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Review

Current Technologies and Target Crops: A Review on Australian Protected Cropping

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Abstract: Protected cropping offers a way to bolster food production in the face of climate change and deliver healthy food sustainably with fewer resources. However, to make this way of farming economically viable, we need to consider the status of protected cropping in the context of available technologies and corresponding target horticultural crops. This review outlines existing opportunities and challenges that must be addressed by ongoing research and innovation in this exciting but complex field in Australia. Indoor farm facilities are broadly categorised into the following three levels of technological advancement: low-, medium- and high-tech with corresponding challenges that require innovative solutions. Furthermore, limitations on indoor plant growth and protected cropping systems (e.g., high energy costs) have restricted the use of indoor agriculture to relatively few, high value crops. Hence, we need to develop new crop cultivars suitable for indoor agriculture that may differ from those required for open field production. In addition, protected cropping requires high start-up costs, expensive skilled labour, high energy consumption, and significant pest and disease management and quality control. Overall, protected cropping offers promising solutions for food security, while reducing the carbon footprint of food production. However, for indoor cropping production to have a substantial positive impact on global food security and nutritional security, the economical production of diverse crops will be essential.

Keywords: protected cropping; vertical farm; soil-less culture; crop performance; indoor agriculture; food security; resource sustainability

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1. Introduction

The global population is expected to reach almost 10 billion in 2050, with the majority of growth forecasted to occur in large urban centres across the world [1,2]. As the population increases, food production must increase and meet nutrition and health needs while simultaneously achieving the United Nations Sustainable Development Goals (UN SDGs) [3,4]. Declining arable land and the adverse impacts of climate change on agriculture pose additional challenges that compel innovations in future food production systems to meet increasing demand in the next few decades. For example, Australian farms are frequently exposed to climate variability and are susceptible to long-term climate change impacts. Recent droughts across eastern Australia in 2018–19 and 2019–20 adversely affected farm businesses, thereby adding to the emerging effects of climate change on Australian agriculture [5].

Protected cropping, also known as indoor farming [6]—ranging from low-tech polytunnels to medium-tech, partially environmentally controlled greenhouses, to high-tech 'smart' glasshouses and indoor farms—could help to enhance global food security in the 21st century. However, while the vision of a self-sustainable metropolis is appealing as a way of tackling contemporary challenges, the uptake of indoor farming has not matched the excitement and optimism of its proponents. Protected cropping and indoor farming involve a greater use of technology and automation to optimise land use, thereby offering exciting solutions to improve future food production [7]. Around the world, the development of urban agriculture [8,9] 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 impetuses have come in the form of available markets, i.e., protected cropping proliferated in Spain [10] because of the country's easy access to Northern European markets. Together with existing challenges, the ongoing COVID-19 pandemic could provide the required impetus to transform the urban agriculture [11].

If urban agriculture is to play a significant role in improving food security and 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 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 relative to traditional crop types, as well as medicinal plants, can be grown in environmentally controlled farms [12,13].

The imminent need to improve urban food security and reduce the carbon footprint of food can be addressed by innovations in the agri-food sectors, such as protected cropping and vertical indoor farming. These range from low-tech poly-tunnels with minimal environmental control, 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 [12]. 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 agri-food sector. 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 in Australia.

2. Current Techniques and Technologies in Protected Cropping

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 [14]. 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 [15,16]. Australia's greenhouse area is estimated to be around 1300 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% [17]. Globally, plastic greenhouses and glasshouses constitute around 80% and 20%, respectively, of the total greenhouses produced [16].

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 [18]. 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 account for <50 ha each [17].

Based on the Australian Horticulture Statistics Handbook (2014–2015) and discussions with industry, the 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%), with 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) [17]. Within Australia, statistics for GVPs of specific greenhouse horticulture products are not readily available [15].

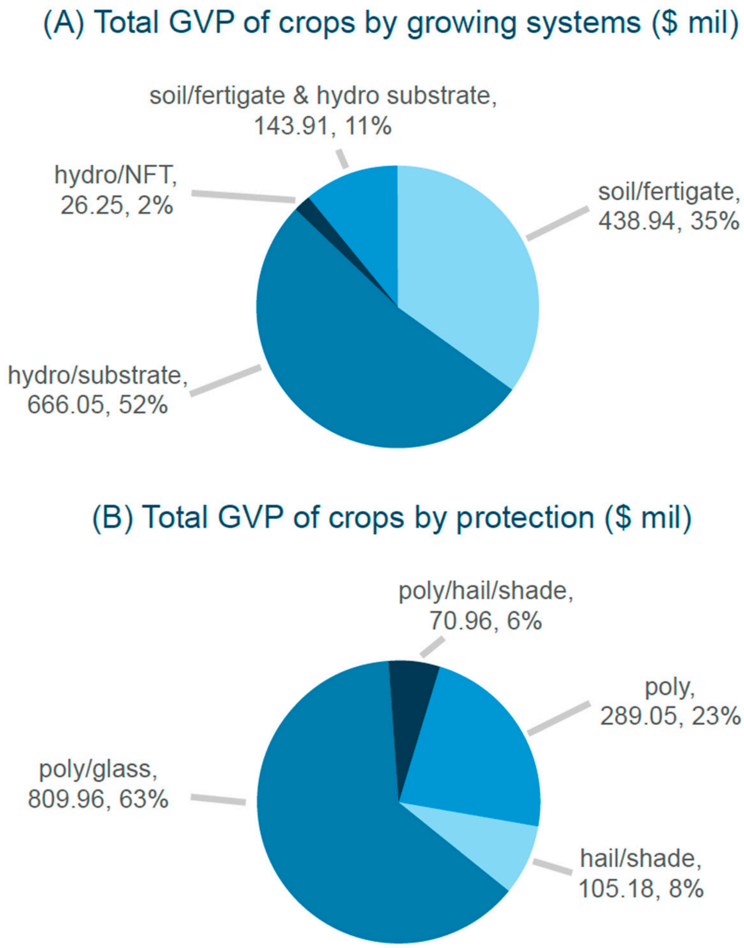

Figure 1. Total gross value production (GVP) of crops under protected cropping (2017) by growing system (**A**) and protection (**B**). Hydroponics/substrate-based production involves soilless plant growth using an inert medium such as rockwool. Soil/fertigate-based production involves plant growth using 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. $ refers to AUD.

Among the 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%) [19,20].

Australia has very few established advanced vertical farms, largely due to the fact that it has few densely populated cities. However, Australia has about a 1000 ha greenhouse area [16,17] and the export of fresh vegetable and fruits substantially increased from 2006 to 2016 for Australia [16] with increasing under-cover cropping. 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 the following three levels of technological advancement: low-, medium- and high-tech. Each is discussed in greater detail in the following sections.

2.1. New Technologies for Low-Tech Poly-Tunnels

Low-tech greenhouse facilities that contribute the most to protected cropping have several limitations which require technological solutions to help in their transition into profitable medium- or high-tech facilities producing high quality crops with minimal resources. Low-tech poly-tunnels account for 80–90% of the greenhouse crop production globally [20] and in Australia [17]. Considering the large proportion of low-tech poly-tunnels in protected cropping and their low levels of climate, fertigation and pest control, it is important to address the associated challenges in order to increase the production and economic returns to the growers.

The low-tech level encompasses various types of poly-tunnels which can range from makeshift metal structures with plastic coverings to permanent purpose-built structures. Generally, they are not controlled beyond the ability to lift the plastic covering when it becomes too hot or cloudy outside. These plastic covers protect the crop from hail, rain and cold weather and extend the growing season to some extent. These cheap structures offer a viable return for investment in vegetable crops such as lettuce, beans, tomatoes, cucumber, cabbage and zucchini. Farming in these poly-tunnels is performed in the soil, whilst more advanced operations can use large pots and drip-irrigation for tomatoes, blueberries, eggplants or peppers. However, while low-tech protected cropping makes sense for small growers, such techniques suffer from several shortcomings. Their lack of environmental control affects the consistency of the size and quality of the product and therefore reduces the market access of these products for demanding customers such as supermarkets and restaurants. Given that the crop is generally planted in the soil, these farmers are also faced with numerous pest and soil-borne diseases (e.g., persistent nematode infestation). Industry and research partners require innovations in providing solutions across facility design and crop management systems as well as smart trading systems to export produce and maintain a constant supply chain. Incentives and support from funding bodies and technological innovations (e.g., biological control, partial automation in irrigation and temperature control) from universities and companies could help growers transition to more advanced technological cropping systems.

2.2. Upgrading Medium-Tech Greenhouses with Innovations and New 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. 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 is being investigated to reduce energy cost and carbon footprints in medium-tech greenhouses [21–23].

While many greenhouses are still made of PVC or glass cladding, smart films can be applied to these structures or can be 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.

2.3. Innovations of Science and Technology 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) has opened new dimensions for high-tech greenhouses [24–28]. 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 used in image recognition is being used to monitor crop health and recognise signs of disease, enabling quicker, better-informed decision making for crop management and harvesting—which, these days, can be accomplished by robot arms rather than human labour. Internet-of-Things (IoT) offers solutions for automation that can be customized specifically for greenhouse applications [29]. Thus, AI and IoT can contribute significantly in the area of modern agriculture by controlling and automating farming activities [30].

Research and development in the field of agricultural robots has grown significantly in the past decade [31–33]. An autonomous crop harvesting system for capsicum that approaches commercial viability was demonstrated with a harvesting success rate of 76.5% [31] in Australia. Prototypes of robots for de-leafing tomato plants, harvesting capsicum (bell peppers) and pollinating tomato crops [34,35] have been developed in Europe and Israel, and could be commercialised in the near future.

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, which can even be used 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 translate to time and money well invested.

2.4. Developing Vertical Farms for Future Needs

In recent years, a rapid development in indoor 'vertical farming' across the world has been witnessed, especially in countries with large populations and insufficient land [36,37]. Vertical farming represents USD 6 billion in value but remains a small fraction of the multi-trillion-dollar global agricultural market [38]. There are various iterations of vertical farming but all of them use vertically stacked soil-less or hydroponic growing shelves in a fully enclosed and controlled environment, which allows for a high degree of automation, control and consistency [39]. However, vertical farming remains limited to high-value and short-life-cycle crops due to the high energy costs despite offering 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) [40]. 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 on municipality buildings in New York and Paris. Indoor vertical farming has a bright future, especially in the wake of the COVID-19 pandemic and is well positioned to increase its share of the global food market, due to 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.

3. Target Crops in Protected Cropping

Currently, crops suitable for indoor agriculture are limited in number due to the crop limitations for indoor growth as well as protected cropping limitations such as high energy cost (for illumination, heating, cooling and running various automated systems) which allows specific high value crops [41–43]. However, the economical production of a diverse array of edible crops is essential if protected cropping is to have a significant impact on global food security [12,13,44]. Crop cultivars for protected vegetable cultivation differ significantly from those of open field production that are bred for tolerance of a wide range of environmental conditions, which is not necessarily required in protected cropping. The 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) (Adopted from [13]).

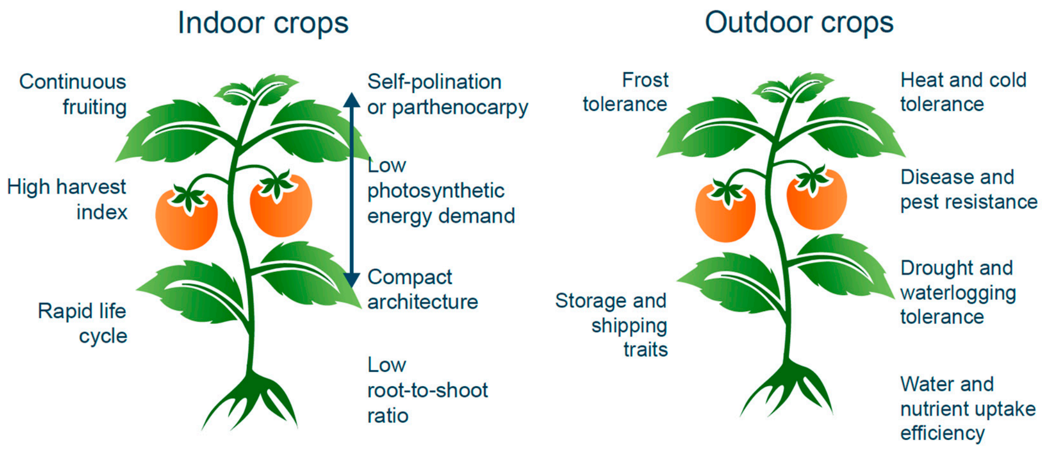

Figure 2. Desirable traits for fruiting crops grown indoors under controlled-environment conditions relative to crops grown outdoors under field conditions.

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);
- Small trees (cherries, chocolate, mango, almonds) are other viable options [13].

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

3.1. Existing Crops 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 [15,45]. In Australia, the development of large-scale controlled-environment facilities has been limited primarily to those constructed for growing tomatoes [15]. The 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 the 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).

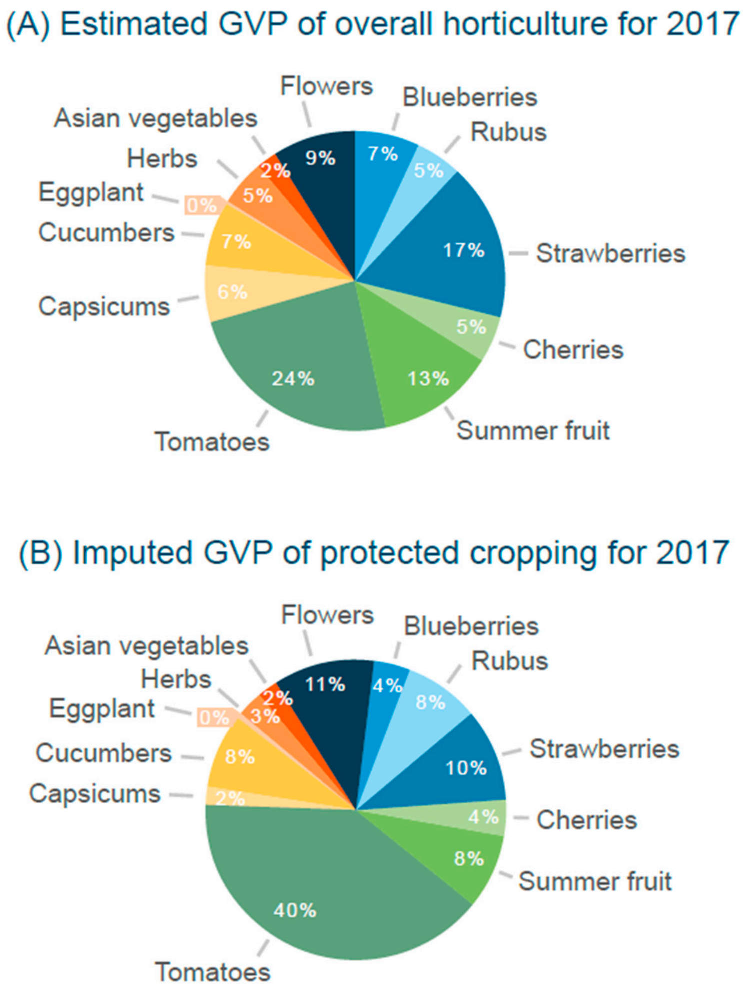

Figure 3. Estimated gross value of production (GVP) for overall combined field and protected-cropping vegetable production (**A**) and imputed GVP of crops cultivated under protected cropping in 2017 (**B**) for Australia.

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 of the remaining crops 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 the following two options: increase sales of these crops in international markets; and/or to encourage some of the country's existing greenhouse growers to transition to the production of 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 [17]. Currently, energy- and labour-intensive indoor farming is restricted to high-value crops that can be produced in the short term with a low energy input [46,47].

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 [7], the fact that such crops require relatively less light for photosynthesis [48] and because most of the plant biomass produced can be harvested [46,49]. There is great potential to improve the yields and quality of crops grown in urban farms [12].

3.2. Industry Survey: Where Do Participants' Interests Lie?

The identification of key research topics is essential to improve the efficiency of public and privately funded research for the future of protected cropping. For instance, the Future Food Systems Co-operative Research Centre (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. Its 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.

The 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).

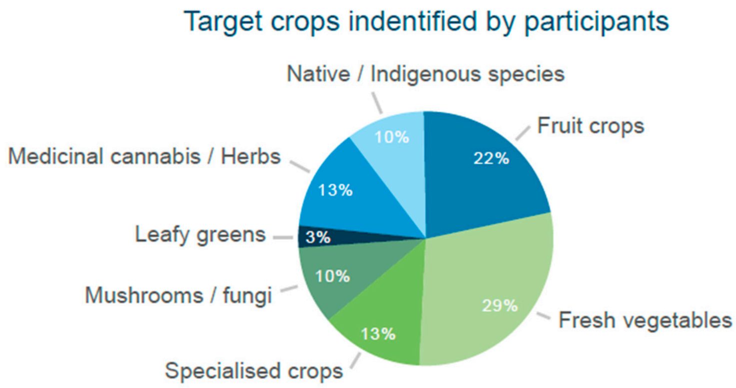

Figure 4. Classification of the crops produced currently by FFSCRC participants in protected cropping facilities and hence, of participants' likely interest in finding solutions for growing these crops more productively under cover.

The survey was based on information about the participants available online; acquiring more detailed information will be crucial to understanding and meeting the specific requirements of the participants.

3.3. Breeding New Cultivars for Controlled-Environment Facilities

Breeding technologies available for the improvement of vegetable and other crop plants are advancing rapidly [50]. In protected cropping, a dynamic economic sector with rapid changes in market trends and consumer preferences, choosing the right cultivar is critical [44,51]. There are many studies that assess adapting high-value crops such as tomato and eggplant for greenhouse production [52,53]. New breeding technologies [50] have facilitated the development of new cultivars with desired traits, and some companies have started designing plants for growth in controlled environments under LED lights [20]. However, cultivars have been bred mostly to maximise yield under highly variable field conditions [46]. Crop traits such as tolerance to drought, heat and frost—which are desirable in field-grown crops but typically carry 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, a low root-to-shoot ratio, improved performance under low photosynthetic-energy input, and desirable consumer traits including taste, colour, texture and specific nutrient content [12,13]. Additionally, 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 [54,55] and increase the nutritional value of crops, including proteins (quantity and quality), vitamins A, C and E, carotenoids, flavonoids, minerals, glycosides and anthocyanins [12]. 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 cherry plants were engineered using CRISPR–Cas9 to combine the following 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 [56]. A review of molecular breeding to create optimized crops discussed the added value of agricultural products by developing agricultural crops with health benefits and as edible medicines [46]. The main approaches to develop agricultural crops with health benefits were identified as the accumulation of large quantities of a desirable intrinsic nutrient or reduction in undesirable compounds, and the accumulation of valuable compounds that are not normally produced in the crop.

4. Challenges and Opportunities in Protected Cropping and Indoor Farming

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 promote the consistent delivery of quality produce, attracting returns that far outweigh the additional production costs [18]. Key challenges in protected cropping include:

- High capital costs, due to high land prices in inner-urban and peri-urban areas;
- High energy consumption;
- Demand for skilled labour;
- Disease management without chemical controls; and
- Development of nutritional quality indexes—to define and certify quality aspects of the produce—for crops grown indoors.

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

4.1. 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 [57]. The growth environment factors 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. Oftentimes, 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 [6]. Glazing materials and innovative glass technologies such as Smart Glass [58] offer promising 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. Glazing materials have the potential to reduce electricity consumption, by absorbing excess solar radiation and redirecting the light energy to generate electricity using photovoltaic cells [59,60].

However, the covering materials affect the greenhouse microclimates [61,62] including light [63] and it is therefore important to assess the impact of novel glazing materials on plant growth and physiology, resource use, crop yield and quality in environments in which factors such as CO_2, temperature, nutrients and irrigation are rigorously controlled. For instance, semi-transparent Organic Photovoltaics (OPVs) based on the blend of regioregular poly(3-hexylthiophene) (P3HT), and phenyl-C61-butyric acid methyl ester (PCBM) were tested to cultivate pepper plants (*Capsicum annuum*). Under the shade of OPVs, the pepper plants produced 20.2% more fruit mass and shaded plants were 21.8% taller at the end of the growing season [64]. In another study, the reduction in PAR caused by flexible photovoltaic panels on the roof did not affect the yield, plant morphology, number of flowers per branch, fruit colour, firmness and pH [65].

An ultra-low-reflective ‘smart glass’ film, Solar Gard™ ULR-80 [58], is currently being tested in glasshouse production. The aim 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 [66,67]. Eggplant trials under SG demonstrated higher energy and fertigation efficiency [42], but also reduced eggplant yield, due to high rates of flower and/or fruit abortion as a consequence of light-limited photosynthesis [58]. The SG film used may need modification to generate optimal light conditions and minimise light limitations for high-carbon-sink fruits such as eggplant.

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).

4.2. Pest and Disease Management

Although controlled protected-cropping facilities may minimise pests and diseases, once introduced, they are extremely difficult and costly to control without using toxic synthetic chemicals. Vertical indoor farming allows for the close monitoring of crops for signs of pest or disease, manually and/or automatically (using sensing technologies) and adopting emerging robotic technologies and/or remote-sensing procedures will facilitate the early detection of outbreaks and removal of diseased and/or infested plants [7].

Novel integrated pest management (IPM) methods [68] will be required for the effective management of pests in greenhouses. Appropriate management strategies (cultural, physical, mechanical, biological and chemical), 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 [44]. The 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 (e.g., aphid midge, green lacewing, etc.) 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.

4.3. Crop Quality and Nutritional Values

Protected cropping provides growers and industry partners with high yields and high-quality produce year-round [69]. Cultivating premium fruits and vegetables, however, requires the high-throughput testing of nutritional and quality parameters [70]. 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 [66]. Moreover, the 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 including growth environment and crop management practices will need to be optimised to enhance the production and plant nutrient density of these high-value crops.

4.4. Employment and Skilled-Labour Availability

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 the increasing demand for highly skilled growers, the supply of suitably skilled workers remains low [18,71]. 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 and marketing and retail staff [7]. Establishing multipurpose commercial scale advanced facilities would provide an opportunity to address research questions, thereby furthering the aim 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.

5. Conclusions

In high-tech greenhouses with smart technology, there is 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 constitute 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. The 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.

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, a 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 necessary boost 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.

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