Future Food Systems

Protected cropping

Current technologies and target crops

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About Future Food Systems

The Future Food Systems Cooperative Research Centre (CRC) is a national initiative created to drive innovation and growth in the agrifood sector by accelerating adoption of STEM technologies and cluster approaches to industry development, resilience and sustainability. It is funded as part of the Australian Government's CRC Program, established to drive industry-led collaborations between researchers and the community to improve the competitiveness, productivity and sustainability of Australian industries, especially in sectors where Australia has a competitive strength.

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Introduction

If Australia is to bolster its food production in the face of climate change and deliver healthy food sustainably, it needs to produce more with less. Protected cropping offers a way to do this. However, to make this way of farming economically viable in Australia, we need to consider the status of protected cropping in the context of available technologies and corresponding target horticultural crops. This report outlines existing opportunities, as well as challenges that must be addressed by ongoing research in this exciting but complex field.

Global population is expected to reach almost 10 billion in 2050, with the majority of growth forecast to occur in large urban centres across the world (United Nations, 2018, 2019). To feed this projected urban population, we will need to increase food production by at least 60 per cent (Valin et al., 2014) while minimising the impact of this production on the environment.

Despite prolonged drought and widespread bushfires in Australia in 2019, the value of farm production reached $59 billion over 2019–2020 due to higher commodity prices. However, extreme heatwaves and low water availability in major growing regions over this period reduced Australian summer crop, fruit and vegetable production (ABARES, 2020).

In its December 2020 quarterly report, ABARES forecast that the gross value of agricultural production would rise by 7% to $65 billion in 2020-21, driven by favourable growing conditions; however, overall value of exports would likely fall by an estimated 7% year-on-year to $44.7 billion.

According to ABARES, COVID-19 containment measures ‘have had a limited impact on agricultural markets’. This is due partly to consumers switching from restaurant dining to home consumption; and partly to the fact that horticulture – worth $12 billion-plus annually – was impacted less by the pandemic than were other agricultural commodities (notably, broadacre crops and livestock), as the bulk of Australia’s horticultural products are consumed domestically.

Nevertheless, declining arable land and adverse climate-change impacts on agriculture remain. These factors will compel innovations in future food production systems so as to meet demand for food, locally and globally, in the next few decades.

Protected cropping, also known as indoor farming (Rabbi et al., 2019) – ranging from low-tech poly-tunnels to medium-tech, partially environmentally-controlled greenhouses, to high-tech ‘smart’ glasshouses and indoor farms – could enhance global food security significantly. Involving a greater use of technology and automation to optimise land and resource use, it offers exciting solutions for improving food production (Benke and Tomkins, 2017).

However, while the vision of a self-sustainable metropolis as a way of tackling contemporary challenges is appealing, the uptake of indoor farming has lagged behind the excitement and optimism of its proponents.

Around the world, the development of urban agriculture (Mougeot, 2006; Pearson et al., 2010) has often occurred after chronic and/or acute crises, such as light and space limitations in the Netherlands; the collapse of the motor industry in Detroit; the real-estate market crash on the US East Coast; and the Cuban missile crisis blockade. Other impetus has come in the form of available markets: for example, protected cropping proliferated in Spain (Tout, 1990) because of that country’s easy access to Northern European markets.

The COVID-19 pandemic is currently accelerating the trend towards protected cropping uptake as countries focus on streamlining food supply chains and bolstering self-sufficiency.

That said, if urban agriculture is to play significant roles in bolstering food security and improving human nutrition, it needs to be scaled globally so that it has the capacity to grow a broad array of products in a more energy-, resource- and cost-efficient manner than is currently possible.

Enormous opportunities exist for improving crop productivity and quality. This can be achieved by pairing advancements in environmental controls, pest management, phenomics and automation with breeding efforts targeting traits that improve plant architecture, crop quality (taste and nutrition) and yield.

A greater diversity of current and emerging crops, as well as medicinal plants, can be grown in environmentally controlled farms than is currently the case (O’Sullivan et al., 2020, 2019)

In this review, we discuss the status of protected cropping in the context of available technologies and corresponding target horticultural crops, outlining the opportunities and challenges that need to be addressed by ongoing research.

Current techniques and technologies in protected cropping

Protected cropping is Australia's fastest-growing food-producing sector, with huge growth potential; however, it requires scientific and technological solutions to become a key global player. Funding support and practical technological innovations – new methods of biological control; solutions for partial automation of tasks like irrigation and temperature control – could help growers using low-tech systems transition to more productive, profitable medium-tech ones. Medium-tech facilities require significant technological upgrades to compete with large-scale food production from poly-tunnel-deploying farms and high-quality produce from high-tech greenhouses. This part of the sector needs scientific and technological solutions generated by industry-university collaborations: new crop genotypes, integrated pest management, automated fertigation, climate control and robotic assistance in crop management and harvest. Meanwhile, high-tech glasshouses would benefit from incorporating technological advances in crop physiology, fertigation, recycling and lighting. Vertical farms also have a bright future, especially post-pandemic.

Protected cropping is the fastest-growing food-producing sector in Australia, valued at around $1.5 billion per annum at the farm gate in 2017.

It is estimated that around 30% of all Australian farmers grow crops in some form of protected cropping system, and that crops grown under cover comprise around 20% of the total value of vegetable and flower production (Protected Cropping Australia, 2020).

In Australia, the estimated greenhouse vegetable production area is highest for South Australia (580 ha), followed by New South Wales (500 ha) and Victoria (200 ha), while Queensland, Western Australia and Tasmania each account for < 50 ha (Smith, 2020).

In 2019, the total land area devoted to protected cropping – which, broadly, involves growing crops under all types of covering – was estimated at 5,630,000 hectares (ha) globally (Produce Grower, 2019). The total area of vegetables and herbs grown in greenhouses (permanent structures) has been estimated to be about 500,000 ha globally, with 10% of these crops grown in glasshouses and 90% in plastic greenhouses (Hadley, 2017; Rabobank, 2018).

Australia's greenhouse area is estimated to be around 1,300 ha, with high-tech greenhouses (around 14 individual businesses, each occupying less than 5 ha) accounting for 17% of this area, and low-tech/medium-tech greenhouses accounting for 83% (Smith, 2020). Plastic greenhouses and glasshouses make up around 80% and 20%, respectively, of the total (Rabobank 2018).

Based on the Australian Horticulture Statistics Handbook (2014–2015) and discussions with industry, gross value of production (GVP) of fruits, vegetables, and flowers was estimated for 2017. Among the growing systems deployed, crops grown in hydroponic/substrate-based production systems (52%) were valued the highest, followed by the those grown under soil fertigation systems (35%); in a combination of soil fertigation and hydroponic/substrate-based systems (11%); and using a hydroponics/nutrient film technique (NFT) (2%) (*Figure 1a*).

Similarly, among the protection types, crops grown under poly/glass coverings (63%) had the highest GVP, followed by those grown under poly covers (23%), hail/shade covers (8%); and combined poly/hail/shade covers (6%) (Figure 1b). Within Australia, statistics for GVPs of specific greenhouse horticulture products are not readily available (Hadley, 2017).

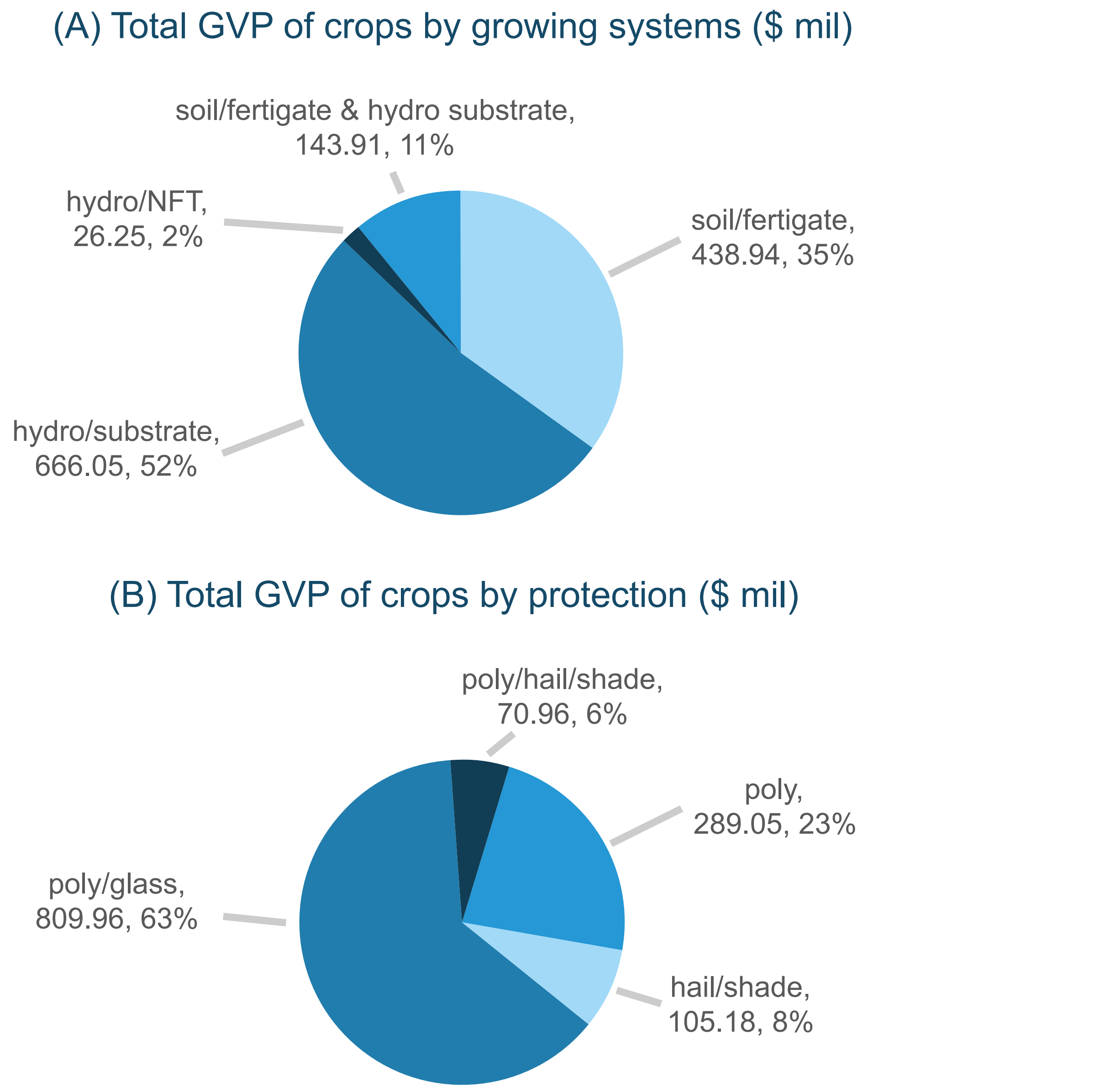


Figure 1. Total gross value production (GVP) of crops under protected cropping (2017) by growing system (a) and protection (b). Hydroponics/substrate-based production involves soilless plant growth using an inert medium such as rockwool. Soil/fertigate-based production involves plant growth using soil with fertigation (combined application of fertiliser and water). The hydroponics/nutrient film technique (NFT) entails circulating a shallow stream of water containing dissolved nutrients that passes across the roots of plants in watertight channels. 'Poly' refers to polycarbonate. Hail/shade coverings, usually of mesh or cloth, protect crops from hail and block a proportion of excessive light.

Among controlled-environment facilities in the United States, glass or polycarbonate (poly) greenhouses (47%) are more common than indoor vertical farms (30%), low-tech plastic hoop houses (12%), container farms (7%) and indoor deep-water culture systems (4%). Among growing systems, hydroponics (49%) is more common than soil-based (24%), aquaponic (15%), aeroponic (6%) and hybrid (aeroponics, hydroponics, soil) systems (6%) (Agrilyst, 2017; World Wildlife Fund, 2020).

Australia has few established advanced vertical farms, due largely to the fact that it has few densely populated cities. However, in comparison to other nations, Australia has a relatively greater number of advanced greenhouse facilities, producing fresh fruit and vegetables for export.

Although Australia has made a great start in indoor farming and the sector has huge growth potential, it requires time to mature and further development to become a key player at the global scale.

Currently, commercially oriented indoor farm facilities can be categorised into three levels of technological advancement: low-, medium- and high-tech. Each is discussed in greater detail in the following sections.

New technologies for low-tech poly-tunnels

Growing systems incorporating low-tech poly-tunnels account for 80–90% of greenhouse crop production, globally (World Wildlife Fund, 2020) and in Australia (Smith, 2020). These low-tech facilities have several limitations, however – notably, with regard to the control of climate, pests and fertigation. Given the large proportion of low-tech poly-tunnels in Australia's protected cropping sector, addressing such challenges is crucial. Technological solutions are needed to help growers make the transition from low-tech systems into more productive, profitable medium- or high-tech facilities producing high-quality crops with minimal resources.

Low-tech protected-cropping facilities encompass various types of poly-tunnels, which can range from makeshift metal structures with plastic coverings to permanent, purpose-built structures. The plastic covers protect the crop from hail, rain and cold weather and extend the growing season. These cheap structures offer a viable return for investment in vegetable crops such as lettuce, beans, tomatoes, cucumber, cabbage and zucchini. Farming in poly-tunnels is done in the soil, while more advanced operations can use large pots and drip-irrigation for tomatoes, blueberries, eggplants or peppers.

However, while they make sense for small farms, poly-tunnel facilities suffer from several shortcomings.

Generally, these facilities are not controlled – beyond providing a grower with the option of lifting the plastic covering when it gets too hot or cloudy outside. This lack of environmental control affects the consistency of the product, with regard to both size and quality, therefore reducing market access to demanding customers such as supermarkets and restaurants. Given that crops under low-tech poly-tunnel facilities are generally planted in the soil, these farmers also have to combat incursions by numerous pests and soil-borne diseases, such as persistent nematode infestation.

Industry and research partners require innovations providing solutions across facility design and crop-management systems, as well as smart trading systems that enable them to export produce and maintain a constant supply chain. Incentives and support from funding bodies, coupled with practical technological innovations (such as new methods of biological control, and solutions for the partial automation of tasks like irrigation and temperature control) from universities and companies could help growers currently using low-tech protected-cropping systems transition to using more technologically advanced ones.

Upgrading medium-tech greenhouses with innovations and next-gen technologies

Medium-tech protected cropping is a broad category encompassing controlled-environment greenhouses and glasshouses. This part of the protected-cropping sector requires significant technological upgrades if it is to compete with large-scale food production in farms deploying low-tech poly-tunnels and high-quality produce from high-tech greenhouses.

Unfortunately, statistics are not available for greenhouse horticulture operations in Australia (Hadley, 2017).

The environmental control in medium-tech greenhouses is usually partial or intensive and the temperature of some greenhouses can be controlled by manually opening the roof, while more advanced facilities have cooling and heating units. The use of solar panels and smart films are being investigated to reduce energy costs and carbon footprints in medium-tech greenhouses (Emmott et al., 2015; Marucci et al., 2018; Torrellas et al., 2012).

While many greenhouses are still made of PVC or glass cladding, 'smart' films can be applied to these structures or incorporated into greenhouse design to increase energy efficiency. Generally, high-end greenhouses use growing media such as Rockwool blocks with carefully calibrated liquid fertiliser receipts at different growth stages to maximise crop yields. CO_2 fertilisation is sometimes used in medium-tech greenhouse to boost yield and quality.

The medium-tech protected cropping sector will benefit from industry-university partnerships to generate advanced scientific and technological solutions, including new crop genotypes with high yield and quality, integrated pest management, fully automated fertigation and greenhouse climate control, and robotic assistance in crop management and harvest.

Sci-tech innovations for high-tech greenhouses

High-tech glasshouses can incorporate the latest technological advances in crop physiology, fertigation, recycling and lighting. In large-scale commercial greenhouses, for instance, 'smart glass' technology; solar photovoltaic (PV) systems; and supplemental lighting, such as LED panels, can be used to improve crop quality and yields. Producers are also increasingly automating critical and/or labour-intensive areas such as crop monitoring, pollination and harvesting.

The development of artificial intelligence (AI) and machine learning (MI) are opening new dimensions for high-tech greenhouses (Caponetto et al., 2000; Guo et al., 2017; Hassabis, 2017; Hemming et al., 2019; Taki et al., 2018).

AI is a set of computer-encoded rules and statistical models trained to discern patterns in big data and perform tasks generally associated with human intelligence. AI is used in image recognition by Facebook and in language translation by Google. Now, similarly powerful algorithms are being used to monitor crop health and recognise signs of disease, enabling quicker, better informed decision-making with regard to crop management and harvesting – which, these days, can be accomplished by robot arms rather than human labour.

Prototypes of robots for de-leafing tomato plants, harvesting capsicum (bell peppers) and pollinating tomato crops (Balendonck, 2017; Yuan et al., 2016) have been developed in Europe and Israel, and could be commercialised within the next 10 years. In Australia, at the QUT Centre for Robotics, a robotic prototype known as Harvey has been developed for picking capsicums in greenhouse environments.

Moreover, labour-management software systems for large-scale high-tech greenhouses will optimise the efficiency of workers significantly, improving the economic prospects of these businesses. The IT and engineering revolution will continue to empower protected cropping and indoor farming, allowing growers to monitor and manage their crops from computers and mobile devices, using these even to make critical farming and market decisions.

High-tech greenhouses have the highest potential to benefit the Australia protected cropping sector, hence ongoing research and innovation into these facilities is likely to be time and money well invested.

Developing vertical farms for future needs

In recent years, there has been rapid development in indoor 'vertical farming' across the world, especially in countries with large populations and insufficient land (Meharg, 2016; Thomaier et al., 2015). Vertical farming represents US$6 billion in value but remains a small fraction of the multi-trillion-dollar global agricultural market.

There are various iterations of vertical farming but all of them use vertically stacked growing shelves in fully enclosed and controlled environments that allow for a high degree of automation, control and consistency (Despommier, 2013).

To date, however, artificial lighting is very expensive so the industry remains limited to high-value and short life-cycle crops, and to those with a high 'harvest index' (the mass of harvestable product relative to total plant mass), including lettuce, leafy greens and herbs. Vertical farming is also making small inroads into the more complex fruiting crops, such as berries.

Although highly energy-intensive, vertical farming offers unmatched productivity per square metre and high levels of water and nutrient efficiency.

The technological dimension of vertical farming – and in particular, the advent of 'smart' glasshouses – is likely to attract growers eager to work with emerging computer and big-data technologies such as AI and the Internet of Things (IoT) (Yang et al., 2018).

Currently, all forms of indoor farming are energy- and labour-intensive, although there is scope for great advancement in both automation and energy-efficiency technologies.

Already, the most advanced forms of indoor agriculture supply their own energy on site and are independent of the general utility grid.

Rooftop gardens can range from simple designs on top of city buildings to the corporate rooftop enterprises that can be found on municipality buildings in New York and Paris.

Indoor vertical farming has a bright future, especially in the wake of the COVID-19 pandemic. This form of protected cropping is well positioned to increase its share of the global food market due to several factors: its highly efficient production system; reductions in supply-chain and logistics costs; potential for automation (minimising handling); and easy access to both labour and consumers.

Target crops in protected cropping

Right now, relatively few crops are suitable for indoor agriculture, thanks to limitations on indoor growth in many species, and limitations in protected-cropping systems– such as high energy costs across Australia. Right now, horticultural crops best suited to indoor growing facilities include those that grow on vines or bushes; high-value specialist crops; medicinal and cosmetic crops; and small trees. However, if protected cropping is to have a significant impact on global food security, cost-effective production of a diverse array of edible crops is crucial. Hence, we need to develop new crop cultivars that will differ significantly from those required for open field production. Development such cultivars will require the optimisation of traits such as self-pollination, indeterminate growth and robust roots. In the following sections, we discuss existing crops and the development of new cultivars for indoor agriculture.

Currently, only some crops are suitable for indoor agriculture, due not just to limitations on indoor growth in many species, but to the limitations of protected-cropping systems themselves – such as the high cost of energy (for illumination, heating, cooling and running various automated systems) across Australia, which makes this sort of production system cost-prohibitive for all but high-value crops.

However, economical production of a diverse array of edible crops is essential if protected cropping is to have a significant impact on global food security (Food and Agriculture Organisation, 2013; O'Sullivan et al., 2019, 2020).

Crop cultivars for the protected cultivation of vegetables differ significantly from those required for open field production; the latter are bred for tolerance to a wide range of environmental conditions, many of which are not an issue in protected cropping facilities.

Development of suitable cultivars will require the optimisation of several traits (such as self-pollination, indeterminate growth, robust roots) that differ from the traits viewed as desirable in outdoor crops (*Figure 2*; O'Sullivan et al., 2020).

Currently, the fruits and vegetables best adapted for indoor farming include:

- those that grow on vines or bushes (tomato, strawberry, raspberry, blueberry, cucumber, capsicum, grape, kiwifruit);
- high-value specialist crops (hops, vanilla, saffron, coffee);
- medicinal and cosmetic crops (seaweed, Echinacea); and
- small trees (cherries, chocolate, mango, almonds) (O'Sullivan et al., 2020).

In the following sections, we discuss current existing crops and the development of new cultivars for indoor agriculture in more detail.

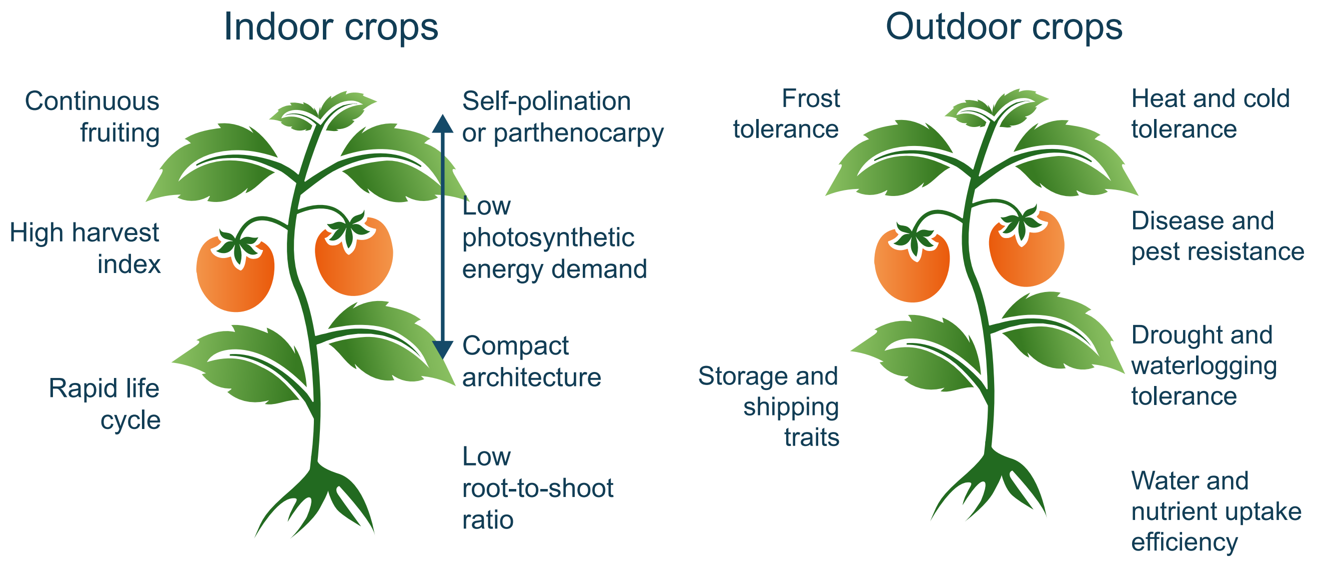


Figure 2. Desirable traits for fruiting crops grown indoors under controlled-environment conditions relative to crops grown outdoors under field conditions (O'Sullivan et al., 2020)

Crops typically grown in low, medium and high-tech facilities

Low- and medium-technology protected-cropping systems produce mainly tomato, cucumber, zucchini, capsicum, eggplant, lettuce, Asian greens and herbs. In terms of area, quantity of fruit produced and number of businesses, tomato is the most important horticultural vegetable crop produced in greenhouses, followed by capsicum and lettuce (Hadley, 2017; Montagu, 2018).

In Australia, the development of large-scale controlled-environment facilities has been limited primarily to those constructed for growing tomatoes (Hadley, 2017). Estimated GVP of fruits, vegetables and flowers for 2017, in the field and in protected-cropping facilities, demonstrates the dominance of tomato in the Australian protected-cropping sector.

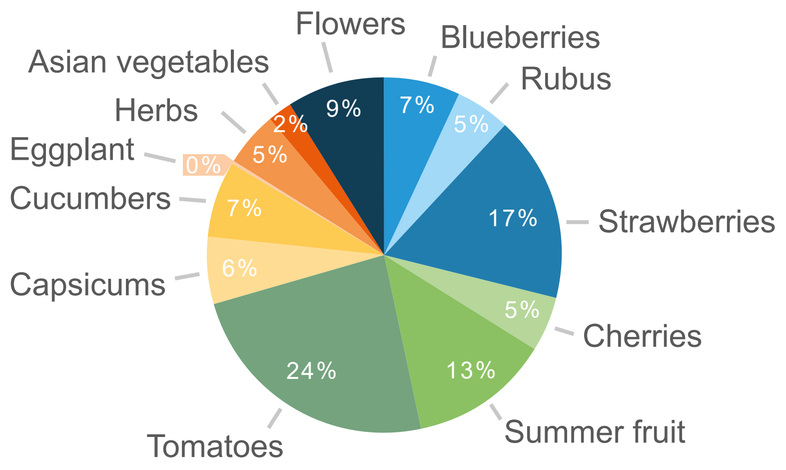
The overall estimated GVP for 2017 with regard to field and under-cover production of horticultural crops was highest for tomato (24%), followed by strawberry (17%), summer fruits (13%), flowers (9%), blueberry (7%), cucumber (7%) and capsicum (6%), with Asian vegetables, herbs, eggplant, cherry and berries each accounting for less than 6% (Figure 3a). Among these, the GVP of crops grown in protected-cropping systems was highest for tomato (40%), which led by a significant margin relative to other crops including flowers (11%), strawberry (10%), summer fruits (8%) and berries (8%), with each remaining crop accounting for less than 5% (Figure 3b). However, the Australian domestic market has been saturated by greenhouse tomatoes, which leaves the protected cropping industry with two options: to increase sales of these into international markets; and/or to encourage some of the country's existing greenhouse growers to transition to producing other high-value crops.

The proportion of individual crops cultivated under protection was highest for berries (85%) and tomato (80%), followed by flowers (60%), cucumber (50%), cherry and Asian vegetables (each 40%), strawberry and summer fruits (each 30%), blueberry and herbs (each 25%), and finally, capsicum and eggplant, at 20% each (Smith, 2020).

To date, energy- and labour-intensive indoor farming has been restricted to high-value crops that can be produced in the short term with low energy input (Hiwasa-Tanase and Ezura, 2016; Kozai, 2016) In plant 'factories', the predominant crops grown currently are leafy greens and herbs, due to these crops' short growing periods (because fruits and seeds are not required) and high value (Benke and Tomkins, 2017), the fact that such crops require relatively less light for photosynthesis (Kwon and Lim, 2011) and because most of the plant biomass produced can be harvested (Cocetta et al., 2017; Hiwasa-Tanase and Ezura, 2016).

There is a great potential to improve the yields and quality of crops grown in urban farms (O'Sullivan 2019).

(A) Estimated GVP of overall horticulture for 2017



(B) Imputed GVP of protected cropping for 2017

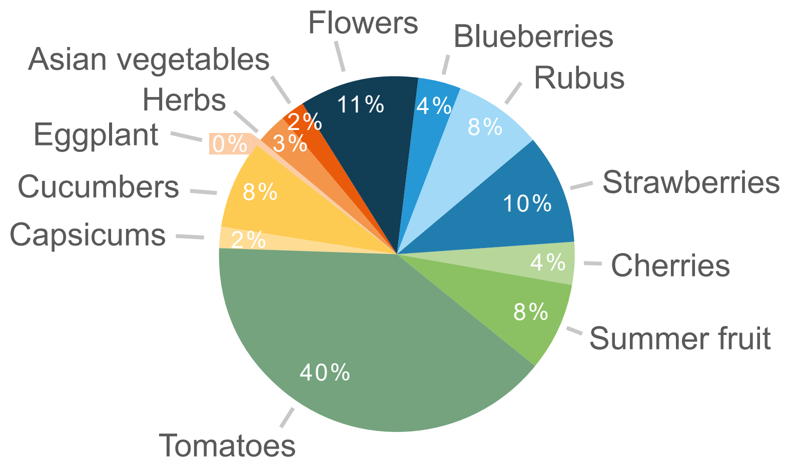


Figure 3. Estimated gross value of production (GVP) for overall combined field and protected-cropping vegetable production (a) and imputed GVP of crops cultivated under protected cropping for 2017(b)

Industry survey: where do CRC participants' interests lie?

The Future Food Systems CRC (FFSCRC), initiated by New South Wales Farmers Association (NSW Farmers), University of New South Wales (UNSW) and Food Innovation Australia Ltd (FIAL), consists of a consortium of more than 60 founding industry, government and research participants. FFSCRC research and capability programs aim to support participants in optimising the productivity of regional and peri-urban food systems, taking new products from prototype to market, and implementing rapid, provenance-protected supply chains from farm to consumer. To that end, the FFSRC provides a collaborative research environment aimed at improving protected cropping in order to boost our capacity to export top-quality horticultural produce and help Australia become a leader in science and technology for the protected-cropping sector.

Future Food Systems CRC participants were surveyed to identify target crops for indoor agriculture. Among the participants who identified target crops, interest in fresh vegetables (29%) was greatest, followed by interest in fruit crops (22%); medicinal cannabis, other medicinal herbs and specialised crops (13%); native/indigenous species (10%); mushrooms/fungi (10%); and leafy greens (3%) (*Figure 4*). The survey was based on web information about FFSCRC participants available online; acquiring more detailed information will be crucial if the CRC is to understand and meet the specific requirements of its participants.

Target crops indentified by participants

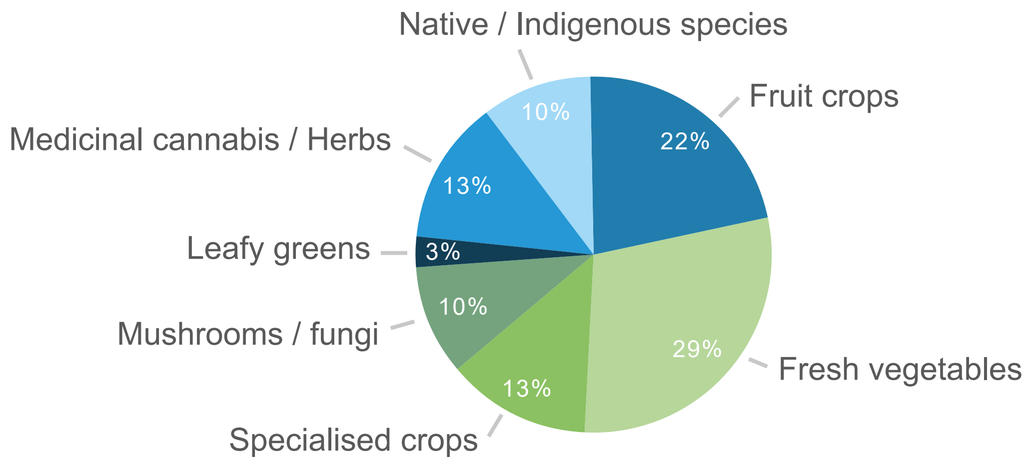


Figure 4. Classification of the crops produced currently by CRC participants in protected cropping facilities and hence, of participants' likely interest in finding solutions for growing these crops more productively under cover

Breeding new cultivars for controlled-environment facilities

Breeding technologies available for the improvement of vegetable and other crop plants are advancing rapidly (Jones, 2016).

In protected cropping, a dynamic economic sector with rapid changes in market trends and consumer preferences, choosing the right cultivar is critical (Food and Agriculture Organization, 2013; Tüzel & Leonardi, 2009).

There are many studies that assess adapting high-value crops such as tomato and eggplant for greenhouse production (Bergougnoux, 2014; Taher et al., 2017). New breeding technologies (Jones, 2016) have enabled the development of new cultivars with desired traits, and some companies have started designing plants to grow in controlled environments under LED lights (World Wildlife Fund, 2020).

To date, however, cultivars have been bred mostly to maximise yield under highly variable field conditions (Hiwasa-Tanase and Ezura, 2016) Crop traits such as tolerance to drought, heat and frost – desirable in field-grown crops but typically carrying yield penalties – are generally not needed in indoor agriculture.

Key traits that can be targeted for adapting higher-value crops to indoor agriculture include short life cycles, continuous flowering, low root-to-shoot ratio, improved performance under low photosynthetic-energy input, and desirable consumer traits including taste, colour, texture and specific nutrient content (O'Sullivan et al., 2020, 2019). Also, breeding specifically for higher quality will produce highly desirable products with high market value.

Light spectrum, temperature, humidity and nutrient supply can be managed so as to alter the accumulation of target compounds in leaves and fruits (Hasan et al., 2017; Piovene et al., 2015) and increase the nutritional value of crops, including proteins (quantity and quality), vitamins A, C and E, carotenoids, flavonoids, minerals, glycosides and anthocyanins (O'Sullivan et al., 2019). For instance, naturally occurring mutations (in grapevine) and gene editing (in kiwifruit) have been used to modify plant architecture, which will be useful for indoor growing in restricted spaces.

In a recent study, tomato and ground cherry plants were engineered using CRISPR–Cas9 to combine three desirable traits: a dwarf phenotype, a compact growth habit and precocious flowering. The suitability of the resulting 'edited' tomato varieties for use in indoor farming systems was validated using field and commercial vertical-farm trials (Kwon et al., 2020).

Challenges and opportunities in protected cropping and indoor farming

While advanced protected-cropping facilities typically have minimal environmental impacts, undercover crop production is more energy-intensive than many other farming methods. That said, indoor cropping mitigates the harmful impacts of weather and pests, ensures traceability and enables improved quality control. This means growers can deliver quality produce consistently year-round, bringing returns that more than offset additional production costs. There are challenges, however: high start-up costs; pricey skilled labour; high energy consumption; and issues around pest and disease management and quality control. In the following sections, both challenges and opportunities are discussed.

Advanced protected-cropping and indoor-farming facilities have a relatively small environmental impact. While growing crops under cover is more energy-intensive than many other farming methods, the ability to mitigate the impacts of weather, ensure traceability and grow better-quality food enable the consistent delivery of quality produce, attracting returns that far outweigh the additional production costs (Protected Cropping Australia, 2020).

Key challenges in protected cropping include:

- high capital start-up costs, due in large part to high land prices in inner-urban areas;
- high energy consumption;
- demand for skilled labour;
- the need for disease management without chemical controls; and
- the need to develop nutritional quality indexes – to define and certify quality aspects of the produce – for crops grown indoors.

In the following sections, we discuss some of the challenges and opportunities associated with protected cropping.

Optimal conditions for high productivity and efficient resource use

A greater understanding of crop requirements at different growth stages and under various light conditions is essential if growers are to maintain cost-effective crop production in controlled environments.

Efficient management of the greenhouse environment, including its climatic and nutritional elements, and structural as well as mechanical conditions, can increase fruit quality and yields significantly (Shamshiri et al., 2018).

The key environmental factors affecting greenhouse crop production include air and root-zone temperatures, relative humidity (RH), light quality and quantity, carbon dioxide (CO_2) availability, and measures for controlling plant diseases and insect pests. All these parameters can influence plant growth, evapotranspiration rates and physiological cycles.

Among the climatic factors, solar radiation is the most important as photosynthesis requires light, and crop yield is directly proportional to sunlight levels up to the light saturation points for photosynthesis. Photosynthesis also depends on temperature, and all crops have optimal temperature ranges (e.g., tomato growth, for example, is optimised at temperatures of 20–22°C during the day and 17–19°C overnight) – yet the most cost-efficient temperature range for greenhouse operations is 23–27 °C by day and 13–16°C at night (Rabbi et al., 2019; Shamshiri et al., 2018) The ideal relative-humidity range in a greenhouse is between 60% and 80%, depending on the crop (Hadley, 2017; Rabbi et al., 2019) It is important that new cultivars and crops in protected-cropping facilities be tested rigorously using a suite of environmental growth conditions – temperature, light, CO_2, humidity and suchlike – in order to find the optimal combination for maximising productivity and quality.

Often, precise environmental control requires high energy expenditure, reducing the profitability of controlled-environment agriculture. Energy required for greenhouse heating and cooling remains a major concern and a target for those seeking to reduce energy costs (Rabbi et al., 2019)

Glazing materials and innovative glass technologies offer exciting opportunities for reducing the cost associated with maintaining greenhouse temperature and controlling environmental variables.

Nowadays, innovative glass technologies and effective cooling systems are being incorporated into protected cropping in glasshouse facilities. Primary research objectives include assessing the impact of novel glazing materials on plant growth and physiology, crop yield and quality in environments in which factors such as CO_2, temperature, nutrients and irrigation are rigorously controlled.

An ultra-low-reflective ‘smart glass’ film, ULR-80, is currently being tested in glasshouse production. The goal is to realise the potential of glazing materials with adjustable light transmittance and reduce the high energy cost associated with operations in high-tech greenhouse horticulture facilities. Smart glass (SG) film is being applied to the standard glass of individual glasshouse bays in facilities growing vegetable crops using commercial vertical-cultivation and management practices.

Eggplant trials under SG demonstrated higher energy and resource-use efficiency, but also reduced eggplant yield, due to high rates of flower and/or fruit abortion as a consequence of light-limited photosynthesis (Chavan et al., 2020). The SG film used may need modification to generate optimal light conditions and minimise light limitations for high-carbon-sink fruits such as eggplant. Currently, the SG is being tested with a capsicum crop; preliminary results show significant energy savings without negative effects on plant photosynthesis, growth, yield and fruit quality. Leafy vegetables such as lettuce will be tested under smart glass next.

The use of novel energy-saving glazing materials such as smart glass provides an excellent opportunity to reduce the energy cost of glasshouse operations and optimise light conditions for the cultivation of target crops. Smart cover films such as Luminescent-Light Emitting Agricultural Films (LLEAF) have the potential to enhance as well as control vegetative growth and reproductive development in medium-tech protected cropping. LLEAF panels could be tested on a variety of flowering and non-flowering crops to determine whether they help to increase vegetative and reproductive growth (by altering physiological processes that underpin plant growth and crop productivity and quality).

Pest and disease management

Controlled protected-cropping facilities may minimise pests and diseases, but if these are introduced, via workers or by other means, they are extremely difficult and costly to control without using toxic synthetic chemicals. Strict hygienic practices are essential to minimise the risk of introducing pathogens and biological contamination into the growing space.

On the plus side, vertical indoor farming allows close monitoring of crops for signs of pest or disease, manually and/or automatically (using sensing technologies). Adopting emerging robotic technologies and/or remote-sensing procedures facilitates these sophisticated modes of cultivation, enabling early detection of outbreaks and removal of diseased and/or infested plants (Benke and Tomkins, 2017).

Novel integrated pest management (IPM) methods (Pilkington et al., 2010) will be required for the effective management of pests in greenhouses. Appropriate management strategies, along with good cultural practices, advanced monitoring techniques and precise identification can improve vegetable production while minimising reliance on pesticide applications.

An integrated approach to disease management involves the use of resistant cultivars, sanitation, sound cultural practices and the appropriate use of pesticides (Food and Agriculture Organization, 2013). Development of novel IPM strategies can minimise labour costs and the need to apply chemical pesticides. Take, for example, the use of new, commercially reared, naturally beneficial bugs to manage crop pests and reduce reliance on chemical control. Testing various new IPM strategies, in isolation and in combination, will aid in developing crop- and facility-specific recommendations for growers.

Crop quality and nutritional values

Protected cropping provides growers and industry partners with high yields and high-quality produce year-round (Sonneveld and Voogt, 2009). Not surprisingly, therefore, increasing numbers of growers are becoming interested in producing high-quality produce in high-tech greenhouses.

Cultivating premium fruits and vegetables (Treftz and Omaye, 2015), however, requires high-throughput testing of nutritional and quality parameters. Basic fruit quality parameters include moisture content, pH, total soluble solids, ash, fruit colour, ascorbic acid and titratable acidity, and advanced nutritional parameters including sugars, fats, protein, vitamins and antioxidants; firmness and water loss measurements are also crucial to defining quality indexes. Moreover, high-throughput quality testing of crop produce could be incorporated into an automated greenhouse operations system.

Screening available crop genotypes for quality parameters will provide new high-value, nutrient-rich varieties of fruit and vegetables for growers and consumers. Agronomic strategies will need to be optimised to enhance the production and plant nutrient density of these high-value crops.

Employment and availability of skilled labour

The labour requirements for the protected-cropping industry are expanding (> 5% per annum) and it is estimated that more than 10,000 people throughout Australia are currently employed directly by the industry. Despite its high levels of automation, large-scale protected cropping requires a significant labour force, especially for crop establishment, crop maintenance, mechanical pollination and harvesting produce. With increasing demand for highly skilled growers, the supply of suitably skilled workers remains low (Protected Cropping Australia, 2020; Vegetable Australia, 2020). A skilled workforce will also be required for the development of urban vertical farming, which will generate new careers for technologists, project managers, maintenance workers, marketing and retail staff (Benke and Tomkins, 2017).

The National Vegetable Protected Cropping Centre (NVPCC) on the Hawkesbury campus of Western Sydney University (WSU) provides an opportunity to address research questions furthering the goal of maximising productivity in a diversity of crops while providing education and training in skills likely to be in high demand in the future protected-cropping sector.

These courses include the Tertiary Pathway in Protected Cropping, Graduate Diploma in Protected Cropping, Graduate Certificate in Protected Cropping, Master of Science (Greenhouse Horticulture major) and Masterclass in Protected Cropping (delivered by Graeme Smith Consulting).

Summary and conclusions

Innovations in protected cropping and vertical farming can help to bolster food security while shrinking the carbon footprint of food production. In high-tech greenhouses with smart technology, there's substantial potential to boost profitability by automating key tasks, especially in labour-intensive areas. However, for indoor cropping production to have a substantial positive impact on global food security, economical production of diverse crops will be essential. This will require developing cultivars optimised for various key traits and finding cost-effective solutions to primary challenges including start-up costs, energy consumption, skilled labour, pest management and quality-index development.

The imminent need to improve urban food security and reduce the carbon footprint of food can be addressed by innovations in the agrifood sectors, such as protected cropping and vertical indoor farming. These range from low-tech poly-tunnels with minimal environmental control to medium-tech, partially environmentally controlled greenhouses to high-tech glasshouses and vertical farming facilities with state-of-the-art technologies.

Protected cropping is the fastest growing food-producing sector in Australia, in terms of scale of production and economic impact (O'Sullivan et al., 2019). The Australian protected-cropping industry consists of high-tech facilities (17%), glasshouses (20%) and hydroponic/substrate-based crop-production systems (52%), indicating the need and opportunity to develop the agrifood sector.

In high-tech greenhouses with smart technology, there is a great potential to improve profitability by automating critical and/or labour-intensive areas such as crop monitoring, pollination and harvesting. The development of AI, robotics and ML are opening new dimensions for protected cropping.

Vertical farms remain a small fraction of the global agricultural market and, despite being highly energy-intensive, vertical farming offers unmatched productivity with high levels of water and nutrient efficiency.

Economical production of diverse crops is essential if protected cropping production is to make a significant positive impact on global food security.

Low- and medium-technology protected-cropping systems produce mainly tomato, cucumber, zucchini, capsicum, eggplant and lettuce crops, along with Asian greens and herbs. To date, the development of large-scale controlled-environment facilities in Australia has been limited primarily to growing tomatoes.

Developing suitable cultivars will require optimising several key traits that differ from those considered desirable in outdoor crops. Key traits that can be targeted for indoor agriculture include:

- a reduced crop life cycle;
- continuous flowering;
- low root-to-shoot ratio;
- increased performance under low photosynthetic energy input; and
- desirable consumer traits, such as taste, colour, texture and specific nutrient contents.

In addition, breeding specifically for higher-quality, nutritionally denser crops will produce desirable horticultural (and potentially, medicinal) products with excellent market value.

The profitability and sustainability of protected cropping depends on developing solutions to primary challenges including start-up costs, energy consumption, skilled labour, pest management and quality-index development.

Novel glazing materials and technological advancements currently being researched or trialled offer solutions to address one of the most pressing protected-cropping challenges. These advancements could, potentially, provide the boost necessary to help the protected-cropping sector transition to a sustainable and cost-efficient level of energy-efficiency and fulfil growing demands for food security, while maintaining crop quality and nutritional content, and minimising harmful environmental impacts.

It is hoped that the collaborative research conducted through the FFSRC's three interlinked research programs will help cement Australia's position on the world stage as a major exporter of top-quality horticultural (including, potentially, medicinal) produce, and boost its reputation as an innovator of science and technology in the protected-cropping and indoor farming sector.

Further information

Protected Cropping Toolkit (Protected Cropping Australia, March 2020)
https://protectedcropping.net.au/protected-cropping-toolkit/

A series of practical, informational videos from Protected Cropping Australia, the main industry body for Australia's protected cropping operators, large and small. Topics covered include (list the video titles here).

Reports, publications and fact sheets (Hort Innovation)
https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/

Useful information for growers from the peak industry body for Australia's horticulture sector – an estimated 30 per cent of which consists of commercial protected-cropping operations that range from major growers to boutique operations located across all states and territories.

Here, you'll find resources on a broad variety of fruits and vegetables grown by PC operators across Australia, including blueberries, strawberries, rubus (raspberries, blackberries), tomatoes, melons, cucumbers, capsicum, salad (including Asian) greens, herbs, chillies, eggplant and more.

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