016/j.enbuild.2015.04.053.

[8] Orsini F, Gasperi D, Marchetti L, Piovene C, Draghetti S, Ramazzotti S, et al. Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. Food Secur 2014;6:781–92. https://doi.org/10.1007/s12571-014-0389-6.

[9] Food and Agriculture Organization of the United Nations. Database on arable land. 2016. https://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC?end=2013&start=1961&view=chart. [Accessed 7 April 2023].

[10] Graamans L, Baeza E, van den Dobbelsteen A, Tsafaras I, Stanghellini C. Plant factories versus greenhouses: comparison of resource use efficiency. Agric Syst 2018;160:31–43. https://doi.org/10.1016/j.agsy.2017.11.003.

[11] Barbosa GL, Gadelha FDA, Kublik N, Proctor A, Reichelm L, Weissinger E, et al. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. Int J Environ Res Publ Health 2015;12:6879–91. https://doi.org/10.3390/ijerph120606879.

[12] Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. Int J Life Cycle Assess 2015;20:350–66. https://doi.org/10.1007/s11367-014-0836-9.

[13] Vertical urban farm de Schilde | urban nature atlas. 2021. https://una.city/nbs/hague/vertical-urban-farm-de-schilde. [Accessed 7 April 2023].

[14] Urban Farmers. Take the Hague. 2015. https://takethehague.nl/en/location/urban-farmers. [Accessed 7 April 2023].

[15] Ferme Abattoir. 2018. https://bigh.farm/fr/ferme-abattoir/. [Accessed 7 April 2023].

[16] Al-Kodmany K. The vertical farm: a review of developments and implications for the vertical city. Buildings 2018;8:24. https://doi.org/10.3390/buildings8020024.

[17] Benke K, Tomkins B. Future food-production systems: vertical farming and controlled-environment agriculture. Sustain Sci Pract Pol 2017;13:13–26. https://doi.org/10.1080/15487733.2017.1394054.

[18] Smith P. Delivering food security without increasing pressure on land. Global Food Secur 2013;2:18–23. https://doi.org/10.1016/j.gfs.2012.11.008.

[19] Shamshiri RR, Kalantari F, Ting KC, Thorp KR, Hameed IA, Weltzien C, et al. Advances in greenhouse automation and controlled environment agriculture: a transition to plant factories and urban agriculture. Int J Agric Biol Eng 2018;11:1–22.

[20] Engler N, Krarti M. Review of energy efficiency in controlled environment agriculture. Renew Sustain Energy Rev 2021;141:110786. https://doi.org/10.1016/j.rser.2021.110786.

[21] Vadiee A, Martin V. Thermal energy storage strategies for effective closed greenhouse design. Appl Energy 2013;109:337–43. https://doi.org/10.1016/j.apenergy.2012.12.065.

[22] van Beveren PJM, Bontsema J, van Straten G, van Henten EJ. Optimal control of greenhouse climate using minimal energy and grower defined bounds. Appl Energy 2015;159:509–19. https://doi.org/10.1016/j.apenergy.2015.09.012.

[23] Nadal A, Llorach-Massana P, Cuerva E, López-Capel E, Montero JI, Josa A, et al. Building-integrated rooftop greenhouses: an energy and environmental assessment in the mediterranean context. Appl Energy 2017;187:338–51. https://doi.org/10.1016/j.apenergy.2016.11.051.

[24] Buckley S, Sparks R, Cowdery E, Stirling F, Marsching J, Phillips N. Enhancing crop growth in rooftop farms by repurposing CO2 from human respiration inside buildings. Front Sustain Food Syst 2022;6.

[25] Montero JI, Baeza E, Heuvelink E, Rieradevall J, Muñoz P, Ercilla M, et al. Productivity of a building-integrated roof top greenhouse in a Mediterranean climate. Agric Syst 2017;158:14–22. https://doi.org/10.1016/j.agsy.2017.08.002.

[26] Chen J, Yang J, Zhao J, Xu F, Shen Z, Zhang L. Energy demand forecasting of the greenhouses using nonlinear models based on model optimized prediction method. Neurocomputing 2016;174:1087–100. https://doi.org/10.1016/j.neucom.2015.09.105.

[27] Llorach-Massana P, Peña J, Rieradevall J, Montero JI. LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems. Renew Energy 2016;85:1079–89. https://doi.org/10.1016/j.renene.2015.07.064.

[28] Yeo U-H, Lee S-Y, Park S-J, Kim J-G, Choi Y-B, Kim R-W, et al. Rooftop greenhouse: (1) design and validation of a BES model for a plastic-covered greenhouse considering the tomato crop model and natural ventilation characteristics. Agriculture 2022;12:903. https://doi.org/10.3390/agriculture12070903.

[29] Popa M, Alexuta D, Balas VE. Fuzzy-interpolative control of temperatures for the intelligent rooftop greenhouse. J Intell Fuzzy Syst 2022;43:1793–7. https://doi.org/10.3233/JIFS-219280.

[30] Yeo U-H, Lee S-Y, Park S-J, Kim J-G, Cho J-H, Decano-Valentin C, et al. Rooftop greenhouse: (2) analysis of thermal energy loads of a building-integrated rooftop greenhouse (BiRTG) for urban agriculture. Agriculture 2022;12:787. https://doi.org/10.3390/agriculture12060787.

[31] Specht K, Siebert R, Thomaier S. Perception and acceptance of agricultural production in and on urban buildings (ZFarming): a qualitative study from Berlin, Germany. Agric Hum Val 2016;33:753–69. https://doi.org/10.1007/s10460-015-9658-z.

[32] Zambrano-Prado P, Orsini F, Rieradevall J, Josa A, Gabarrell X. Potential key factors, policies, and barriers for rooftop agriculture in EU cities: Barcelona, Berlin, Bologna, and Paris. Front Sustain Food Syst 2021;5.

[33] Arora NK, Mishra I. United Nations sustainable development goals 2030 and environmental sustainability: race against time. Environ Sustain 2019;2:339–42. https://doi.org/10.1007/s42398-019-00092-y.

[34] Paré G, Trudel M-C, Jaana M, Kitsiou S. Synthesizing information systems knowledge: a typology of literature reviews. Inf Manag 2015;52:183–99. https://doi.org/10.1016/j.im.2014.08.008.

[35] James KL, Randall NP, Haddaway NR. A methodology for systematic mapping in environmental sciences. Environ Evid 2016;5:7. https://doi.org/10.1186/s13750-016-0059-6.

[36] Koletsi D, Karagianni A, Pandis N, Makou M, Polychronopoulou A, Eliades T. Are studies reporting significant results more likely to be published? Am J Orthod Dentofacial Orthop 2009;136:632.e1–5. https://doi.org/10.1016/j.ajodo.2009.02.024.

[37] Payen FT, Evans DL, Falagán N, Hardman CA, Kourmpetli S, Liu L, et al. How much food can we grow in urban areas? Food production and crop yields of urban agriculture: a meta-analysis. Earth's Future 2022;10:e2022EF002748. https://doi.org/10.1029/2022EF002748.

[38] Appolloni E, Paucek I, Pennisi G, Stringari G, Gabarrell Durany X, Orsini F, et al. Supplemental LED lighting improves fruit growth and yield of tomato grown under the sub-optimal lighting condition of a building integrated rooftop greenhouse (i-RTG). Horticulturae 2022;8:771. https://doi.org/10.3390/horticulturae8090771.

[39] Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero J-I, Rieradevall J. Barriers and opportunities regarding the implementation of rooftop Eco.Greenhouses (RTEG) in mediterranean cities of Europe. J Urban Technol 2012;19:87–103. https://doi.org/10.1080/10630732.2012.717685.

[40] Rufí-Salís M, Petit-Boix A, Villalba G, Ercilla-Montserrat M, Sanjuan-Delmás D, Parada F, et al. Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture. Int J Life Cycle Assess 2020;25:564–76. https://doi.org/10.1007/s11367-019-01724-5.

[41] Bambara J, Athienitis A. Experimental evaluation and energy modeling of a greenhouse concept with semi-transparent photovoltaics. Energy Proc 2015;78: 435–40. https://doi.org/10.1016/j.egypro.2015.11.689.

[42] Muñoz-Liesa J, Royapoor M, López-Capel E, Cuerva E, Gassó-Domingo S, Josa A. Improving urban metabolism: Bi-directional energy and environmental benefits of rooftop greenhouse and building integration. 16th IBPSA Conference; 2019.

[43] Jans-Singh MK, Ward R, Choudhary R. Co-Simulation of a rooftop greenhouse and a school building in London, UK, Rome, Italy. 2019. p. 3266–73. https://doi.org/10.26868/25222708.2019.210355.

[44] Gholami M, Barbaresi A, Tassinari P, Bovo M, Torreggiani D. A comparison of energy and thermal performance of rooftop greenhouses and green roofs in mediterranean climate: a hygrothermal assessment in WUFI. Energies 2020;13: 2030. https://doi.org/10.3390/en13082030.

[45] Zhang Y, Yang Y, Dubois M-C. Light for life: new light solutions for urban plant sites. Acta Hortic 2022:417–34. https://doi.org/10.17660/ActaHortic.2022.1337.57.

[46] Muñoz-Liesa J, Royapoor M, Cuerva E, Gassó-Domingo S, Gabarrell X, Josa A. Building-integrated greenhouses raise energy co-benefits through active ventilation systems. Build Environ 2022;208:108585. https://doi.org/10.1016/j.buildenv.2021.108585.

[47] Benis K, Reinhart C, Ferrão P. Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts. J Clean Prod 2017;147:589–602. https://doi.org/10.1016/j.jclepro.2017.01.130.

[48] Gould D, Caplow T. 8 - building-integrated agriculture: a new approach to food production. In: Zeman F, editor. Metropolitan sustainability. Woodhead Publishing; 2012. p. 147–70. https://doi.org/10.1533/9780857096463.2.147.

[49] Parada F, Gabarrell X, Rufí-Salís M, Arcas-Pilz V, Muñoz P, Villalba G. Optimizing irrigation in urban agriculture for tomato crops in rooftop greenhouses. Sci Total Environ 2021;794:148689. https://doi.org/10.1016/j.scitotenv.2021.148689.

[50] Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J. Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. J Sci Food Agric 2013;93:100–9. https://doi.org/10.1002/jsfa.5736.

[51] Pons O, Nadal A, Sanyé-Mengual E, Llorach-Massana P, Cuerva E, Sanjuan-Delmàs D, et al. Roofs of the future: rooftop greenhouses to improve buildings metabolism. Procedia Eng 2015;123:441–8. https://doi.org/10.1016/j.proeng.2015.10.084.

[52] Sanyé-Mengual E, Martinez-Blanco J, Finkbeiner M, Cerdà M, Camargo M, Ometto AR, et al. Urban horticulture in retail parks: environmental assessment of the potential implementation of rooftop greenhouses in European and South American cities. J Clean Prod 2018;172:3081–91. https://doi.org/10.1016/j.jclepro.2017.11.103.

[53] Sanjuan-Delmás D, Llorach-Massana P, Nadal A, Ercilla-Montserrat M, Muñoz P, Montero JI, et al. Environmental assessment of an integrated rooftop greenhouse for food production in cities. J Clean Prod 2018;177:326–37. https://doi.org/10.1016/j.jclepro.2017.12.147.

[54] Benis K, Turan I, Reinhart C, Ferrão P. Putting rooftops to use – a Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates. Cities 2018;78:166–79. https://doi.org/10.1016/j.cities.2018.02.011.

[55] Corcelli F, Fiorentino G, Petit-Boix A, Rieradevall J, Gabarrell X. Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation. Resour Conserv Recycl 2019;144:321–36. https://doi.org/10.1016/j.resconrec.2019.01.040.

[56] Muñoz-Liesa J, Royapoor M, López-Capel E, Cuerva E, Rufí-Salís M, Gassó-Domingo S, et al. Quantifying energy symbiosis of building-integrated agriculture in a mediterranean rooftop greenhouse. Renew Energy 2020;156:696–709. https://doi.org/10.1016/j.renene.2020.04.098.

[57] Torres Pineda I, Cho JH, Lee D, Lee SM, Yu S, Lee YD. Environmental impact of fresh tomato production in an urban rooftop greenhouse in a humid continental climate in South Korea. Sustainability 2020;12:9029. https://doi.org/10.3390/su12219029.

[58] Muñoz-Liesa J, Toboso-Chavero S, Mendoza Beltran A, Cuerva E, Gallo E, Gassó-Domingo S, et al. Building-integrated agriculture: are we shifting environmental impacts? An environmental assessment and structural improvement of urban greenhouses. Resour Conserv Recycl 2021;169:105526. https://doi.org/10.1016/j.resconrec.2021.105526.

[59] Muñoz-Liesa J, Cuerva E, Gassó-Domingo S, Gabarrell Durany X, Nemecek T, Josa A. Guidelines to optimize covering and structural materials in rooftop-integrated greenhouses: an environmental assessment. Acta Hortic 2022:285–94. https://doi.org/10.17660/ActaHortic.2022.1356.34.

[60] Muñoz-Liesa J, Cuerva E, Parada F, Volk D, Gassó-Domingo S, Josa A, et al. Urban greenhouse covering materials: assessing environmental impacts and crop yields effects. Resour Conserv Recycl 2022;186:106527. https://doi.org/10.1016/j.resconrec.2022.106527.

[61] Peña A, Rovira-Val MR, Mendoza JMF. Life cycle cost analysis of tomato production in innovative urban agriculture systems. J Clean Prod 2022;367: 133037. https://doi.org/10.1016/j.jclepro.2022.133037.

[62] Balas MM, Popa M, Muller EV, Alexuta D, Muresan L. Intelligent roof-top greenhouse buildings. In: Balas VE, Jain LC, Balas MM, Shahbazova SN, editors. Soft computing applications. Cham: Springer International Publishing; 2021. p. 65–75. https://doi.org/10.1007/978-3-030-52190-5_5.

[63] Balas MM, Balas VE, Lile R, Balas SV. Fuzzy-interpolative control for intelligent roof-top greenhouse buildings. In: Shahbazova SN, Kacprzyk J, Balas VE, Kreinovich V, editors. Recent developments and the new direction in soft-computing foundations and applications: selected papers from the 7th world conference on soft computing, may 29–31, 2018. Baku, Azerbaijan, Cham: Springer International Publishing; 2021. p. 567–76. https://doi.org/10.1007/978-3-030-47124-8_46.

[64] Balas MM, Lile R, Copolovici L, Dicu A, Cincar K. Human-plant symbiosis by integrated roof-top greenhouses. In: Balas VE, Jain LC, Balas MM, Shahbazova SN, editors. Soft computing applications. Cham: Springer International Publishing; 2021. p. 76–83. https://doi.org/10.1007/978-3-030-52190-5_6.

[65] Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J. Integrating horticulture into cities: a guide for assessing the implementation potential of rooftop greenhouses (RTGs) in industrial and logistics parks. J Urban Technol 2015;22:87–111. https://doi.org/10.1080/10630732.2014.942095.

[66] Specht K, Siebert R, Thomaier S, Freisinger U, Sawicka M, Dierich A, et al. Zero-acreage farming in the city of Berlin: an aggregated stakeholder perspective on potential benefits and challenges. Sustainability 2015;7:4511–23. https://doi.org/10.3390/su7044511.

[67] Specht K, Sanyé-Mengual E. Risks in urban rooftop agriculture: assessing stakeholders' perceptions to ensure efficient policymaking. Environ Sci Pol 2017; 69:13–21. https://doi.org/10.1016/j.envsci.2016.12.001.

[68] Nadal A, Pons O, Cuerva E, Rieradevall J, Josa A. Rooftop greenhouses in educational centers: a sustainability assessment of urban agriculture in compact cities. Sci Total Environ 2018;626:1319–31. https://doi.org/10.1016/j.scitotenv.2018.01.191.

[69] Ercilla-Montserrat M, Sanjuan-Delmás D, Sanyé-Mengual E, Calvet-Mir L, Banderas K, Rieradevall J, et al. Analysis of the consumer's perception of urban food products from a soilless system in rooftop greenhouses: a case study from the Mediterranean area of Barcelona (Spain). Agric Hum Val 2019;36:375–93. https://doi.org/10.1007/s10460-019-09920-7.

[70] Harada Y, Whitlow TH. Urban rooftop agriculture: challenges to science and practice. Front Sustain Food Syst 2020;4. https://doi.org/10.3389/fsufs.2020.00076.

[71] Appolloni E, Orsini F, Specht K, Thomaier S, Sanyé-Mengual E, Pennisi G, et al. The global rise of urban rooftop agriculture: a review of worldwide cases. J Clean Prod 2021;296:126556. https://doi.org/10.1016/j.jclepro.2021.126556.

[72] Glaros A, Marquis S, Major C, Quarshie P, Ashton L, Green AG, et al. Horizon scanning and review of the impact of five food and food production models for the global food system in 2050. Trends Food Sci Technol 2022;119:550–64. https://doi.org/10.1016/j.tifs.2021.11.013.

[73] Orsini F, Appolloni E, D'Ostuni M. Can cities provide food in the XXI century? A review on the role of building-integrated agriculture. Acta Hortic 2022:13–26. https://doi.org/10.17660/ActaHortic.2022.1345.2.

Acta Universitatis agriculturae Sueciae

Doctoral Thesis No. 2023:95

Horticultural production occurs in various production systems, dominated by greenhouse and open-field production. During the last decade, alternative production systems with more advanced technologies, such as LED lighting and artificial intelligence, have started to appear, e.g., plant factories with artificial lighting. This opens up new opportunities where increased attention from venture capitalists and investors highlights food-tech as an innovative field of interest. Innovation adoption can accelerate firms' possibilities especially if they can adopt relevant knowledge from other production systems.

Annie Drottberger received her graduate education at the Department of People and Society and the Department of Biosystems and Technology, SLU Alnarp. Her undergraduate degrees are MSc in Horticulture and BSc in Business Administration, received at the Swedish University of Agricultural Sciences.

Acta Universitatis agriculturae Sueciae presents doctoral theses from the Swedish University of Agricultural Sciences (SLU).

SLU generates knowledge for the sustainable use of biological natural resources. Research, education, extension, as well as environmental monitoring and assessment are used to achieve this goal.

ISSN 1652-6880

ISBN (print version) 978-91-8046-242-6

ISBN (electronic version) 978-91-8046-243-3