Cannabis in Australia: cultivating at scale and lessons from overseas markets

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Executive summary

The Australian medicinal cannabis industry is one of the most rapidly evolving and growing sectors of horticulture in the country. During the course of this project, it has grown from infancy to become a significant market within the global cannabis landscape with an estimated retail value of approximately $500 million in 2024. With this rapid growth set to continue over the next decade, challenges and opportunities exist for producers, manufacturers, distributors, and legislators to grow the Australian cannabis industry in a sustainable and responsible direction with world-leading practices and sensible legislation.

Based on research across 16 countries, this report provides recommendations to drive a sustainable and profitable cannabis industry in Australia. The author visited dozens of farms to view production practices, discuss legislative frameworks, and investigate the application of emerging technology in the cultivation and processing of cannabis and cannabis products.

Cannabis is a unique horticultural crop, with a high level of variation in cultivation techniques, technology applied, and different forms of end-product for different uses. The potential for further deregulation within Australia represents a significant opportunity for market expansion. Producers in Australia have some competitive advantages in terms of cultivation, including access to high-skilled agricultural talent, favourable environmental conditions, and a well-developed pharmaceutical industry.

Key insights from international markets emphasise the importance of a regulatory framework that is robust, well thought-out, and prioritises public health whilst not overburdening producers with legislative or financial barriers.

Looking ahead, the Australian cannabis industry will continue to expand with most conservative estimates predicting a tripling of the 2022 industry by 2030, and the most optimistic predicting up to a 100-fold increase in a legalisation scenario. This report highlights the need for strategically planned cultivation facilities, with a heavy focus on efficient and appropriately sized cultivation facilities, collaboration on regulatory development including a cultivation framework, and learning from international models to develop a robust and efficient industry in which producers can leverage the competitive advantages local producers may have. Implementing best management practices across the Australian cannabis industry in the future will achieve consistent, reproducible, safe, and high-quality cannabis products.

Lastly, it should be noted that all figures and statistics quoted and presented in this report are, to the best of the author's knowledge, true and accurate at the time of writing. Due to the dynamic nature of the cannabis industry both within Australia and worldwide, it is inevitable that some of these figures will be out of date by the time of publication.

Keywords: cannabis; medicinal cannabis; horticulture; indoor farming; greenhouse; glasshouse; postharvest processing;

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Foreword

I am from Hobart, Tasmania, and attended the University of Tasmania from 2009-2012 where I graduated with a Bachelor's of Agricultural Science with Honours, specialising in plant nutrition and source-sink relationships in small fruit crops. After working in the small-fruit and nursery industries in operational and technical roles for several years, I returned to the University of Tasmania to pursue a Doctorate of Philosophy (PhD) in Horticultural Science. I graduated with my PhD in 2019 with a research project investigating pre and postharvest factors affecting berry fruit quality. Following this I commenced work for Tasmanian Botanics Pty Ltd in the recently-established medicinal cannabis industry.

In 2017 Tasmanian Botanics was one of the first companies to successfully obtain the required licenses from the Office of Drug Control (ODC) to begin work constructing a purpose-built facility for the production of cannabis for medical purposes in Australia. In 2019, the company was granted the final permits to begin commercial cultivation, which was the beginning of an exciting journey in the Australian cannabis industry.

I had always been personally interested in the commercial production of the cannabis plant and the underlying physiology of secondary metabolite production in medicinal plants. During my early career as a plant physiologist, I followed the process leading to the legalisation of cannabis for medical use in 2017 with interest. Whilst I was sceptical at the time of the viability of an industry developing in Australia due to the conservative political environment, I was excited by any potential opportunities to work in the space. Cannabis is a remarkably diverse plant producing an extraordinarily large number of unique and valuable secondary metabolites, with a multitude of commercial uses including medicine, food, and fibre production. In my roles since joining the industry I have been fortunate enough to grow some of the first legal cannabis plants and commercial-scale cannabis crops in Australia, and have watched the industry flourish to a viable and exciting position entering 2024.

With the rapid expansion of the cannabis industry both in Australia and around the world in various forms, I decided to pursue an opportunity for a Nuffield scholarship in 2022. Being able to travel to more mature cannabis industries as well as rapidly developing markets sharing similarities to Australia was a unique and extremely valuable experience that has since had a massive influence on my career and professional outlook.

Table 1. Travel itinerary

Note: Due to the nature of the cannabis industry, I have omitted naming visits undertaken to non-licensed cannabis producers and facilities, as well as several facilities where strict non-disclosure agreements were signed. Visits to multiple Australian facilities over the course of three years have been omitted.

Travel date	Location	Key visits (not all listed)
June 6-10, 2022	Denmark: Odense Germany: Berlin	Little Green Pharma Nordic Supreme Wittenberg Gemüse GmbH Various illicit producers
June 13-17, 2022	The Netherlands: Amsterdam, Horst	Greentech Horticultural Conference Delphy Perfect Plants World Horti Center Light4Food Plagron Koppert Cress Various non-licensed producers
June 20-25, 2022	Portugal: Lisbon Spain:	Clever Leaves Sabores Purpura MIFCO Medicinal Plants Almeria region – various low tech greenhouses
November 8-15, 2022	USA: Los Angeles Sacramento	Blue lagoon Various indoor facilities California Cannabis Co Los suentos farms
November 16-21, 2022	USA: Bend Takilma Las Vegas	Phylos Bioscience Progressive Plant Research Willamette valley (various producers)

		Golden leaf Marijuana Business Conference, Las Vegas Planet 13
November 22-26, 2022	Canada: Toronto, Montreal, Vancouver, Delta	Agmedica Origine Nature Keirton industries Pure Sun Farms Saints cannabis Greenhead cannabis Medzcann The Green Organic Dutchman Various non-licensed producers
June 11-15, 2023	Israel	Cullception Greenkom Netafim Various non-licensed producers

Acknowledgments

This project has been generously sponsored by the JM Roberts Charitable Trust and the Tasmanian Institute of Agriculture. I would like to express my enormous gratitude to these sponsors, whom without this support the project would not be possible. I hope that this project and my ongoing contribution to Tasmanian and Australian horticulture, and particularly the medicinal cannabis industry, can reflect my appreciation for the opportunity to undertake this project.

The travel component of this project was supported by Tasmanian Botanics Pty Ltd, and I would like to thank the management and staff at Tasmanian Botanics for continued operational and practical support throughout the course of this project. In particular, the highly skilled and dedicated cultivation team, who do the hard work day in and out, growing thousands of consistent, high-quality plants to provide medicine to the Australian market.

I would like to thank the members of my Global Focus Program, who contributed to my passion for collaboration in the agricultural community and the Nuffield program throughout our five-week trip, which was the highlight of my scholarship.

Most importantly I would like to express my deepest appreciation of my partner Clare and son Freddie, who have supported, underwritten and encouraged my passion for this project and industry. This support, allowing me to complete my travel and studies at their own sacrifice has been immensely gracious and I cannot thank you enough for your support.

Abbreviations

APIs	Active Pharmaceutical Inputs
CBDA	Cannabidiolic acid
CBD	Cannabidiol
CBG	Cannabigerol
CBGA	Cannabigerolic acid
CEA	Controlled Environment Agriculture
COGS	Cost of goods sold
DLI	Daily light integral
EC	Electrical conductivity
GACP	Good Agricultural and Collection Practices
GMP	Good Manufacturing Practice
GPP	Good Production Practices (Guide for Cannabis)
ha	Hectare
HVAC	Heating Ventilation and Air Conditioning systems
IPM	Integrated Pest Management
kg	Kilogram
OCS	Ontario Cannabis Store
ODC	Office of Drug Control
PhD	Doctorate of Philosophy
PBS	Pharmaceutical Benefit Scheme
PPFD	Photosynthetic Photon Flux Density
TGA	Therapeutic Drugs Administration
THC	Tetrahydrocannabinol
THCA	Tetrahydrocannabinolic acid
THCV	Tetrahydrocannabivarin
USA	United States of America

Objectives

This project broadly aimed to investigate global trends in the cultivation, processing, manufacturing, marketing, and legislation of cannabis and cannabis products throughout global markets. At the commencement of this project, the Australian cannabis industry was in its infancy but expanding rapidly. Through investigating the progress of trends in these areas within mature and growing overseas markets, Australian producers and legislators can make informed decisions regarding the future of cannabis production in Australia.

The major goals of this project were:

- Identify and document various cultivation and postharvest processing techniques and technologies in use around the world, and assess their applicability to the cultivation of cannabis in Australia.

- Document the challenges and opportunities surrounding the future legislation of the legal cannabis industry both internationally and within Australia.

- Investigate consumer trends in mature and emerging medical and adult-use cannabis markets, and evaluate how consumption trends in more mature markets may guide Australian producers.

- Make recommendations to industry and government regarding the cultivation and regulation of cannabis in Australia for the local and overseas markets.

- Utilise this research to foster growth, collaboration, and communication within the Australian cannabis industry.

Cannabis is a diverse plant with a wide range of medicinal, recreational, and industrial use cases and associated cultivation and processing techniques. For the purposes of this project and report, the majority of work focused on the production of high delta-9-tetrahydrocannabinol (THC) flower for the medical and adult-use markets, with a minor focus on cannabidiol (CBD) flower production, extracts, oils, edibles, and other novel cannabis products and delivery formats.

Introduction

The global cannabis industry encompasses the production, distribution, and sale of cannabis and cannabis-derived products for both medical and recreational use. Although the legal status of cannabis varies by country, the industry has seen rapid growth in recent years due to ongoing deregulation, legalisation, and decriminalisation efforts. Since 2019, the number of countries with some form of a legal cannabis industry has increased from 50 to 70, with significant deregulation trends in North America, Western Europe, and parts of Australasia.

In Australia, the cannabis industry has progressed from its infancy since the legalisation of medicinal cannabis in 2017. The projected retail value of the Australian cannabis market is expected to reach between $500 million and $1.5 billion by 2030 (Australian Institute of Health and Welfare 2024; Penington Institute 2023; Shoebridge 2023), potentially exceeding these estimates with further deregulation or legalisation for adult use.

As the Australian cannabis industry develops, observing trends in socioeconomically similar countries with more mature cannabis markets can provide valuable insights. Canada and the United States of America (USA) have been leaders in the industry's growth, accounting for most of the world’s legal production and sales. The US legal cannabis market is expected to reach US$43 billion by 2025 (Malabadi et al. 2024), while Canada's market was valued at CAD$6.4 billion in 2023 (The Ontario Cannabis Store 2023). Cannabis was legalised for adult use in Canada in 2017, creating a federally regulated recreational market. In the US, cannabis remains federally illegal, but various states regulate their medicinal or recreational markets. Currently, 236 million Americans have access to medical cannabis in 38 states, and 145 million have access to adult-use markets in 18 states.

In agricultural terms, cannabis is currently the fifth most valuable crop grown in the US, according to a 2022 report by Leafly (Leafly, 2022), returning over US$6 billion to American farmers in 2020. This places it above cotton, rice, and peanuts in farm gate value, only being beaten in value by corn, soybeans, hay, and wheat.

In Europe, several countries, including Germany, the Netherlands, Israel, Spain, and Portugal, have legalised medical cannabis or cannabis cultivation in some form. Germany decriminalised personal use and cultivation in early 2024, with plans to develop a legal adult-use market. Other countries with decriminalisation, pilot legalisation programs, or proposed legislation include Switzerland, Malta, France, Italy, the Czech Republic, and Romania.

The global cannabis industry faces ongoing challenges including inconsistent regulation, financing difficulties due to the plant’s legal status in many jurisdictions, and production scaling issues. However, the potential for growth and increasing acceptance of cannabis for medical and recreational use suggest that the industry will continue to expand, becoming a major horticultural and medical industry globally.

The expansion of the industry creates opportunities for legal producers but also requires continuous research and development of cultivation and postharvest techniques to drive production efficiencies and profitability in an increasingly

competitive market. This report aims to identify opportunities and challenges for cannabis producers in Australia and provide recommendations to ensure the industry's productive growth with a focus on local cultivation.

In the rapidly evolving global cannabis landscape, techniques, technologies, and best practices for improving productivity, quality, and profitability can change quickly. Successful producers must adapt to shifting consumer preferences and industry standards. By observing trends in more mature markets, forward-thinking farms can develop competitive advantages in price, quality, and market access. This report will explore these evolving dynamics and provide actionable insights for the Australian cannabis industry.

The Australian cannabis industry

This project explored where Australia may lie in the global cannabis landscape in the medium and long term. The potential growth of the Australian market will depend on any changes in the regulatory environment, but general growth and trends will likely follow those seen in more mature markets. The following section explores the current legislation and framework, and market size including local and important production. Further sections explore the future of the Australian cannabis cultivation industry, following detailed discussion on cultivation and postharvest production methods globally.

Legislation and framework

The Australian medicinal cannabis industry was initiated in 2016, when the coalition government amended the *Narcotic Drugs Act 1967* to legalise the cultivation and manufacture of cannabis for medicinal and research purposes. This legislative change laid the groundwork for the development of a regulated industry, allowing for the controlled production of cannabis to meet the growing demand for medicinal use.

Market size

In the seven years since its inception, the Australian medicinal cannabis industry has experienced significant growth, an increase in the availability of products for patients, high levels of uptake and interest from patients, and progress in the willingness of healthcare providers to prescribe cannabis products.

In 2019, the total sales of cannabis products in Australia were estimated to have been around $30 million in retail value (Penington Institute 2023), which increased to approximately $230 million in 2021 and is estimated at $500 million in 2024. This value is expected to continue to grow based on several scenarios, as shown in Figure 1, ranging from continued modest growth under the current medicinal system to potential exponential growth under a regulated adult-use scenario (MTP Connect 2021; Shoebridge 2023), which is discussed later in this report.

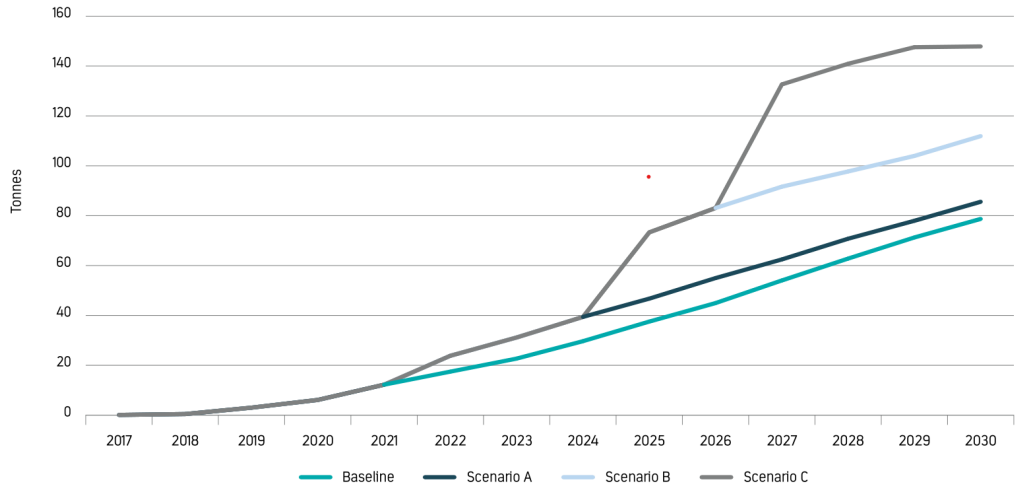

Figure 1. A comparison of three models to predict the demand for dried flower in Australia under different legislative scenarios (MTP Connect 2021)

Several factors have driven the rapid expansion of the Australian medicinal cannabis market including easing restrictions on supply, increased patient awareness, and a significant increase in cannabis-oriented health clinics which specialise in prescribing cannabis products. Some of these have come under criticism in 2024 for alleged flagrant breaches of pharmaceutical advertising laws, with the TGA issuing an increasing number of fines to various companies in the value chain for breaches of advertising standards. Despite this, patient numbers continue to grow rapidly, with approvals for new scripts in 2024 increasing by more than 50% over 2023 levels (Jones 2024).

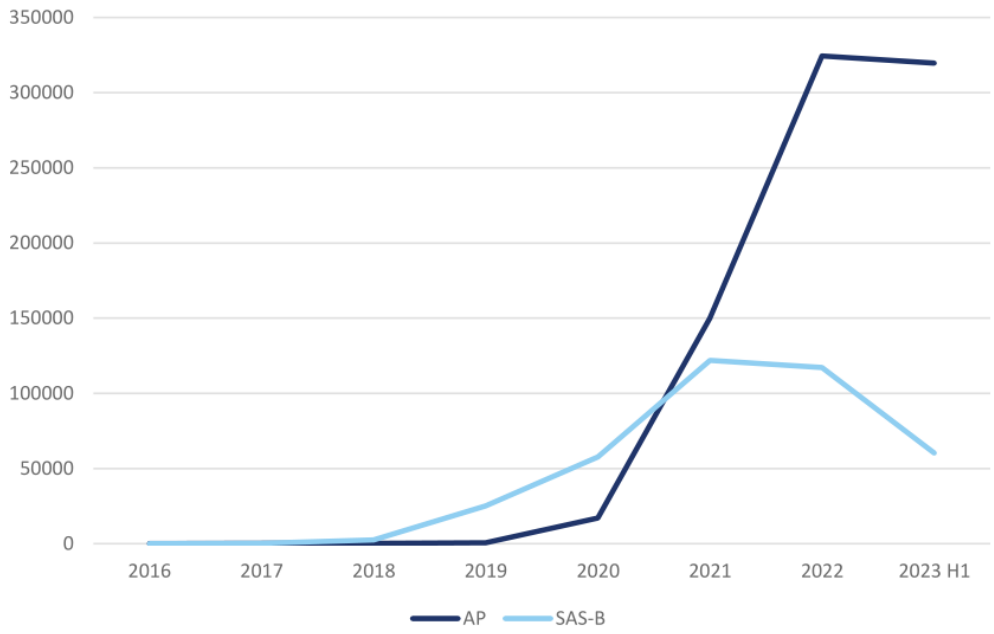

Figure 2. Number of approvals per year for medicinal cannabis prescriptions under two access pathways (Authorised Prescribers and Special Access Scheme) between 2016 and 2023 (Penington Institute 2023).

In the initial years of the medicinal cannabis scheme, oils were predominantly prescribed. Since 2021 however, the growth of the flower segment has been dominant, with flower sales making up approximately 70% of new products and patient reviews (Figure 3).

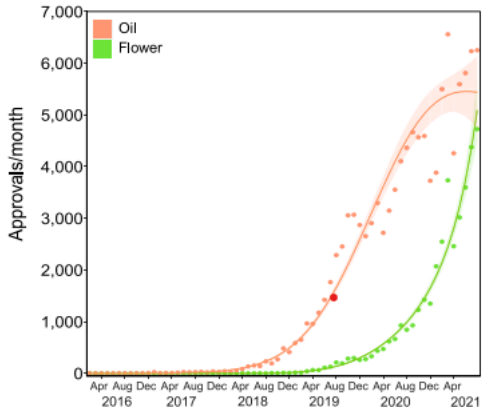

Figure 3. A breakdown of cannabis oil and flower prescription approvals per month in Australia. In 2021/2022, growth in flower prescriptions quickly outstripped those for oils (MacPhail et al., (2022))

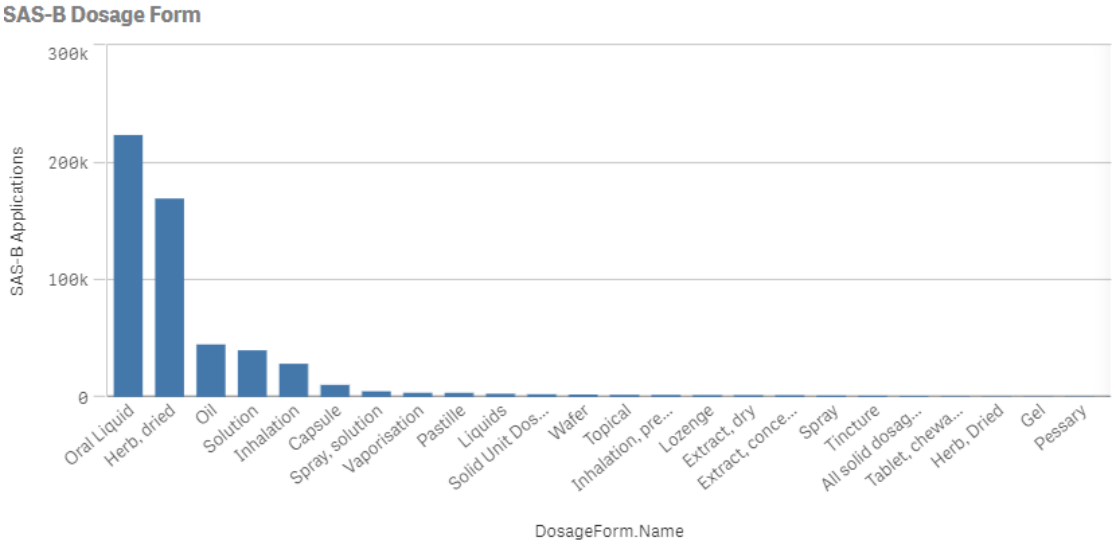

Figure 4. Current cumulative prescription formats from SAS-B applications (Therapeutic Goods Administration, 2024)

In mature markets, Flower is generally the dominant product format especially in the early stages of medicinal or adult-use schemes. This trend matches similar market trends in more developed international markets as discussed later in this report.

Local and imported production

Despite the rapid growth in patient numbers, local production has significantly lagged in demand, with imported products making up as much as 80% of the market in 2023 (Lane, 2023). Between 2017 and 2023, only 21 growing permits had been issued, and only up to 11 of these permitted entities were producing commercial quantities of dried cannabis flower (>100 kilograms (kg)).

In 2022, local cultivators produced approximately 24 tonnes of cannabis flower (Penington Institute, 2023), increasing to approximately 30 tonnes in 2024. This figure includes both high tetrahydrocannabinol (THC) and high cannabidiol (CBD) flower for extraction and dried flower consumption. The bulk of this local production came from a maximum of five producers, with roughly one-third to half being outdoor or low-tech protected cropping-grown, half being greenhouse-grown (medium to high-tech), and a minor amount being produced indoors. A further exploration of cultivation growing systems is provided in subsequent sections of this report.

Local cultivators face significant challenges, including high up-front license fees, long processing times (up to two years for each major step), costly product testing and compliance requirements, restricted market pathways, and convoluted regulations that do not always ensure high-quality or safe end-products.

Opportunities do exist to leverage Australia's favourable climate, skilled agricultural workforce, and technical expertise within the horticultural industry. Locally grown products may be viewed favourably by consumers from both quality and sustainability perspectives. However, the high regulatory and financial burdens present significant barriers to entry compared to the relatively easy and cheap importation of products.

Many companies in Australia struggle with the slow and convoluted licensing process required to commercialize Australian-grown products in a highly regulated pharmaceutical environment. Additionally, rapid price compression in the Australian retail market and broader economic conditions post-COVID have contributed to a reluctance to invest in cultivation infrastructure.

As the market matures, outdoor-grown options will likely decline slightly in percentage, while indoor-grown flower may increase, and greenhouse-grown flowers will continue to account for most of the capacity produced in Australia. If the legislative landscape eases barriers to entry for local cultivators, a shift towards more and possibly smaller farms may occur, as seen in parts of North America. However, the current high risk, expenditure, and time commitment to begin cultivating in Australia favour large companies aiming to scale production.

Despite challenges and barriers to entry, there are an increasing number of local cultivators of varying sizes entering the market; however, production is still significantly outpaced by an increasing number of imported products. Industry figures have called for more government support for the local industry (Jones, 2024b), though imports will likely always have a competitive advantage as long as the regulatory burden to enter the market remains high. For comparison, an importer can spend as little as approximately $20,000 in fees and charges over around 12 months to bring a product to the Australian market, while local cultivators typically spend years navigating the permitting process and potentially millions of dollars in expenditure before having a saleable product. Similar problems have emerged in other developing markets, such as Israel, where the government launched an anti-dumping probe into Canadian cannabis companies (Lamers, 2024, 2023a). Canada exported 59,986 kilograms of flower in the financial year from April 2022 to March 2023, with Australia importing 26,424 kilograms; 44% of that volume (Lamers, 2023a; Lane, 2023).

Cannabis cultivation in Australia does have potential competitive advantages, including favourable climates, a skilled horticultural workforce, and an advanced pharmaceutical manufacturing sector. However, the regulatory challenges for producers, combined with high wages and energy prices, will continue to make it difficult for a local industry to flourish under the current framework. By capitalising on these competitive advantages and learning from established legal cannabis markets overseas, the industry may avoid some of the major difficulties seen in overseas markets, such as massive overproduction, overinvestment in cultivation infrastructure, heavy taxes on cultivators, fragmented supply chains, and convoluted regulations. However, without easing regulatory burdens or encouraging local production through fiscal means, the risk profile of investing in local cultivation infrastructure will likely remain unattractive in the short term.

The cannabis plant

To understand the complexities around cultivating cannabis at a commercial scale, a solid foundation of the underlying physiochemistry, biochemistry, and taxonomy of the plant is essential for producers.

Botany and taxonomy

The commonly used nomenclature surrounding cannabis botany, varieties, effects, and uses can be somewhat misleading and departed from standard botanical practices. Amongst legacy market producers and recreational users, cannabis is usually loosely categorised into either 'sativa' or 'indica' type plants, with varieties or chemovars referred to as 'strains'. Flowers from indica labelled plants are generally expected by users to produce more calming or sedative effects, whilst sativa plants will produce more energising effects for the user. This classification system is often criticised by taxonomists and cultivators as misleading to consumers as some literature has shown there to be little evidence that indica/sativa labelling is genetically relevant. Further, no consistent regulation consists in terms of labelling and marketing, so many commercial strain labels do not consistently align with the chemical diversity of the product (Smith et al. 2022).

Most modern literature has come to settle on the monotypic model for cannabis classification, where all cannabis plants fall under the *Cannabis sativa* species, with subspecies being recognised as *Cannabis sativa* and *Cannabis indica* (Simiyu, Jang, and Lee 2022). This model is supported by DNA barcode analysis by McPartland (2018), who used barcode gaps to identify that *C. sativa* and *C. indica* should not be considered different species, and that the proper nomenclature is *C. sativa* subsp. *sativa* and *C. sativa* subsp. *indica*, as suggested by Small and Cronquist (1976). Hussain et al. (2021) summarised the modern approach to scientifically categorise cannabinoid-producing cannabis chemovars into distinct chemotypical groups. Drug-type cultivars with THC/CBD ratio ≥10 are classified as chemotype I, while those with THC/CBD ratio ranging from 0.2 to 10 are grouped as chemotype II. In contrast, fibre-type cultivars with THC/CBD ratio <0.2 are categorised as chemotype III (Hussain et al. 2021; Small and Beckstead 1973). Chemotype IV also has low THC contents but with the potent percentage of CBG. Chemotypes producing very little to almost zero cannabinoid compounds (neutral) are grouped as chemotype V, which are generally used for fibre, food, oil or seed production (hemp).

Despite this, even in the most mature markets the historical indica/sativa classification is preferred by most users and producers, and can be seen as a useful introduction to the diverse physiological and psychological effects that different cannabis flowers can produce for the end user.

For the purpose of this report and project, I have focused primarily on 'type I' plants, which contain THC as their major cannabinoid. Within the medical cannabis industry in Australia, and in most markets visited during this project, the indica and sativa

labelling and discussion continues to be commonly used, and so ingrained in the culture of cannabis consumers that it is unlikely to be replaced.

Cannabis trichomes

Cannabis trichomes are tiny, hair-like structures on the surface of cannabis plants, primarily found on the bracts of female flowers. These trichomes are crucial because they house most of the plant's secondary metabolites including cannabinoids, terpenes, and flavonoids. There are several types of trichomes but the most significant for cannabinoid production are the capitate stalked trichomes. These trichomes have a glandular head where cannabinoids and terpenes are produced and stored. The head contains secretory cells that synthesise these compounds, which are then secreted into a storage cavity within the trichome head, making them essential for the plant's therapeutic properties. This storage cavity is the ‘mushroom head’ shaped structure visible under magnification in a mature cannabis flower (Figure 5).

Figure 5. A close-up image of trichomes covering a female cannabis flower (source: Author)

Trichome development and morphology are influenced by various factors, including the plant's age and genotype. Research has shown that the density and type of trichomes can vary significantly depending on these factors. In high THC-containing capitate trichomes develop differently over the flowering period. Early in flower development, sessile capitate trichomes are more prevalent, but as the plant matures, there is a significant increase in stalked capitate trichomes. These trichomes not only

vary in number but also in their structural features such as stalk length and glandular head size, which can affect the overall cannabinoid content of the plant (Punja, Sutton, and Kim 2023).

The trichome structure can influence the suitability of a cultivar for dried flower production, where manual or automated postharvest activities may be more likely to damage long-stalked trichomes. Cultivars with easily separated and large trichome heads may be more suitable for value-added extraction like hash production where mechanical separation of trichome heads is the intended outcome. For outdoor and low-tech cultivation strategies, these genotypes are often sought after to streamline postharvest processing and increase the quality of extracts.

The primary function of trichomes is a defence mechanism for the plant through housing the array of secondary metabolites produced. The resinous nature of the trichomes makes them sticky, which can trap insects, while the phytochemicals, particularly terpenes, can act as insect repellents (Compton 2023; Punja, Sutton, and Kim 2023), or may provide some pathogen resistance (Toffolatti et al. 2021).

Cannabinoid biochemistry

Cannabis is a relatively unique horticultural crop in that the primary desired production is for the oils produced by the plant, but the end-product is typically the whole dried flower. Adding complexity to cultivation, the ‘bag appeal’ of flower is typically a major selling point, with trichome coverage, bud size, and colour development being key drivers of a flower’s saleability.

The primary compounds of interest for both therapeutic and recreational use are the cannabinoids, which are unique to the Cannabis plant and are most commonly delta-9-tetrahydrocannabinol (THC) and CBD, though over 100 unique cannabinoids exist, with some minor cannabinoids gaining popularity in modern cultivars (Small and Beckstead 1973; Specchio, Pietrafusa, and Cross 2020).

THC is the primary psychoactive compound in cannabis and is the most sought after cannabinoid. It acts on the endocannabinoid system in the human body, specifically the CB1 receptors, leading to feelings of euphoria and relaxation. CBD is non-psychoactive and has been studied for its potential therapeutic benefits, including treating anxiety, inflammation, and certain forms of epilepsy.

Cannabis biochemistry is a complex and rapidly evolving field, with ongoing research aimed at unlocking the full potential of the Cannabis plant and its various compounds for medicinal and recreational use.

Cannabis cultivation: approaches to cultivating at a commercial scale

Cultivation practices in the global cannabis industry vary substantially depending on the climate, legislative environment, the intended end-product, and the capital funding available to the producer. Techniques range from low-cost, low-input methods such as open field row cropping and micro-scale regenerative approaches, to ultra-high-tech greenhouses, fully sealed indoor facilities, and vertical farms with the ability to control every environmental variable through advanced sensors and active climate control.

This project examined the advantages, opportunities, and potential application of a range of cultivation methods and how they may be applied by Australian producers. One of the most important decisions a company must make when establishing a cultivation facility is what product they are aiming to produce. This will determine what cultivation strategy can work to produce the desired results at the chosen site and within the legislative framework available to them. Typically, the more controlled and input-intensive the cultivation operation, the higher quality the end-product, although this is also dependent on a large number of variables.

The following approaches to cultivating cannabis for medical or recreational purposes are the most common methods used to produce high-THC cannabis flowers.

Outdoor cultivation

Outdoor cultivation of cannabis is generally the lowest cost option for both capital and operating expenses for producers, but it often comes with the highest risk of crop loss and typically produces the lowest value dried biomass. Plants are grown using various techniques including in-ground planting, raised beds, or in pots placed directly on the ground, horticultural gutters, or on weed mat/compacted ground. The most common approach for outdoor flower production is row cropping, with plants spaced at 1 plant per 1-3 linear metres, and inter-row spacing varying between 1.5-3 metres in width.

Major risks involved with outdoor production include both abiotic and biotic stresses which can degrade the quality and yield of the flower produced or cause catastrophic crop failure in extreme circumstances. Due to the nature of the end-product; typically being heated and inhaled rather than orally ingested and lack of agronomic research in cannabis production, very few agrichemicals have been deemed safe for use on the crop. This limitation necessitates the use of integrated pest management (IPM) practices to maintain crop health and ensure consumer safety. Consequently, outdoor cannabis cultivators must be particularly vigilant in monitoring and managing environmental conditions and pest pressures to mitigate these risks effectively. For this reason, site selection is perhaps the most important factor in determining the suitability of an outdoor cannabis crop; locations with other intensive horticultural and agricultural operations in close proximity should be avoided, as the pest load in the environment will be too high.

Figure 6. Outdoor cannabis production in Australia (source: Author)

Site selection will also determine the suitability in terms of the environment for outdoor cannabis. Only specific environments are suitable for production at a commercial scale when the aim is to produce products suitable for sale as dried flower. Generally, only the highest quality outdoor-grown flower can be sold as a dried flower product, and the marketable yield of A-grade buds is low per area cultivated. Secondary dried flower products, such as pre-ground flower and pre-rolled joints, are common uses for good quality outdoor-grown cannabis flowers. In these products, visual quality is less of a concern, and minimal processing is required to obtain a profitable price.

For extraction-grade cannabis, biotic and abiotic stresses are less of a risk, but may still significantly impact the yield and quality of biomass produced. While extraction processes can mitigate the effects of minor quality issues, significant stress impacts can lead to lower biomass yield and reduced product quality.

The demand for outdoor-grown flower varies significantly between markets and should be a major consideration to cultivators. The capability of outdoor-grown flower to capture a subset of the market relies on a low production cost, the ability to value-add, and an attractive retail price. In markets where value-adding to these flowers is limited by regulations such as medical markets or where product formats like pre-rolls and edibles are more heavily taxed, outdoor cultivation may not be as viable. In well-developed retail markets where consumption of impulse-buy products such as pre-rolls and vape pens is high, outdoor-grown cannabis farms can be an attractive option for producers.

Hemp production

Broadacre outdoor cultivation, often referred to as hemp production, is a related but effectively separate industry to cannabis for medical or adult-use purposes, though the distinction is often not clear to consumers or regulators. Hemp varieties of cannabis are commonly produced for food or fibre purposes and as such typically do not contain significant amounts of active cannabinoids. Varieties grown for these purposes are taxonomically *Cannabis sativa*¸ but have been selectively bred for long fibrous stalks for fibre production, heavy seed production for oil extraction, or a combination of these traits for multi-use crops.

The production of hemp generally involves the cultivation of both male and female plants indiscriminately, so is incompatible with cannabis production in the same geographic region due to cannabis being a wind-pollinated plant. When a female cannabis plant intended for high cannabinoid flower production is pollinated, the plant will direct energy towards seed production, reducing the quality of the flower significantly. Conversely, when a female cannabis flower remains unpollinated, the size and potency can continue to increase significantly, in what is theorised to be an evolutionary adaptation to increase the chance of fertilisation in environments where pollen is scarce (Small and Naraine 2016). The risk of contamination from commercial hemp crops to a cannabis facility should always be considered by cultivators, as it may be a major source of crop loss. Some localities have implemented exclusion zones, where hemp crops cannot be planted within a certain distance of cannabis facilities. In regions where hemp and cannabis are both grown, cross-pollination of cannabis crops has led to an increasing number of legal disputes (Schaneman 2019). Generally, an exclusion zone of 5 km is thought to be sufficient to reduce the risk of pollination of cannabis crops by commercial hemp (Small and Antle 2003).

With the continued deregulation of cannabis cultivation and cannabinoid production, it is likely that almost all biomass for extraction purposes, especially for isolates and active pharmaceutical inputs (APIs) will be produced at a commercial, broadacre scale. This will most likely take place in equatorial geographic regions with favourable year-round growing conditions and cheap input costs, however, if the associated processing and extraction facilities exist, production in temperate areas is also possible. Biomass can be then quickly dried, and mass-extracted using ethanol or other solvents, and further processed to produce large amounts of distillates or isolates of the desired cannabinoids. This process is already becoming common in certain US states, particularly for CBD, and has resulted in the rapid reduction of the price of bulk cannabinoids.

Greenhouse and protected cultivation

Greenhouse and protected cropping approaches are the most common large scale approaches I observed across North American markets, particularly in southern states and historical production areas such as California and Oregon. Protected cropping offers cannabis cultivators greater control over environmental conditions compared to outdoor cultivation, but is generally more cost efficient than fully indoor options. By utilising structures such as greenhouses, hoop houses, and other controlled environment agriculture (CEA) systems, growers can manipulate light, temperature, humidity, and CO_2 levels to enhance plant growth and yield. These methods not only extend the growing season but also can reduce the risks associated with abiotic and biotic stresses, resulting in higher quality and more consistent cannabis products.

Low-tech protected cropping

Low-tech protected cropping systems, such as hoop houses, shade cloth structures, and simple greenhouses, provide an affordable way for cannabis cultivators to improve growing conditions and protect crops from environmental stressors. These systems offer basic protection against adverse weather, pests, and diseases while allowing for some control over temperature and humidity.

While low-tech protected cropping systems do not offer the same level of environmental control as higher-tech greenhouses, they can be a valuable tool for growers targeting low-cost markets. These systems can improve the yield and quality of cannabis crops with a relatively low investment, however can potentially exacerbate pest and pathogen problems in some scenarios. Without adequate IPM strategies, pest numbers in these environments can grow quickly to damaging levels, and inadequate airflow can quickly lead to pathogen pressure. Cultivators operating in low-tech protected enclosures should pay careful attention to not grow plants too dense or too large, have proper IPM strategies in place prior to cultivating, and select their cultivars carefully for pest and disease resistance.

Figure 7. A low-tech greenhouse in Israel (source: Author)

Low-tech options are a very common approach among non-licensed and small-scale growers in mature markets such as Northern California and Oregon, where a strong legacy market exists and unfavourable market conditions have led to many unlicensed producers. Cannabis produced in low-tech protected cropping environments can be of good quality; however, pesticide use is often high in these situations. For legal producers at a commercial scale, semi-protected and low-tech options can be challenging due to regulatory compliance and the need for more controlled environments to ensure product safety and consistency.

For potential Australian growers, low-tech protected cropping is a viable option for dried flower production, but producers should consider their site selection carefully and understand the risks involved in terms of abiotic stresses, pest and pathogen impact, and market dynamics. Flower produced in low-tech protected cropping environments will be prone to significant price compression in a maturing market. Maintaining low cost of goods sold (COGS) and not overextending production before establishing sales channels will be crucial for growers to be successful.

High and mid-tech greenhouse cultivation

High and mid-tech greenhouse cultivation is the most common option for large scale cultivation facilities, where the approach generally blends aspects of cannabis cultivation adopted from the traditional illicit industry with conventional horticultural techniques and technologies.

Figure 8. A high-tech traditional cannabis greenhouse in Australia (source: Author)

Traditional greenhouses can incorporate a wide range of technology, but typically rely on some combination of forced air ventilation, heat supplied from gas or wood boilers, air exchange and circulation fans, climate screens, high-pressure fog misters, dehumidifiers, and exogenous CO_2 supplementation to control the climate within the greenhouse. Structures are generally constructed with a steel frame and glass, polycarbonate, or plastic (polyethylene or ethylene tetrafluoroethylene in some cases) sheeting to allow light transmission.

Whilst not all greenhouses contain supplemental lighting, it is increasingly common and will significantly increase the yield and quality of crops produced. In most modern high-tech greenhouses, LED fixtures are installed with an output of up to 1200 µmol m^{-2} s^{-1} of photosynthetic photon flux density (PPFD) capacity, which, along with appropriate climate control, will increase the yield substantially. Collado et al. (2024) concluded that supplemental light of up to 700 µmol m^{-2} s^{-1} strongly enhanced photosynthesis and plant growth, increased biomass production, leaf area, and number of branches per square metre in a linear fashion. These results are common in high-tech greenhouses visited during this project, with growers often exceeding 500 grams of dried flower per square metre in good conditions.

One common challenge for cannabis producers was the design and operation of appropriate climate systems to match the increased photosynthetic production and water use of crops under these conditions. Even the best and cleanest greenhouse facilities still must manage pest and pathogen pressure, and abiotic stresses will still exist as the outside climate heavily impacts the conditions inside the greenhouse.

As well as this, the staffing required to maintain good quality cannabis crops in high-tech glasshouses greatly exceeds traditional horticultural crops, so facilities and staff transitioning from conventional horticulture should be well-equipped.

Figure 9. A large, mid-tech cannabis greenhouse in Canada (source: Author)

Figure 10. A high-tech greenhouse in Israel (source: Author)

Semi-closed greenhouse

The semi-closed greenhouse is the most advanced option in the greenhouse cultivation section and is an attractive solution for large scale producers. These structures are a modern evolution to greenhouse design which utilise a range of technology in order to increase the extent of climate control possible in a greenhouse with the aim of increasing production efficiencies. The concept was first developed in the early 1980s by engineer and greenhouse builder, Donald McNally (Timalsena 2013). The concept received no commercial uptake at the time due to perceived commercial feasibility, however, in the mid-2000s Houwelings Hothouse Group in North America, in collaboration with greenhouse construction company Kubo, developed a modified Dutch glasshouse design involving internal air circulation, dehumidification, and CO_2 enrichment, representing a major step forward in greenhouse environmental control (Timalsena 2013)

In a semi-closed greenhouse, the reliance on vents and passive climate control is reduced in favour of increased implementation of more advanced climate control systems like active mechanical dehumidification, cooling, heating, and air recirculation in an integrated design (Sapounas et al. 2020; Timalsena 2013). This can result in operational efficiencies through increasing yield, decreasing pest and pathogen pressure, and increasing the quality of plants grown in such a system. Combined with modern lighting systems, advanced sensors, and increasingly smart and reliable greenhouse control software, semi-closed greenhouses are becoming a more attractive solution to producing the highest quality of cannabis at scale. One key advantage is the ability to retain exogenous CO_2 inside the greenhouse whilst treating the existing air, rather than venting the atmosphere and reducing the CO_2 towards atmospheric levels. This can directly lead to significant yield increases, especially for resource-intensive and valuable crops such as cannabis.

Operational challenges in managing semi-closed greenhouses were similar to regular greenhouses, in that operating at the vast scale needed for production efficiencies often introduced an increased risk of pest and pathogen pressure, however generally the risk is reduced if managed correctly.

Other challenges and drawbacks associated with high-tech greenhouses mainly revolve around the scale required to maximize the operational efficiency of these technologies. There is often a higher level of automation in a high-tech greenhouse, which comes with significant capital expense and often requires a larger scale to be efficient. This scale of investment often presents significant downstream challenges in drying, processing, and marketing the volume of material produced.

This was a key factor in the rapid decline of many Canadian publicly listed companies, who collectively built enough high-tech greenhouse capacity to grow many times the market demand but struggled to manage the downstream processing, logistics, and supply chain. Examples of overinvestment include Aurora Cannabis, which had to halt operations at its Aurora Sun facility in Alberta, spanning over 15 hectares (ha), due to overcapacity and high operational costs. Similarly, CannTrust Holdings, The Green Organic Dutchman, Hexo, Sundial, and Tilray faced significant operational setbacks and eventually ceased operations in several facilities. These failures highlight the risk of overextending on cultivation capacity and infrastructure without a proper

assessment of the market and demand. Facilities of this size, with production capacities exceeding 100,000 kg per year in some cases, are rarely needed in any market. Deloitte, (2021) reported that capital expenditure in the Canadian industry between 2018 and 2021 was approximately CAD$28 billion, with the total cumulative sales to that point being $11 billion.

Despite scaling issues and overproduction being a commonly referenced cautionary tale in cannabis for high-tech glasshouses, cases of semi-closed greenhouses successfully producing high-quality cannabis at scale are becoming increasingly common and make up a large proportion of new projects, however, a more appropriate scale of 0.25 – 2 ha designed in a modular fashion for expansion is a more sustainable approach.

During this project, I visited semi-closed operations in Canada, Portugal, and Germany, where the cannabis being produced was of equal quality to advanced indoor operations, but at a significantly reduced cost and with more capability to scale efficiently. This, combined with a reduced carbon footprint and greater scalability of the technology involved, makes semi-closed greenhouses a leading option for cultivating cannabis at scale in Australia.

Figure 11. A semi-closed cannabis greenhouse in Europe (source: Author)

Indoor cultivation

Indoor cultivation of cannabis is generally performed in highly controlled environments where all environmental parameters have the potential to be fully monitored, controlled, and automated, and all necessary plant nutrient requirements can be provided in a precise manner. Indoor cultivation facilities usually have the highest cost of production due to the necessity of providing high levels of light, constant environmental treatment including dehumidification, humidification, heating, cooling, air filtration, and supplemental CO_2 to optimal levels rarely achievable in other environments. Generally, labour and electricity make up most of an indoor facility's cost base, and large indoor facilities usually have by far the highest capital cost to construct of any cultivation method.

The high levels of environmental control possible can more reliably produce very high-quality flower which will usually attract a higher price point, however, the economic damage of crop failure or operational inefficiencies are amplified. The most successful indoor facilities I visited during this project were small and modular, targeting boutique, high-end cannabis which makes up a small percentage of the total market in most areas.

Figure 12. High tech, double-tiered indoor facilities in USA (source: Author)

While indoor cultivation facilities can more reliably produce high-quality flower, scaling these facilities is often difficult and risky due to the high capital expenditures for advanced heating, ventilation and air conditioning systems (HVAC), lighting, and automation technologies. The importance of site selection is still vital, as areas with access to renewable energy sources or favourable energy tariffs can significantly lower the cost of electricity, which is one of the largest expenses in indoor cultivation. Cultivators in these regions can potentially leverage competitive advantages to produce premium products at a cheaper price point, so this should be a key consideration for Australian cultivators entering this space. Typically, an indoor facility should aim to access or generate power production for $0.10 - $0.15 per Kilowatt hour in order to produce flower for an acceptable cost.

Figure 13. Various Indoor cannabis production facilities in Canada, (source: Author)

Indoor farming of cannabis, and in general, does come under scrutiny from an environmental perspective due to the high energy demand required to produce crops. Stanghellini and Katzin (2023) calculated that for the same yield of plants produced, an indoor farm uses twice the energy of a high-tech greenhouse and over 100 times that of open-field production. In California, indoor cannabis production is estimated to use 3% of the state's total electricity (Mills 2012; Yip 2020). Summers, Sproul, and Quinn (2021) calculated that indoor production of cannabis in the United States was responsible for between 2,283 to 5,184 kilograms of CO_2-equivalent per kg of dried flower grown

The high energy requirements of indoor-grown cannabis, often generated from non-renewable sources, may be a challenge for indoor producers if consumers and value chains in general focus on more sustainably grown products. Most existing markets seem to have escaped large levels of scrutiny of the sustainability of cultivation practices, though I did observe a significant number of environmentally grown products gaining popularity in parts of Oregon and California specifically. This may also be an opportunity for indoor farms that utilise renewable energy for production to leverage this for marketing opportunities.

While indoor cultivation of cannabis can be capital-intensive and presents scaling challenges, it offers the highest level of control over the growing environment, usually resulting in superior product quality and reduced risk of crop failure. By leveraging geographic advantages and adopting energy-efficient technologies, cultivators can mitigate some of the high costs associated with indoor production. As the cannabis market continues to evolve, the ability to produce high-quality, consistent products will remain a key differentiator for successful cultivators in both developed and developing markets. Indoor-grown cannabis may be more resistant to price compression in the higher end of the market, though this is likely to still be a competitive environment as the market matures.

Postharvest cannabis processing

Like many horticultural products, the postharvest handling of cannabis is crucial to the overall yield, quality, consistency, and saleability of the final product. Once the plant is harvested, the quality of the product can no longer be improved; it can only be maintained or degraded through the subsequent handling processes. Best practices in postharvest handling vary widely, and scaling these processes efficiently poses challenges due to the high manual handling requirements, the fragile nature of the product, and the expensive capital costs associated with well designed and implemented postharvest equipment.

Postharvest handling of cannabis is an area that is not well-researched at an academic level, though a range of drying, curing, and manicuring techniques and technologies have been developed from the legacy market. Equipment and techniques have improved with deregulation which are continually improving the capability of producers to scale efficiently whilst maintaining the quality of flower, though this is often the most significant challenge for a producer.

Drying

Drying is the first critical step in postharvest processing. Generally, cannabis is dried slowly to preserve its terpene profile and cannabinoid content as well as continue to enable enzymatic degradation of chlorophyll. Most small and medium scale facilities dry plants by hanging or placing them on ventilated trays in a controlled-environment room at 15-21°C with a humidity level of 45-55%. This process usually takes 7-14 days, depending on the environmental conditions and the density of the flower.

Figure 14. Cannabis drying facilities in Europe, (source: Author)

Variations of this technique are common, and several emerging technologies have been applied including vacuum freeze drying, oven drying, microwave-assisted hot air drying, and microwave-assisted freeze drying.

Further research is needed to assess the suitability of such technologies in commercial environments, though Al Ubeed, Wills, and Chandrapala (2022) suggested that advancements with these technologies may improve the quality and safety of cannabis drying, and that vacuum freeze-drying is the best method to retain the phytochemical profile of cannabis flowers. Spadafora et al., (2024) reported that freeze-drying was useful at preserving cannabinoids, but may reduce other volatile compounds, and recommended tray drying followed by storage in glass rather than high-density polyethylene for retention of aroma. Most producers visited in this project considered hang-drying as a best management practice for consistency and quality, but it was common to observe large scale facilities facing challenges achieving this at scale.

Figure 15. Cannabis can be bucked prior to or after drying (source: Author)

Curing

Curing follows the drying process and is thought to enhance the quality of the final product. During curing, the dried cannabis is stored in airtight containers and kept in a controlled environment to further develop its secondary metabolite profile which contributes to the aroma and flavour, while breaking down undesirable compounds like chlorophyll. This process can take several weeks to several months. At large scale and particularly Good Manufacturing Practice (GMP) certified facilities, curing is not always undertaken, as qualification of the parameters can be problematic and storage and maintenance of large quantities can be resource intensive.

Trimming and Manicuring

After curing, the cannabis is trimmed and manicured to remove excess leaves and stems, enhancing the aesthetic appeal and quality of the product. This step can be performed manually or with the help of automated trimming machines. Manual trimming is labour intensive but can result in a higher quality product, whereas automated trimming is more efficient and cost-effective. Most large scale facilities in Europe and Canada utilise some combination of automatic and manual trimming, whilst in the USA it is more common to utilise very cheap labour to manually trim.

Packaging and Storage

Finally, the dried, cured, and trimmed cannabis is packaged and stored. Proper packaging protects the product from light, air, and moisture, which can degrade its quality over time. Many cultivators use vacuum-sealed or nitrogen-filled packaging to extend the shelf life of their products. Additionally, cannabis should be stored in a cool, dark place to maintain its potency and freshness.

Figure 16. Cannabis bulk storage in an indoor farm in Canada (source: Author)

Summary of cultivation approaches

While there is no single best approach to cannabis cultivation, certain techniques are more suited to producing high-quality flower versus extraction-grade biomass with a range of options possible depending on the target market. Cultivators should define their desired end-product, price point, and develop a clear strategy for achieving that product when designing a cultivation facility. It is common, particularly in newly legalised markets, for producers to over-extend on cultivation infrastructure or target a particular market segment without controlling expenditure. In many cases, producers invest heavily in large scale, high-tech facilities without fully understanding the market dynamics or their target consumers.

A lack of strategic planning, combined with poorly legislated or open-license markets without a staged approach to building capacity, has resulted in massive boom and bust cycles. The Canadian market from 2017 to 2024 is a prime example, where rapid expansion led to oversupply and subsequent market crashes. Similar patterns have been observed in multiple states in the USA, where initial enthusiasm and investment gave way to market corrections and consolidations.

The most successful cultivation companies typically have taken a staged approach, employing staff with strong backgrounds in commercial plant production as well as knowledge of cannabis market trends. The most important factors in designing a cultivation facility include site selection, cultivar selection, and understanding the target product to be produced.

For Australian producers, it is reasonable to expect cultivation trends to closely follow those in North America. Heavy market compression and competition will put inefficient operations at a disadvantage, while producers who can successfully lower costs ahead of their competition and still produce high-quality flower will be most successful. Price and THC percentage will likely be the primary drivers of most sales, with consumers having little brand loyalty for most of the market. High-quality craft-grade products may be less susceptible to price compression, but competition in this segment is still likely to be strong.

Most production will likely occur in mid to high-tech greenhouses 0.2-2 ha in size, and small, modular indoor farms that can scale as demand grows. Outdoor production and low-tech protected cropping options are viable for a target market segment but must be well designed and scaled sustainably with a focus on value-adding products and efficient use of resources to produce budget-friendly products.

What could the future of the Australian cannabis landscape look like?

With the continued expansion of the cannabis industry both in Australia and overseas, it seems that the further deregulation of cannabis is likely. The form and timeline that this takes will shape the future of the industry and the capacity for local producers to enter the market. Part of this project aimed to examine how the Australian cannabis industry, including market size, regulation, and consumer trends, may develop over the next decade.

Prohibition of cannabis has been a failure

A report from the Penington Institute (2023) highlights the significant financial burden of cannabis prohibition in Australia. In the 2015-16 period, over $1.7 billion was spent on enforcement efforts, including $1.1 billion on imprisonment, $475 million on policing, $62 million on courts, $52 million on legal aid and prosecution, and $25 million on community corrections. The report suggests that decriminalising cannabis could save taxpayers up to $850 million each year. Legalisation could result in even greater savings, potentially more than $1.2 billion annually, combined with the potential tax benefits and job creation.

Cannabis use is widespread in Australia, with over a third of Australians over the age of 14 (37% or 7.6 million people) having tried it at least once. In 2019, around 2.4 million Australians used cannabis, reflecting global usage by approximately 200 million people. Additionally, over the past 12 years, there have been 700,000 cannabis-related arrests in Australia, with more than 90% of these being for personal use or possession (Australian Institute of Health and Welfare 2024).

What happens to medical cannabis if Australia shifts to adult-use?

In Canada, the number of active registered medicinal cannabis patients dropped significantly after 2018, when adult-use cannabis became available. In October 2018, there were 345,520 active registrations, whilst in March 2023, this number had dropped to 212,700 (Lamers 2023). This drop is likely due to the ease of access and low prices of adult-use cannabis in Canada post-deregulation.

In existing North American markets that have shifted from medicinal to adult-use, the time frame averages eight years between the two, as shown in Figure 17, (New Frontier Data 2023). This transition has also generally led to the contraction of medicinal schemes with a large boom in adult-use production. In Michigan, where recreational sales began in late 2019, the value of medicinal sales has steadily declined whereas adult use sales exceeded US$3 billion in 2023 and more than $300 m per month in early 2024 (Figure 18).

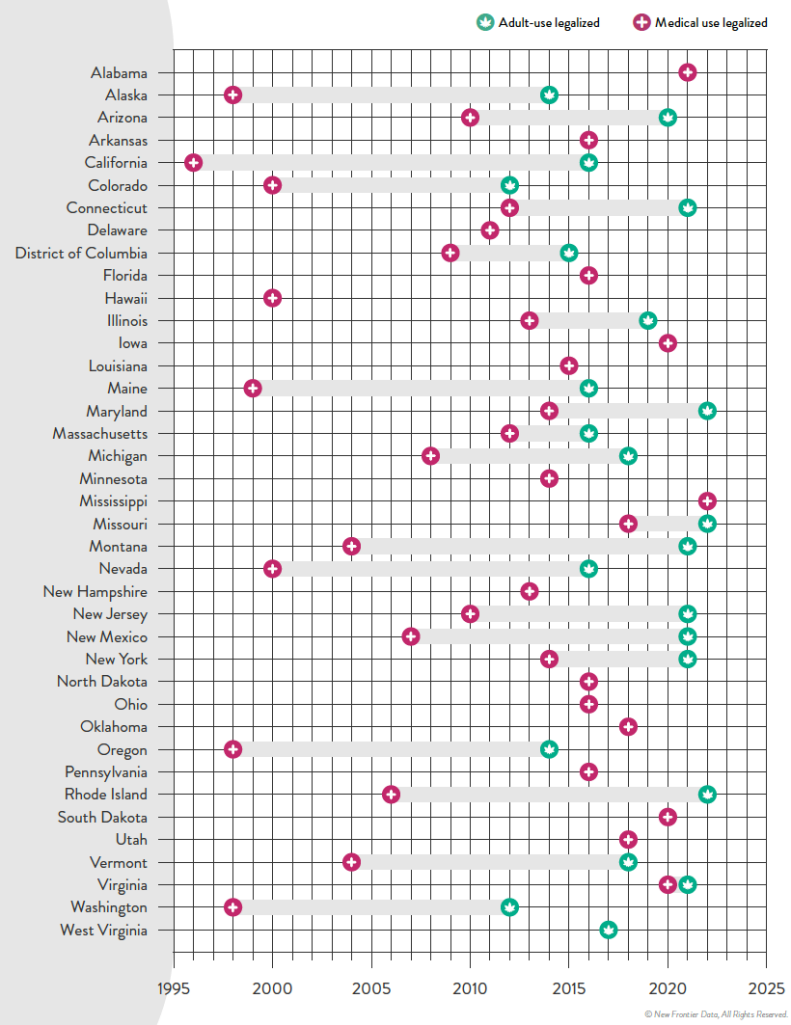

Figure 17. The average timeframe between medical-use and adult-use legislation in American states (New Frontier Data, 2023).

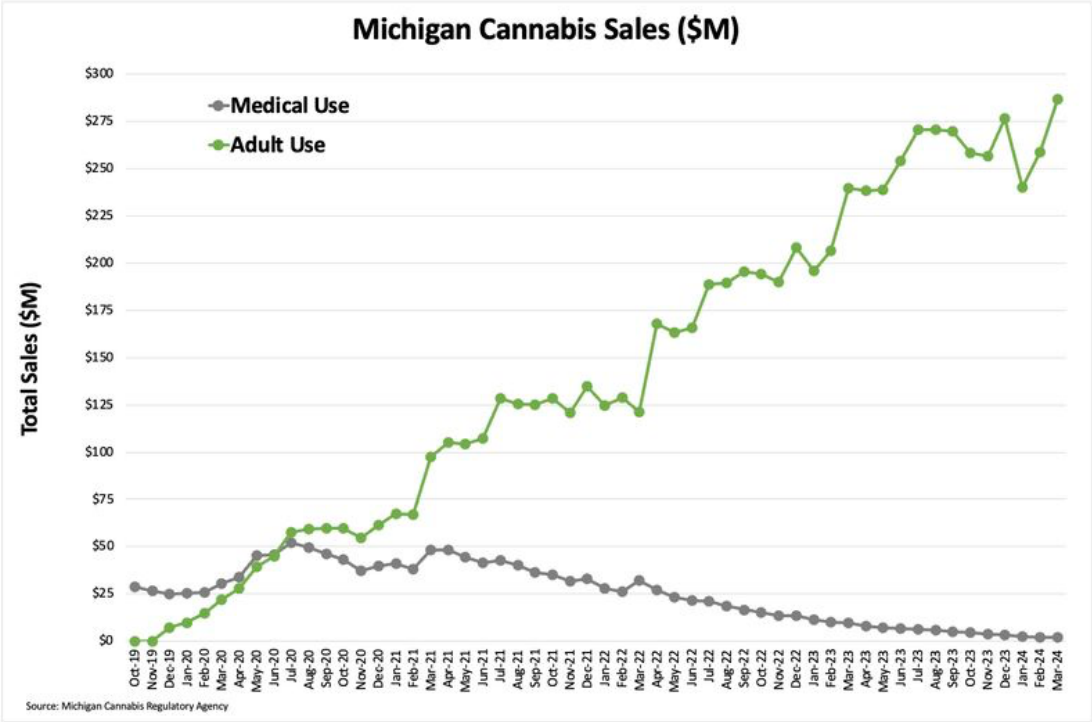

Figure 18. Michigan total monthly adult use and medical use cannabis sales (New Frontier Data, 2023)

Market size

The future of cannabis in Australia is an industry with massive growth potential, though the extent of expansion within the industry will be largely governed by the regulatory environment set by the government. Estimates of the potential size and value of the cannabis industry in Australia vary, with multiple bodies having modelled a series of possible scenarios.

MTP Connect (2021) estimated that by 2030, demand for medicinal cannabis in Australia will be around 80,000 kg of dried plant matter under current baseline demand projections, but noted, that several demand uplift scenarios exist. These included subsidisation, pharmaceutical benefit scheme (PBS) listings, an increased willingness to prescribe, and increased production efficiencies. The study estimated that under the most optimistic demand uplift scenarios the demand for medical cannabis in Australia could approach 150,000 kg by 2030.

In early 2023, The Australian Greens developed a proposed plan to legalise cannabis at the federal level. The party claimed to have compelling constitutional law advice that recommended a mechanism for federal legalisation of adult-use cannabis at a national level (Shoebridge 2023). The proposal cited advice from constitutional law Professor Patrick Keyzer, that the federal government could utilise one of several constitutional mechanisms surrounding the government's capability to regulate plant variety rights, to allow for legal cultivation at a national level.

The Greens use the modelling cited in this report to suggest that the legalisation of cannabis could generate $1.9 billion in tax revenue in its first year and up to $3 billion in its ninth year at a 15% excise, or $2.7 billion and $3.8 billion at these times respectively with a 25% excise, as illustrated in Tables 2 and 3, putting a total retail value at up to $16 billion annually.

Table 2. Estimates of tax revenue from the Parliamentary Budget Office of a regulated adult-use cannabis market in Australia with a 15% excise (Shoebridge 2023)

	2022-23	2023-24	2024-25	2025-26	2026-27	2027-28	2028-29	2029-30	2030-31	2031-32	2032-33	Total to 2025-26	Total to 2032-33
Revenue													
Tax revenue													
Administered tax													
Cannabis excise	-	-	*1,150.0*	*1,310.0*	*1,460.0*	*1,580.0*	*1,670.0*	*1,550.0*	*1,480.0*	*1,350.0*	*1,270.0*	***2,460.0***	***12,820.0***
GST	-	-	*710.0*	*780.0*	*870.0*	*930.0*	*1,020.0*	*940.0*	*910.0*	*820.0*	*790.0*	***1,490.0***	***7,770.0***
Company tax	-	-	-	*810.0*	*910.0*	*990.0*	*1,050.0*	*1,100.0*	*1,010.0*	*930.0*	*860.0*	***810.0***	***7,660.0***
Total – administered tax	-	-	***1,860.0***	***2,900.0***	***3,240.0***	***3,500.0***	***3,740.0***	***3,590.0***	***3,400.0***	***3,100.0***	***2,920.0***	***4,760.0***	***28,250.0***
Total – tax revenue	-	-	**1,860.0**	**2,900.0**	**3,240.0**	**3,500.0**	**3,740.0**	**3,590.0**	**3,400.0**	**3,100.0**	**2,920.0**	**4,760.0**	**28,250.0**
Non – tax revenue													
Administered non-tax													
Cannabis licence fees	-	*19.9*	*15.1*	*15.2*	*15.3*	*15.4*	*15.5*	*15.7*	*15.8*	*15.9*	*16.0*	***50.2***	***159.8***
Total – administered non-tax	-	***19.9***	***15.1***	***15.2***	***15.3***	***15.4***	***15.5***	***15.7***	***15.8***	***15.9***	***16.0***	***50.2***	***159.8***
Total – non-tax revenue	-	***19.9***	***15.1***	***15.2***	***15.3***	***15.4***	***15.5***	***15.7***	***15.8***	***15.9***	***16.0***	***50.2***	***159.8***

Table 3. Estimates of tax revenue from the Parliamentary Budget Office of a regulated adult-use cannabis market in Australia with a 25% excise (Shoebridge 2023)

	2022-23	2023-24	2024-25	2025-26	2026-27	2027-28	2028-29	2029-30	2030-31	2031-32	2032-33	Total to 2025-26	Total to 2032-33
Revenue													
Tax revenue													
Administered tax													
Cannabis excise	-	-	*1,940.0*	*2,190.0*	*2,400.0*	*2,600.0*	*2,750.0*	*2,610.0*	*2,460.0*	*2,290.0*	*2,170.0*	***4,130.0***	***21,410.0***
GST	-	-	*710.0*	*780.0*	*870.0*	*930.0*	*1,020.0*	*940.0*	*910.0*	*820.0*	*780.0*	***1,490.0***	***7,760.0***
Company tax	-	-	-	*810.0*	*910.0*	*990.0*	*1,050.0*	*1,100.0*	*1,010.0*	*930.0*	*860.0*	***810.0***	***7,660.0***
Total – administered tax	-	-	***2,650.0***	***3,780.0***	***4,180.0***	***4,520.0***	***4,820.0***	***4,650.0***	***4,380.0***	***4,040.0***	***3,810.0***	***6,430.0***	***36,830.0***
Total – tax revenue	-	-	**2,650.0**	**3,780.0**	**4,180.0**	**4,520.0**	**4,820.0**	**4,650.0**	**4,380.0**	**4,040.0**	**3,810.0**	**6,430.0**	**36,830.0**
Non – tax revenue													
Administered non-tax													
Cannabis licence fees	-	*19.9*	*15.1*	*15.2*	*15.3*	*15.4*	*15.5*	*15.7*	*15.8*	*15.9*	*16.0*	***50.2***	***159.8***
Total – administered non-tax	-	***19.9***	***15.1***	***15.2***	***15.3***	***15.4***	***15.5***	***15.7***	***15.8***	***15.9***	***16.0***	***50.2***	***159.8***
Total – non-tax revenue	-	***19.9***	***15.1***	***15.2***	***15.3***	***15.4***	***15.5***	***15.7***	***15.8***	***15.9***	***16.0***	***50.2***	***159.8***

Other commentators have suggested that these figures may overestimate the size of the potential industry. Rose and Williams (2024) suggest that, based on estimates using the National Drug Strategy Household Survey, a legal, regulated market in Australia would consume 441 tonnes per year for a valuation of approximately $6 billion annually (Figure 19).

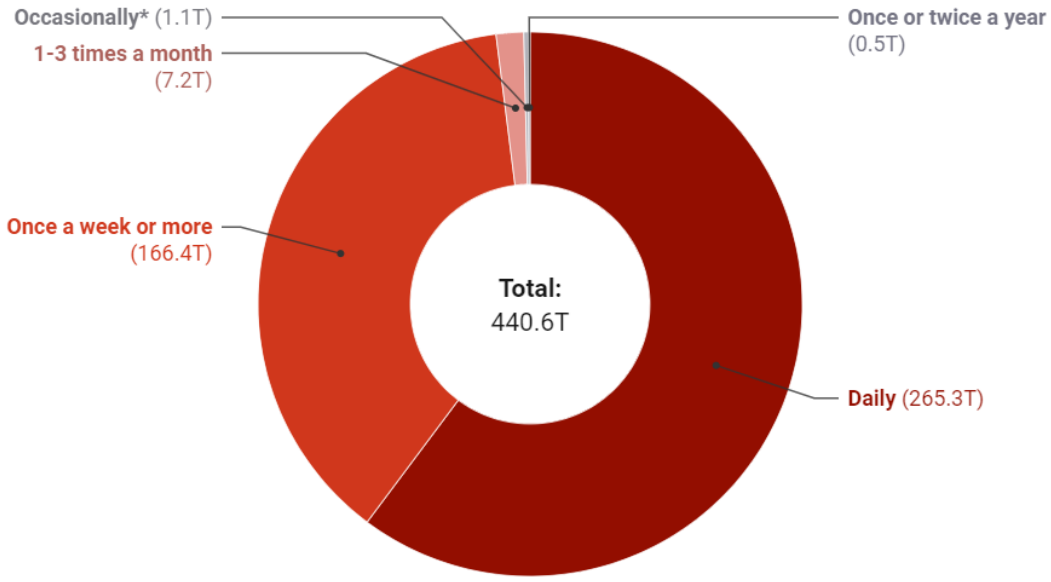

Figure 19. Estimated potential value of a legal cannabis market based on usage data from the National Drug Household Survey (Rose and Williams, (2024))

Whilst estimates of the future size of the industry vary significantly, most experts agree that the current period of rapid growth will continue for the remainder of this decade at least. The most conservative estimates predict a tripling of the 2022 industry by 2030, and the most optimistic predicting up to a 100-fold increase in a legalisation scenario.

Whichever path and timeline eventuate for the development of the cannabis industry in Australia, an opportunity exists for regulators and producers to learn from the experiences of overseas industries, and to develop a robust and efficient industry in which producers can leverage their competitive advantages over imported products.

Perhaps the most important lessons exist around the regulatory framework and commercial something. The successes seen from North American markets include the rapid expansion of a federally regulated model and relatively robust quality standards developed in Canada in a short space of time. Canadians have access to safe, high-quality cannabis from over 3,000 retail locations across all provinces in the country. The legal market is slowly eroding the illicit industry, contributing to reducing organised crime and unsafe product, whilst providing significant amounts of tax revenue. Despite the successes, the market is highly fragmented and massively over-supplied which has led to high levels of inventory destruction and poor commercial environments. The tax burden on legal producers has been labelled as excessive, causing an uncompetitive environment for competition with illicit products and stifling industry growth (Karadeglija 2023).

Market trends

Analysis of current and future trends is essential for producers to guide cultivation strategies and gain competitive advantage as the industry expands. The most established markets in North America frequently collect and publish detailed consumption data, which can be reviewed to assess what products, pricing, and consumer trends will drive demand as the Australian industry matures.

Some of the most complete and detailed data of a well-developed industry come from The Ontario Cannabis Store (OCS). The OCS is the sole legal online retailer of recreational cannabis in Ontario, Canada. In terms of product categories, dried flower has been the dominant seller for the duration of the Canadian adult-use scheme, followed by pre-rolls, vapes, concentrates and novel formulations in order of sales value. Milled flower represents a significant subset of this, and single-strain pre-rolls are the preferred form of pre-rolls, as illustrated in Figure 20.

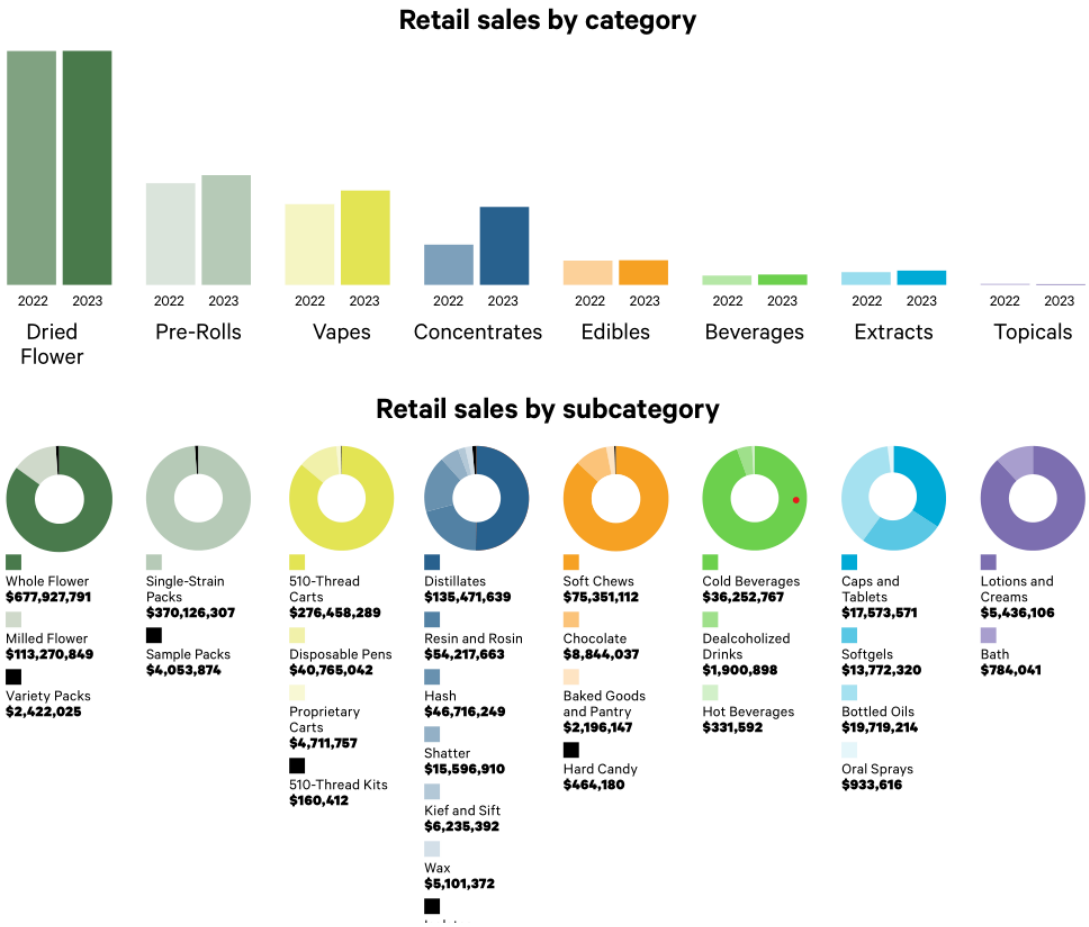

Figure 20. The value of product categories and subcategories sold in the OCS in 2022 and 2023 (The Ontario Cannabis Store, 2023).

In terms of price point and types of cannabis sold, value and mid-tier cannabis products have shown to be the most sold category in Ontario, with three of the five most popular brands being value choices in the dried flower category (Figure 21).

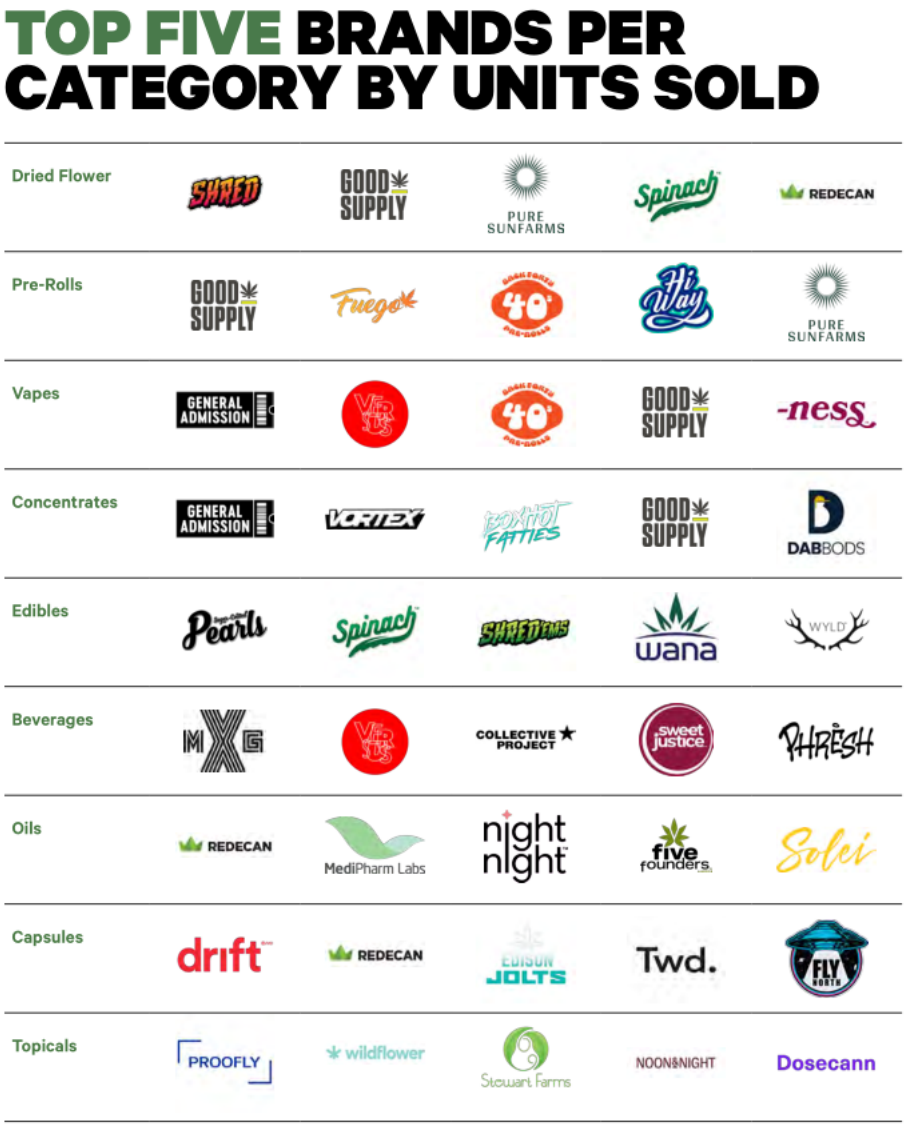

Figure 21. Top brands per category sold by the OCS in 2023. Value-oriented brands dominate the flower and pre-roll markets (The Ontario Cannabis Store, 2023)

On average, the wholesale price of dried flower sold was CAD$4.05 across all product sizes. The OCS (2021) does note that consumers prefer quality, closely followed by potency and price when purchasing cannabis products, and that products which are able to meet satisfactory quality and offer value for money are the leading categories. The OCS (2023),reported that the fastest-growing product categories were edibles and beverages, which consumers reported as convenient and appealing to both new and experienced users.

The cannabis data company Headset (2022) provided an analysis of market trends in the US and Canada. The report found that in the first six months of 2022, flower made up just over 40% of sales by value, but that the pre-roll segment had grown to be the second largest product category across Canada and the third largest in the US. Vape pens were the second largest category reported in the US and the third largest in Canada, with concentrates and edibles being the other major categories by value.

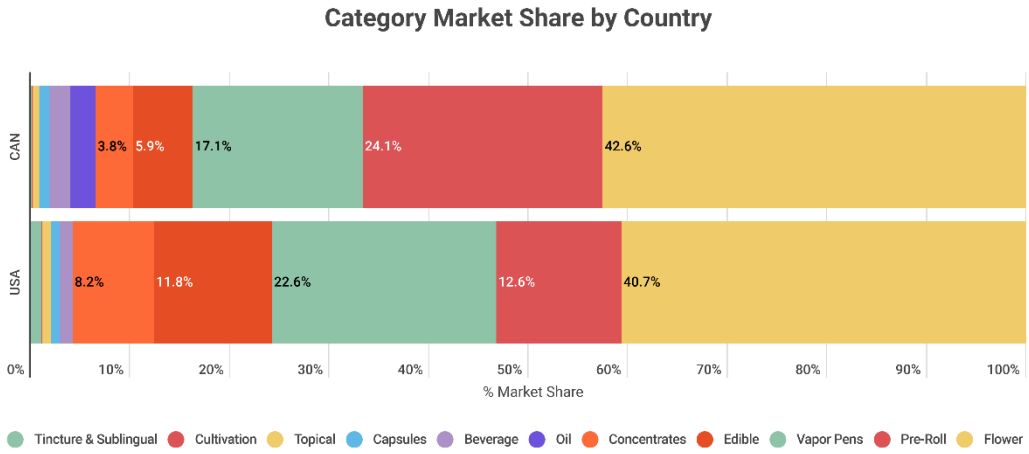

Figure 22. Analysis of market categories across the U.S and Canada in 2022 (Headset, 2022)

In Australia, the categories of pre-rolls, edibles, and concentrates are almost non-existent currently, primarily due to the market being a medical scheme. Vape carts have entered the market in recent years but still make up a minor component compared to overseas markets. It is expected that any further deregulation will result in a significant upshift in the market share of these and other formats, and a reduction in the share of oil and flower within the total market.

These trends may be used to guide cultivation and manufacturing decisions for Australian companies. The secondary processing and value-adding product segments likely present significant opportunities in the event of deregulation, while the market for oil may retract. Dried flower has proven to consistently make up a significant, if not majority, share in all cannabis markets, with sales data indicating that customers prefer a balance between quality, potency, and value. As markets have progressed from medicinal to adult-use, the total share of flower falls, and easy-to-use products such as pre-rolls, pre-ground flower, vape pens, edibles, and beverages increases.

It should be noted that in a North American, dispensary-type scenario, where consumers have the option to enter physical shopfronts, budget options, pre-rolls, and vape pens are often impulse buys. Any legislative framework surrounding packaging, advertising, and retailing of cannabis in an adult-use scenario may heavily affect the consumer trends that appear.

Cultivation framework

To promote the further development of the Australian cannabis cultivation industry, a well thought-out and robust framework to support local cultivators is necessary. Currently, there is no comprehensive quality standard in Australia that governs the production of cannabis from cultivation through to postharvest and packaging activities. Good Agricultural and Collection Practices (GACP) are loosely referred to as production standards pre-harvest, and Good Manufacturing Practices (GMP) must be followed at an undefined stage postharvest, however, GMP is generally only applied from packaging onwards and it is questionable what the application of a standard in the last step of a production process does to ensure quality.

In 2003, the World Health Organisation published *Guidelines on Good Agricultural and Collection Practices (GACP) for Medicinal Plants* to provide a framework to ensure the safe and appropriate cultivation and collection of plants for medicinal purposes. It is unclear when this document began to be referred to as a relevant framework for cannabis producers, but it is often cited within the medicinal cannabis industry, particularly in new and emerging markets, as a standard for cultivators to follow. While the guidelines provide some fundamental principles suitable for the production of medicinal plants, they are largely inadequate as a comprehensive framework for modern medicinal cannabis production facilities.

Despite the shortcomings of this document, limited efforts have been made in emerging markets to develop an appropriate alternative, with effectively no industry or government-led best management practice or regulatory framework existing in Australia.

In terms of more appropriate guidelines, regulations, standards, or frameworks for cannabis cultivators, very little high-quality work exists. Canada, upon legalising in 2017, developed the Good Production Practices Guide for Cannabis (GPP), which includes:

- Microbial limits: establishing acceptable levels of microbial contamination to ensure product safety.
- Cultivation techniques: outlining best practices for growing cannabis to maximise yield and quality while minimising environmental impact.
- Best Management Practices: providing a comprehensive set of guidelines to ensure consistency and quality in cannabis production.
- Regulation: Health Canada regularly inspects and audits producers to ensure compliance with GPP standards.

GPP has been regularly criticised by producers as being costly to comply with, complex to navigate for new entrants to the market, and prone to inconsistencies in reported cannabinoid concentrations on products (Pusiak, Cox, and Harris 2021).

In comparison, Australia’s current medical scheme has the lowest threshold for microbial load in the world, which essentially mandates microbial remediation in the form of irradiation treatments. Aside from this and basic pesticide and heavy metal

testing, no real quality framework exists to guide or govern the practices undertaken by local producers.

For the local industry to develop, an appropriate framework of regulatory standards or best management practices should be created for cultivators to achieve consistent, reproducible, safe, and high-quality cannabis products without being overly burdensome for day-to-day production. While the GACP may provide a basic starting point, the framework should ultimately be industry-led in development, suitable for all modern cannabis facilities, easy to understand, and preferably cover as much of the post-harvest process as possible. The development of any framework should be based on sound horticultural principles and tailored to the specific needs of the Australian market, rather than simply adopting information from overseas jurisdictions.

Conclusions

The Australian cannabis industry is one of the fastest-growing sectors of horticulture in Australia, with rapid expansion expected to continue over the next decade due to ongoing deregulation, destigmatisation, potential legalisation, and growing acceptance of cannabis use for medicinal and adult-use purposes. This trend mirrors international developments where cannabis markets have matured and expanded significantly.

Opportunities for producers are substantial, yet due to the high market value of cannabis, the local demand can be comfortably met by a relatively small area of land and a limited number of producers. The popularity of cannabis cultivation and the perceived lucrativeness of the industry mean that overproduction is a highly likely scenario as the industry matures. This may lead to commoditisation, resulting in price declines and industry consolidation, as observed in most mature or maturing cannabis markets globally. In such a scenario, producers who focus on innovation, quality, and supplying in-demand products at competitive prices will ultimately be the most successful.

The design and implementation of taxation in a legal cannabis market are critical lessons for emerging industries, including Australia. While the economic benefits of high tax revenue are attractive to governments, it is essential to balance the tax burden to support industry growth. In Canada and parts of the US, up to 50% of the price per gram of legally produced cannabis flower is tax, which often makes legal production uncompetitive with black market products and can encourage diversion to the illicit market. Therefore, a balanced approach to taxation is crucial to fostering a competitive and sustainable legal cannabis market.

Lessons from more mature global markets offer valuable insights for producers, manufacturers, investors, and regulators. By learning from the experiences in countries like Canada and states in the US, stakeholders in the Australian cannabis industry can navigate potential pitfalls such as overproduction, excessive taxation, and leverage opportunities for innovation and growth.

Cultivation trends in Australia are likely to follow those already seen in North America, particularly as the industry matures. For producers, success will hinge on making strategic decisions around site selection, cultivar choice, and clearly defining the target product and market segment. Those who can drive down production costs without compromising flower quality will be best positioned to compete. This often requires a staged development approach and expertise in commercial plant production as well as consumer packaged goods.

In conclusion, the Australian cannabis industry is poised for significant growth, though balancing regulatory and economic factors to create a sustainable and competitive market will be challenging. With careful planning and adaptation of best practices from international markets, Australia can establish a thriving cannabis industry that benefits producers, consumers, and the broader economy.

Key findings and recommendations

The Australian cannabis industry will continue to see rapid growth over the next decade. The extent and direction of this growth will be largely dictated by the legislative framework that determines the processfor accessing cannabis in Australia. As of 2024, the market has expanded significantly, arguably outgrowing the current legislative framework. However, there is still little political interest in developing a more suitable regulatory framework. As the industry continues to evolve, this risks seeing the continued lack of investment in local cultivation and manufacturing infrastructure in preference of imported products.

The baseline of growth without any changes to the current system will see the industry grow by up to 400% by 2030 from 2022 levels, whilst a well-designed and regulated adult-use or deregulated medical market could realistically lead to an industry that is more than ten times the size of 2022, with sales in the multiple billions of dollars. While this presents significant opportunities for cultivators, the uncertain regulatory framework, continued downward price pressure, and overseas competition are significant challenges.

To be successful in what will be an increasingly competitive production environment, producers and the industry can take steps to maximise the profitability and sustainability of Australian grown cannabis, including:

1. **Plan cultivation facilities strategically.** Producers should carefully define their goals and desired end-product before designing a cannabis production facility, considering long-term market trends, future price pressures, site suitability, available funding, and resources. Success depends on aligning cultivation strategies with the intended market segment to maintain competitiveness."

2. **Focus heavily on keeping cultivation facilities efficient and appropriately sized.** Cultivators should prepare for significant price compression and intense competition as the cannabis industry matures.

3. **Collaborate on regulatory development.** The industry and regulators should adopt a collaborative, industry-represented approach to cannabis regulation in Australia. Rather than applying fragmented or ill-fitting standards, regulations should be comprehensive, covering cultivation, postharvest processing, and downstream handling.

4. **Learn from international models' failures and successes.** Any future deregulation towards a legal adult-use cannabis market should carefully consider the successes and failures of overseas models, particularly those of Canada and individual American states. Key challenges to address include taxation, regulation, license availability, and financial barriers to entry, which can impact market competitiveness and the ability to displace the illicit market.

References

Al Ubeed, Hebah Muhsien Sabiah, Ronald B. H. Wills, and Jayani Chandrapala. 2022. “Post-Harvest Operations to Generate High-Quality Medicinal Cannabis Products: A Systemic Review.” *Molecules (Basel, Switzerland)* 27 (5). https://doi.org/10.3390/molecules27051719.

Australian Institute of Health and Welfare. 2024. “Alcohol, Tobacco & Other Drugs in Australia, Cannabis.” October 7, 2024. https://www.aihw.gov.au/reports/alcohol/alcohol-tobacco-other-drugs-australia/contents/drug-types/cannabis.

Collado, Cristian E, Seung Jae Hwang, and Ricardo Hernandez. 2024. “Supplemental Greenhouse Lighting Increased the Water Use Efficiency, Crop Growth, and Cutting Production in Cannabis Sativa.” *Frontiers in Plant Science* 15:1371702.

Compton, Simone. 2023. “A Deep Dive into Cannabis Trichomes.” Urbanistic Canada. September 26, 2023. https://urbanistic.ca/blogs/news/all-about-cannabis-trichomes.

Deloitte. 2021. “An Industry Makes Its Mark - The Economic and Social Impact of Canada’s Cannabis Sector.”

Headset. 2022. “Pre-Rolls: An Analysis of Category Trends & Performance.” August 2022. https://www.headset.io/industry-reports/pre-rolls-an-analysis-of-category-trends-performance.

Hussain, Tajammul, Ganga Jeena, Thanet Pitakbut, Nikolay Vasilev, and Oliver Kayser. 2021. “Cannabis Sativa Research Trends, Challenges, and New-Age Perspectives.” *iScience* 24 (12): 103391. https://doi.org/10.1016/j.isci.2021.103391.

Jones, Steve. 2024. “SAS-B Deep Dive: Half-Year Data Illustrates Shifting Sands as Monthly Approvals Hit Almost 20,000.” Cannabiz. July 3, 2024. https://www.cannabiz.com.au/sas-b-deep-dive-half-year-data-illustrates-shifting-sands-as-monthly-approvals-hit-almost-20000/.

Karadeglija, Anja. 2023. “Cannabis Producers Say ‘crushing’ Taxes, Fees Have Made Legal Industry ‘Uneconomic.’” National Post. February 16, 2023. https://nationalpost.com/news/cannabis-producers-taxes-fees-uneconomic.

Lamers, Matt. 2023. “Canadian Medical Cannabis Registrations at Lowest Level since Legalization.” *MJBizDaily* (blog). September 13, 2023. https://mjbizdaily.com/canadian-medical-cannabis-registrations-at-lowest-level-since-legalization/.

MacPhail, Sara L, Miguel A Bedoya-Pérez, Rhys Cohen, Vicki Kotsirilos, Iain S McGregor, and Elizabeth A Cairns. 2022. “Medicinal Cannabis Prescribing in Australia: An Analysis of Trends over the First Five Years.” *Frontiers in Pharmacology* 13:885655.

Malabadi, Ravindra B, Simuzar S Mammadova, Kiran P Kolkar, MR Sadiya, Raju K Chalannavar, and Karen Viviana Castaño Coronado. 2024. “Cannabis Sativa: A

Therapeutic Medicinal Plant-Global Marketing Updates." *World Journal of Biology Pharmacy and Health Sciences* 17 (2): 170–83.

McPartland, John M. 2018. "*Cannabis* Systematics at the Levels of Family, Genus, and Species." *Cannabis and Cannabinoid Research* 3 (1): 203–12. https://doi.org/10.1089/can.2018.0039.

Mills, Evan. 2012. "The Carbon Footprint of Indoor Cannabis Production." *Energy Policy* 46 (July):58–67. https://doi.org/10.1016/j.enpol.2012.03.023.

MTP Connect. 2021. "Australian Medicinal Cannabis Industry Report." https://www.mtpconnect.org.au/images/MTPC_Australian%20Medicinal%20Cannabis%20Industry.pdf.

New Frontier Data. 2023. "2023 U.S. Cannabis Report Market Updates & Projections." New Frontier Data.

Penington Institute. 2023. "Cannabis in Australia, 2023 Report." 2023. https://www.penington.org.au/wp-content/uploads/2023/12/Cannabis-in-Australia-2023-Report.pdf.

Punja, Zamir K., Darren B. Sutton, and Tommy Kim. 2023. "Glandular Trichome Development, Morphology, and Maturation Are Influenced by Plant Age and Genotype in High THC-Containing Cannabis (Cannabis Sativa L.) Inflorescences." *Journal of Cannabis Research* 5 (1): 12. https://doi.org/10.1186/s42238-023-00178-9.

Pusiak, Ryan Jp, Chelsea Cox, and Cory S. Harris. 2021. "Growing Pains: An Overview of Cannabis Quality Control and Quality Assurance in Canada." *International Journal of Drug Policy* 93 (July):103111. https://doi.org/10.1016/j.drugpo.2021.103111.

Rose, Christiern, and Jenny Williams. 2024. "How Can We Measure the Size of Australia's Illegal Cannabis Market – and the Billions in Taxes That Might Flow from Legalising It?" The Conversation. May 10, 2024. http://theconversation.com/how-can-we-measure-the-size-of-australias-illegal-cannabis-market-and-the-billions-in-taxes-that-might-flow-from-legalising-it-229287.

Sapounas, Athanasios, Nikolaos Katsoulas, Bart Slager, Robert Bezemer, and Charlotte Lelieveld. 2020. "Design, Control, and Performance Aspects of Semi-Closed Greenhouses." *Agronomy* 10 (11). https://doi.org/10.3390/agronomy10111739.

Schaneman, Bart. 2019. "Cross-Pollination Drives Growing Disputes between Marijuana, Hemp Farmers." Hemp Industry Daily. November 14, 2019. https://mjbizdaily.com/cross-pollination-could-cost-marijuana-farmers-several-thousands-of-dollars-as-hemp-production-expands/.

Shoebridge, David. 2023. "Let's Legalise It." September 21, 2023. https://assets.nationbuilder.com/davidshoebridge/pages/87/attachments/original/1665451714/220815_Let's_legalise_It_-_Cannabis_Brief_%28no_confidential%29_%284%29.pdf?1665451714.

Simiyu, David Charles, Jin Hoon Jang, and Ok Ran Lee. 2022. "Understanding Cannabis Sativa L.: Current Status of Propagation, Use, Legalization, and Haploid-

Inducer-Mediated Genetic Engineering." *Plants* 11 (9): 1236. https://doi.org/10.3390/plants11091236.

Small, Ernest, and Tanya Antle. 2003. "A Preliminary Study of Pollen Dispersal in Cannabis Sativa in Relation to Wind Direction." *Journal of Industrial Hemp* 8 (2): 37–50. https://doi.org/10.1300/J237v08n02_03.

Small, Ernest, and HD Beckstead. 1973. "Common Cannabinoid Phenotypes in 350 Stocks of Cannabis."

Small, Ernest, and Arthur Cronquist. 1976. "A Practical and Natural Taxonomy for Cannabis." *Taxon* 25 (4): 405–35. https://doi.org/10.2307/1220524.

Small, Ernest, and Steve G. U. Naraine. 2016. "Expansion of Female Sex Organs in Response to Prolonged Virginity in Cannabis Sativa (Marijuana)." *Genetic Resources and Crop Evolution* 63 (2): 339–48. https://doi.org/10.1007/s10722-015-0253-3.

Smith, Christiana J., Daniela Vergara, Brian Keegan, and Nick Jikomes. 2022. "The Phytochemical Diversity of Commercial Cannabis in the United States." *PLOS ONE* 17 (5): e0267498. https://doi.org/10.1371/journal.pone.0267498.

Spadafora, Natasha Damiana, Simona Felletti, Tatiana Chenet, Tiziana Maria Sirangelo, Mirco Cescon, Martina Catani, Chiara De Luca, Claudia Stevanin, Alberto Cavazzini, and Luisa Pasti. 2024. "The Influence of Drying and Storage Conditions on the Volatilome and Cannabinoid Content of Cannabis Sativa L. Inflorescences." *Analytical and Bioanalytical Chemistry* 416 (16): 3797–3809. https://doi.org/10.1007/s00216-024-05321-w.

Specchio, Nicola, Nicola Pietrafusa, and Helen J Cross. 2020. "Source of Cannabinoids: What Is Available, What Is Used, and Where Does It Come From?" *Epileptic Disorders* 22:S1–9.

Stanghellini, Cecilia, and David Katzin. 2023. "The Dark Side of Lighting: A Critical Analysis of Vertical Farms' Environmental Impact." OSF Preprints. https://doi.org/10.31219/osf.io/nsu8h.

Summers, Hailey M., Evan Sproul, and Jason C. Quinn. 2021. "The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States." *Nature Sustainability* 4 (7): 644–50. https://doi.org/10.1038/s41893-021-00691-w.

The Ontario Cannabis Store. 2021. "Ontario Cannabis Store Insights Report." 2021. https://www.doingbusinesswithocs.ca/wp-content/uploads/2022/10/OCS-InsightsReport_Q4-2021.pdf.

The Ontario Cannabis Store. 2023. "OCS By the Numbers Report 2023."

Timalsena, Keshav. 2013. "Using Semi-Closed Greenhouses to Maximise Production While Minimising Inputs and Waste." Nuffield Australia.

Toffolatti, Silvia Laura, Giuliana Maddalena, Alessandro Passera, Paola Casati, Piero Attilio Bianco, and Fabio Quaglino. 2021. "16 - Role of Terpenes in Plant Defense to Biotic Stress." In *Biocontrol Agents and Secondary Metabolites*, edited by Sudisha Jogaiah, 401–17. Woodhead Publishing. https://doi.org/10.1016/B978-0-12-822919-4.00016-8.

Yip, Genevieve. 2020. “Sustainable Cannabis Policy in California: Addressing the Legal Cannabis Industry’s Carbon Footprint.” *Master’s Projects*, May. https://doi.org/10.31979/etd.eagx-enx5.