Department of
Primary Industries

Australian Oilseeds
Federation Inc.

Canola in Australia:

21st century progress

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Editors

Deb Slinger	Trent Potter	Kate Light	Tania Moore
NSW DPI	Yeruga Crop Research	Nutrien Ag Solutions	NSW DPI
Wagga Wagga NSW	Naracoorte SA	Horsham VIC	Griffith NSW

Introduction

Welcome to *Canola in Australia: 21st century progress*.

The focus of this publication is to highlight some of the research and advances made regarding canola production systems in Australia since 1999, building on the experiences shared in *Canola in Australia – the first thirty years*.

This would not have been possible without the support of the many organisations and individuals responsible for driving positive change in the canola industry. The knowledge and expertise shared in this book serves as an enduring record of the research and innovation that helped to shape the Australian canola industry and will be crucial to the continuing success of the industry. We hope you find it a valuable and informative resource.

Canola is widely grown in south-east Australia and Western Australia (WA) in regions with >325 mm annual rainfall, however quick maturing lines and evolving farming systems have increased production in lower rainfall areas.

Canola has secured a place in Australian cropping systems comprising 14% of the total crop area nationally and 25% of the cropped area of NSW and Victoria, including high rainfall regions. In WA's northern region and the Mallee/sandplain near Esperance, canola has increased substantially.

Recognised as a profitable crop in its own right, canola is also an important rotation crop in cereal-dominated systems. Even though canola has been considered a somewhat riskier crop compared with cereals, early sowing, improved varieties, better blackleg control and additional weed control options have enabled the crop to become the third largest annual crop in Australia, after wheat and barley. Current production systems that target optimum flowering periods utilising early sowing, hybrids and increased nitrogen rates are proving profitable in low, medium and high rainfall areas.

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Cover image: NSW DPI's Wagga Wagga Agricultural Institute canola research experiments in 2021, assisting industry with variety selection for frost and heat tolerance and crop protection.

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We gratefully acknowledge all contributors to *Canola in Australia: the first thirty years* (published in 1999 for the 10th IRC in Canberra, Australia) on which this book was based.

We also express our gratitude to the authors, reviewers, editorial team and organisations that committed to updating this information for this book, *Canola in Australia: 21st century progress*, to reflect the last 24 years (1999–2023) of change and innovation in the canola industry.

Astute Ag

Australian Oils Research

Yeruga Crop Research

Contents

Organisation acronyms and initialisms

AgVic	Agriculture Victoria
AgWA	Agriculture Western Australia (now DPIRD)
AOF	Australian Oilseeds Federation
APVMA	Australian Pesticides and Veterinary Medicines Authority
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSU	Charles Sturt University
DAF	Department of Agriculture and Fisheries (Queensland)
DAFF	Department of Agriculture, Fisheries and Forestry (Australia)
DPIRD	Department of Primary Industries and Regional Development (Western Australia)
FSANZ	Food Standards Australia and New Zealand
GA	Grains Australia
GCIRC	Global Council for Innovation in Rapeseed and Canola
GRDC	Grains Research and Development Corporation
GTA	Grain Trade Australia
INRA	Institut national de la recherche agronomique, France
IRC	International Rapeseed Congress
MGP	Marcroft Grains Pathology
NSWA	NSW Agriculture (now NSW DPI)
NSW DPI	New South Wales Department of Primary Industries
NVT	National Variety Trials
OGTR	Office of the Gene Technology Regulator
SARDI	South Australian Research and Development Institute
SGA	Sustainable Grain Australia
TGA	Therapeutic Goods Administration
UA	University of Adelaide
UWA	University of Western Australia

Foreword

Robert Wilson
President – Global Council for Innovation in Rapeseed and Canola (GCIRC)

After growing up on the family farming enterprise in central Victoria, I spent most of my working life in agriculture, the last 28 years in the canola industry as canola research manager and most recently as canola market development manager with Pioneer Hi-Bred.

I have witnessed substantial change in agriculture in my professional capacity over this time, and that will continue. It is my view that if we do not embrace and drive changes, agricultural practices, research, innovation and technology could struggle to meet current and future challenges. This is no more to the forefront than here in Australian agriculture where climatic conditions heavily influence the outcomes.

Australia's highly variable climate is projected to become warmer and generally drier in the future. Adapting to this future climate is one of the major challenges for Australian agriculture. Other challenges ahead include reducing agricultures' carbon footprint, nitrogen use, greenhouse gas emissions, biosecurity and government regulations.

Canola in Australia: The first thirty years, published in 1999 to coincide with the 10th International Rapeseed Congress (IRC) in Canberra, provided great insight into canola production from humble beginnings in 1970 when local breeding programs were established following the collapse of the industry in the late 1960s to the disease blackleg.

Canola in Australia: 21st century progress, perfectly coincides with the 16th IRC in Sydney 2023. More than 30 authors from public state and national research organisations, universities and the private sector have contributed. Each chapter highlights the significant improvements made over the past 24 years, including breeding for new herbicide tolerances and genetically modified canola, as well as quantitative yield traits and modified oil profiles. Outside of private sector breeding, much of the research is funded as a co-investment with the Grains Research and Development Corporation (GRDC).

The Australian canola industry has achieved remarkable growth since 1999. The crop has expanded from an area of 1.9 million hectares producing 2.5 million tonnes in 1999, to 3.25 million hectares sown and over 6.5 million tonnes produced in 2021–22, with world class science and industry participation underpinning this achievement. Canola is now the third largest winter crop in Australia behind wheat and barley and has been second in value over the past 2 years.

To be involved with, and participate in, the growth of this golden crop has been rewarding and no matter whether you are a scientist, a canola grower, an experienced agronomist or involved in the supply chain there is plenty to be taken from this excellent read. So please enjoy *Canola in Australia: 21st century progress*.

History – the next chapter: 1999–2023

Trent Potter[1], Justin Kudnig[2] and Don McCaffery[3]

[1] Yeruga Crop Research, Naracoorte SA 5271
[2] Advanta Seeds Pty Ltd, Highett VIC 3190
[3] NSW Department of Primary Industries, Orange NSW 2800

Summary

- The 1999–2000 Australian canola crop was 1.9 million hectares (Mha) and produced 2.5 million tonnes (Mt) of grain. Over the past 3 years (2020–22), the national crop has set a new production record each year averaging 6.6 Mt from 3.25 Mha. These 3 seasons recorded above average to well above average rainfall.
- In the mid–late 1990s the Australian canola industry introduced new herbicide tolerant varieties to control problematic weeds. These came in the form of triazine tolerant (TT) types. In the early 2000s new imidazolinone tolerant (IMI, Clearfield®) varieties were introduced. These varieties provided added herbicide options, allowing canola growing to expand into new areas.
- From 2008 new herbicide tolerant varieties including genetically modified (GM) glyphosate resistant (Roundup Ready®, RR) varieties were introduced. These varieties had more targeted weed spectrum control through wider application windows at higher application rates to effectively manage herbicide resistance. Since 2020 canola technologies have continued to expand. Varieties now have traits such as the TruFlex® gene in glyphosate resistant types, dual herbicide stacks and pod shatter resistance.
- For the last decade the industry has adopted many technologies that have helped to increase dryland and irrigated cropping profitability. These technologies have included yield mapping, variable rate application engineering, unmanned aerial vehicle (UAV) or drone assisted field assessments and precision agriculture.

Production, prices and marketing

New varieties and technologies together with enhanced agronomy and precision agriculture, and higher rainfall seasons and commodity prices, resulted in the industry doubling from 1.9 Mha in 1999 (2.5 Mt grain produced) to 3.9 Mha in 2022 and a record grain production of 8.3 Mt. Figure 1 shows Australian canola production over the past 20 years (2002–03 to 2022–23) on a yearly basis and as a 5-year rolling average.

Western Australia represented over 50% of the national canola crop in 2022; 2.1 Mha grown, 4.3 Mt of grain produced. The eastern states (New South

Wales, Victoria, South Australia and Tasmania) grew 1.8 Mha and produced 4.0 Mt of grain.

Since 2002 prices have generally fluctuated between $390 and $700/t (delivered Newcastle port) and have risen steadily from around 2010 (Figure 2). Prices vary during the season with growers being able to take out fixed tonnage and fixed price contracts. However, as Australia can be impacted by drought, frost and heat wave conditions, most canola is sold at the price available at harvest.

More recently global climatic conditions and associated unrest in some countries have led to large fluctuations in global oilseed supply and demand and canola prices in Australia reached as high as $1100/t before harvest in 2022.

As the canola industry has continued to expand there has been strong growth in the number of companies competing to market the Australian crop. These range from local companies to multinational trading corporations.

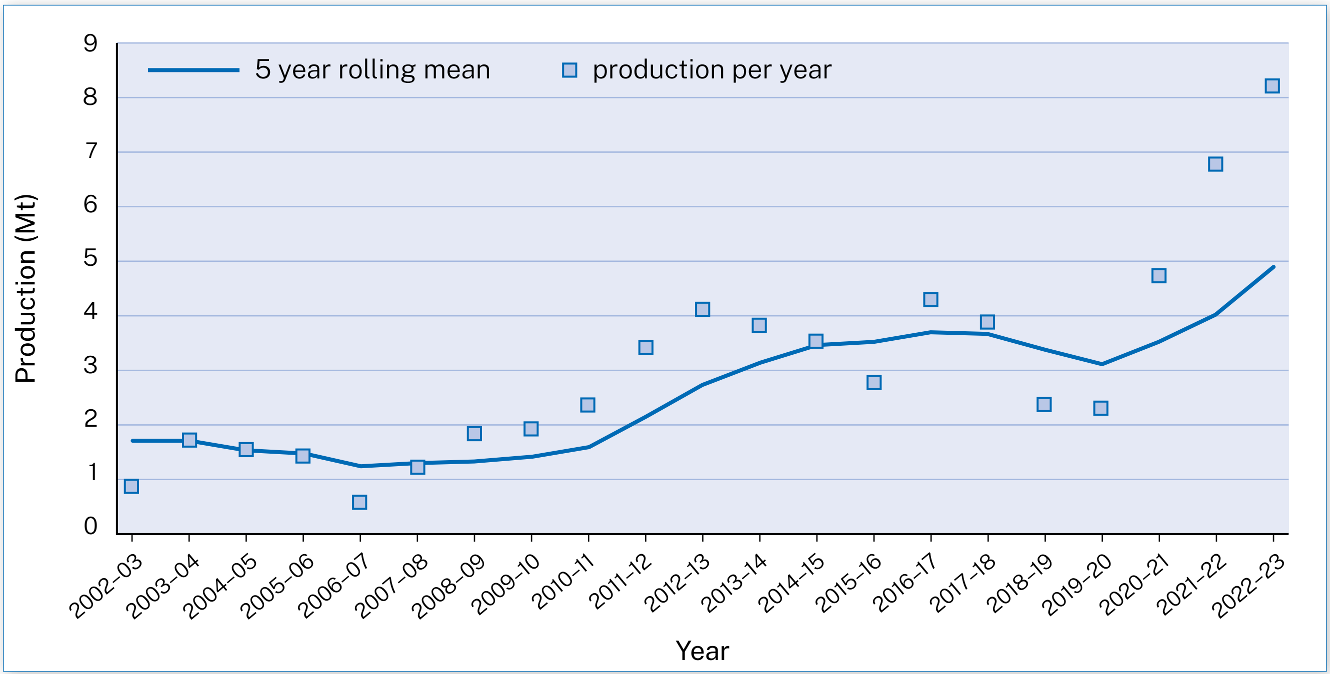


Figure 1 *Australian canola production (Mt), on a yearly basis and as a 5-year rolling mean.*

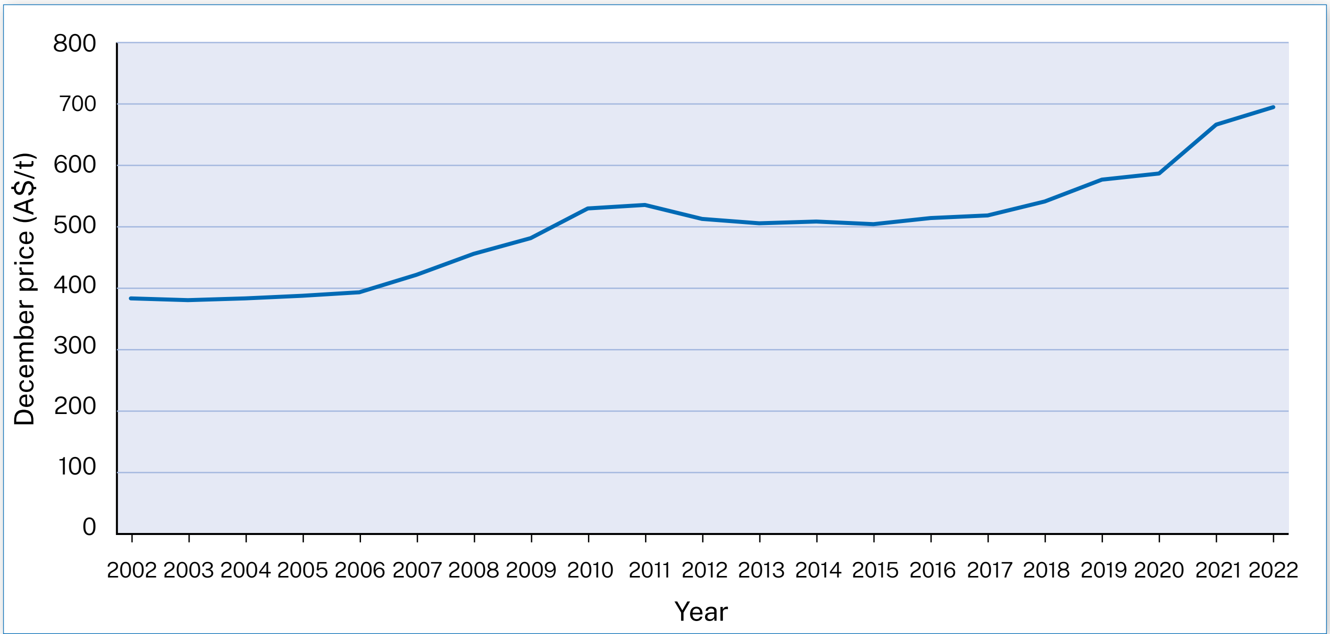


Figure 2 *Canola price at harvest (A$/t) delivered Newcastle port, expressed as a 5-year rolling mean.*

In 2022, Australia's canola production represented nearly 10% of the 80 Mt produced world-wide. Australia is well placed geographically to supply Asian export markets with high-quality canola for oil and meal markets. Australia supplies more than 4–5 Mt of canola annually (15–20% of the world's trade) to Europe, China, Pakistan, Japan and other international markets.

Many technological improvements have produced this increase in canola grain yield, area sown and production.

Breeding

During the 1990s TT open pollinated (OP) varieties were introduced and widely adopted across western and eastern Australia. These varieties allowed for more effective weed control for a range of common weeds in winter cropping rotations than conventional varieties did.

Integrated weed management (IWM) also became an acknowledged part of canola cropping rotations around this time.

Different herbicide tolerant varieties with a range of herbicide actives were introduced in the 2000s. These, together with today's dual stacked technologies, led to a massive expansion of canola into many winter cropping regions across southern Australia's high rainfall zones.

These added management tools:

- enhanced weed control options
- improved IWM strategies
- provided the ongoing ability to handle specific herbicide carry over issues.

This has been especially important given the exponential increase in IMI tolerant crop species and varieties now being grown.

Hybrid canola started with conventional types then progressed to Clearfield®, Roundup Ready® (RR), TT, TruFlex®, and more recently Liberty Link® (glufosinate) herbicide tolerances. With these added options, growers could expand their sowing opportunities and address specific paddock weed spectrum and herbicide resistance challenges. Hybrids are now estimated to comprise 60–70% of the national canola crop.

GM varieties were approved in New South Wales and Victoria in 2008, Western Australia in 2009 and South Australia only in 2021. Tasmania remains GM-free. By 2022, GM canola had a 35% share of the national canola area. Western Australia grew 46% of all GM canola in Australia.

The recent advent of stacked technologies means that growers can now use even more strategies as well as protect their crops from IMI herbicide residue soil carryover. These technologies include TruFlex® + Clearfield®, Clearfield® + Triazine, Glufosinate + Triazine and Glufosinate + TruFlex®. Having these additional weed control options has added more flexibility and sustainability to ongoing crop rotation decisions.

Enhanced crop agronomy and precision agriculture

Several important crop agronomy developments extending from the 2000s through to the 2020s have had a significant effect on crop yield and profitability. Many continue to be important in the rapid expansion of canola in Australia:

- Hybrids have been key to lifting average canola yields consistently across seasons.
- New herbicide technologies have led to an increase in area sown to hybrids. This has resulted in more efficient weed management strategies associated with the following cereal or pulse crops or rotations with pastures.
- Harvest weed seed control (HWSC) measures are now being used by many growers to kill or remove weed seeds by the harvesting process and so reduce seed set of herbicide resistant weeds.
- Research and development conducted by private and public organisations into canola agronomy has provided a new level of understanding about:
  - nitrogen (N), phosphorus and sulfur efficiencies
  - plant population optimisation
  - seed size, seed grading and sowing depth
  - blackleg and sclerotinia diseases and rotations to increase resistance
  - sowing time to ensure flowering phenology optimisation
  - vernal and thermal time factors
  - managing higher biomass crops
  - economics of cutting canola for hay during periods of prolonged drought
  - harvest management including direct-heading and timing of windrowing (swathing).

- New insecticides, fungicides and herbicides made available to the market during the last 20–30 years have provided growers and advisors with more options for their integrated pest management (IPM), integrated disease management (IDM) and IWM programs. New fungicides have helped to protect increasing canola grain yields.
- Precision agriculture is being used by growers managing large areas of canola. This includes using precision seeders along with UAV field assessments and multispectral satellite mapping of farms and individual paddocks during crop planning and during critical growth stages. Normalised difference vegetation index (NDVI) scoring, yield mapping monitors, increased accuracy around soil testing interpretations, variable rate applicators and optical precision spraying has also provided more accurate information for agronomic management recommendations.

The next advance will likely be the adoption of autonomous machinery using artificial intelligence to sow, apply inputs and harvest the crop in a shorter timeframe, increasing operational efficiencies. This will be important as farms become larger and operational timing becomes more critical in the face of a more unpredictable and variable future climate. Dry sowing ahead of germinating rains is now common on farms sowing large areas of canola.

In addition to technology adoption there have been several important enhancements to farming systems and crop management.

The Millennium drought (1997–2009), which impacted much of south-eastern Australia, changed how growers prepare to grow canola. Crop residue (stubble) retention, which provides critical ground cover, and strict summer fallow weed control is now widely adopted to conserve 'out-of-season' rainfall and soil nutrients.

Throughout the 1980s and 1990s canola was generally sown into highly fertile conventionally prepared cultivated paddocks following annual or perennial legume-based pasture. More land is now continuously cropped with little or no legume pasture to supply N. More growers are sowing brown and green manure crops such as vetch or field peas, or pulses such as lentils, faba beans or field peas the year before canola. This system provides a double break for weed control for Australia's main grain crop, wheat, and reduces off-farm N fertiliser costs.

Combining new varieties and technologies

Canola production started to extend into lower rainfall areas in all southern Australian states in the early 2000s. Production occurs where rainfall is as low as 325 mm per year and rain falls mostly in the crop growing season. This expansion was mainly due to growers adopting IMI and glyphosate resistant hybrid canola and their associated increased net return and profitability.

Canola has also increased as a percentage of annual winter crop rotations, replacing up to 20–40% of cereal and pulse production area in some regions in response to:

- greater incidence and severity of cereal stubble and soil-borne diseases
- more positive canola grain commodity pricing
- higher average yields
- higher rainfall seasons
- improved varietal blackleg resistance
- registration of new pre-and post-emergent herbicides and new herbicide tolerant varieties that provide better weed control and IWM options.

In addition to new herbicide traits, the Australian canola industry has also invested in new canola varieties with agronomic or quality traits that:

- help growers manage the agronomic challenges arising from Australia's highly unpredictable and variable climatic conditions (e.g. pod shatter resistance)
- add value (e.g. high oleic low linolenic acid [HOLL] speciality canola).

Further to this, some growers in medium to high rainfall zones are using winter canola types from Europe across different farming enterprises. These graze and grain dual-purpose hybrids comprise around 200,000 ha. Many growers achieve multiple grazing revenue opportunities for their sheep or cattle, capturing dual-purpose crop incomes of $4,000 to $5,000/ha.

HOLL canola was first introduced in 1998 with subsequent improved varieties released from 2004. These types attract a price premium but are lower yielding than mainstream canola. All HOLL canola is produced in a closed loop marketing system. It is estimated that less than 100,000 t is produced annually.

A further change since 1999 was the introduction in 2007 of canola-quality *Brassica juncea* (Juncea canola). Targeted at low-rainfall areas and with drought tolerance superior to canola, this species had inferior yield to short-season early maturing canola, so investment in this crop has ceased.

Brassica carinata is currently being investigated as a potential oil for aviation jet fuel. Its economics will be determined by the market. *B. carinata* has different phenological development to canola and will need different herbicide options to allow it to be grown in most areas.

Future directions, carbon considerations and sustainability

Future directions for canola involve the continued adoption of new technologies that:

- increase production efficiency
- provide agronomic and profitability gains
- address the industry's carbon footprint and sustainability
- allow access to new markets.

Some of the new traits being explored that are expected to become part of the global and national oilseed complex over the next 30 years include:

- improving human nutrition
- oilseed use for aviation fuel
- pharmaceutical and industrial applications.

The CSIRO has established greenhouse gas (GHG) emission values for canola production to maintain access to the European Union (EU) biodiesel market. Australia ranks in the lowest 15% of all countries for GHG emissions, generating approximately 460 kg CO2 equivalent (CO2-eq)/t of canola seed on a dry matter basis, or 20 g of CO2-eq per megajoule of energy.

European fuel companies use Australian canola for biodiesel to help meet their GHG emission requirements at the point of consumption. Emissions are lower in Australia than most countries as producers typically practice minimum or no-till to establish the crop. This helps to preserve soil carbon, soil water and reduces nitrous oxide emissions. In addition, Australian canola production is mostly rainfed rather than irrigated which eliminates energy used for irrigation. This provides Australian canola with a competitive advantage over most other canola suppliers in the EU biodiesel market.

Australia has exported over 22 Mt of canola grain, worth approximately A$15.3 billion to the EU biodiesel market since the Renewable Energy Directive (RED) was introduced in 2018. The EU biodiesel market is highly valued as it generates a premium for Australian producers, primarily because Australian canola is certified as sustainable.

The CSIRO GHG emissions report has identified opportunities to reduce emissions along the supply chain and enhance the environmental credentials of Australian canola exports. Manufacturing fertiliser contributes the largest share of total emissions (47%) as it consumes natural gas via the steam methane reforming (SMR) process. For example, producing urea, the most used N fertiliser worldwide, generates around 1.8 kg CO2-eq per kg. Imports from the Middle East, Malaysia, Indonesia and China, which comprise about 70% of total fertiliser consumption in Australia, generate an additional 110 g of CO2-eq per kg.

Recent CSIRO studies have also shown that dual-purpose graze and grain canola results in lower GHG values than single use canola despite the need to add more N for the grazing biomass removal. The reduction in GHG is due to the portion of total canola GHG devoted to the livestock emissions.

Crop limiting factors: climate

Michelle Miller[1], Dr. Anthony Clark[2] and Kim Broadfoot[2]
[1] Formerly NSW Department of Primary Industries, Wagga Wagga NSW 2650
[2] NSW Department of Primary Industries, Orange NSW 2800

Summary

- Wide variation in climate occurs over the Australian continent with annual rainfall ranging from 325 to more than 600 mm in canola growing areas.
- Large seasonal climate variability brings both extremes in wet and dry conditions, creating risks and management challenges for canola production.
- Climate change over the last few decades and into the future has potential to intensify these challenges for growers.

The climatic environment for canola production

Canola is a cool season crop produced in the southern half of Australia in the winter dominant and uniform seasonal rainfall zones (Figure 3). The crop has moderate to low tolerance of aridity but can be reliably produced in areas with annual rainfall as low as 325 mm, where there is seasonal reliability in autumn such as in Western Australia's grain belt. Generally, canola production is confined to zones where there is 325 mm to over 600 mm of annual rainfall.

The phenological growing season for canola is typically April to October. In winter rainfall areas, 40–60% of annual rainfall is received between April and October compared with 30–50% received for the same period in uniform summer rainfall areas (Bureau of Meteorology 2021).

Optimal sowing times vary from the last week in March to mid May. Most canola crops are grown as dryland crops (no supplementary water). Canola is successfully dry sown in areas of reliable rainfall. In northern areas, adequate levels of stored soil water provided by summer rainfall, and well managed fallow periods, can provide more than 50% of the crop water requirement (Brill 2019). With stored soil water, winter canola can be sown from mid January (late summer) to early autumn (mid–late March) for forage grazing in autumn and winter, and grain harvest in November and December (Brill 2019). In canola production areas, daily temperatures during winter often range from a mean minima of about 2–4°C to mean maxima of 14–18°C. Flowering generally occurs in August and September when temperatures are rising. Grain fill in October and November often occurs under high temperature and low rainfall conditions which can result in low yields and oil content. Critical temperatures for canola growth range from 27 to 30°C (Kirkegaard et al. 2018) however, as a temperate crop, canola is susceptible to high heat events (Lohani et al. 2021). Frosts after flowering have sometimes aborted seeds and reduced yields.

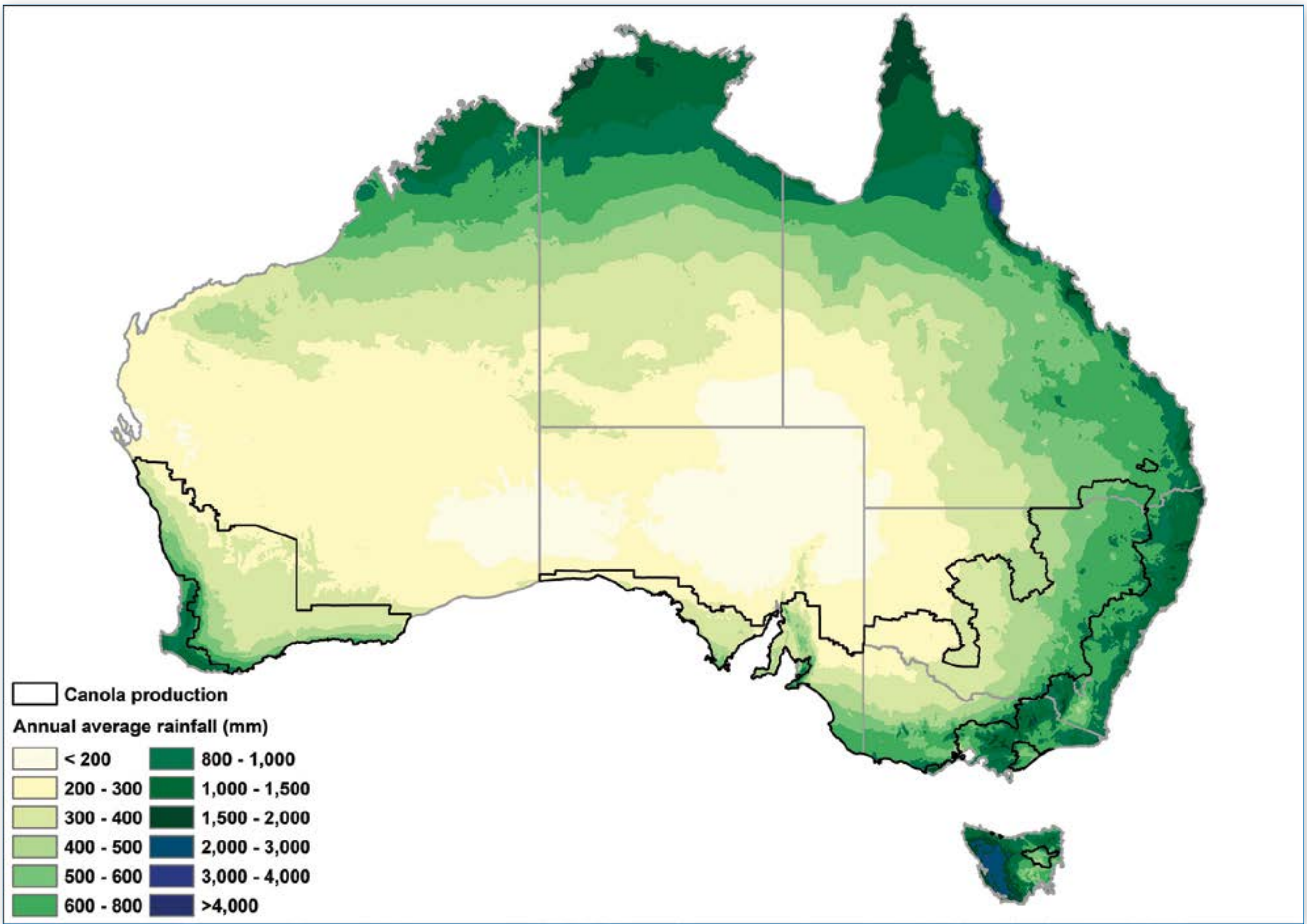


Figure 3 *Australia's annual average rainfall (mm) for the period 1991 to 2020, overlayed with the canola production regions (climate data sourced from the Bureau of Meteorology and the Australian National University – ANUClimate). Production data for the 2019–20 growing season from the Australian Bureau of Statistics, Experimental Regional Agricultural Statistics.*

In winter-dominant rainfall areas, summers can be very dry with northerly to easterly winds which result in high temperatures and evaporation which can impact the crop. Where harvest is delayed due to late spring or early summer rainfall, rain falling on ripe crops leads to a reduction in seed size, the loss of whole pods that break away from the stem, and reduced yields (Brill 2019). In drier seasons, crops with low potential yields can be cut for hay or silage. The growing season ranges from about 150 to 210 days, depending on latitude, rainfall, temperature, and sowing date.

Risks associated with variable seasonal conditions

Australia has a continental climate where several global and local systems give rise to high seasonal and inter annual variation. Growers are exposed to variability from climate systems such as the El Niño Southern Oscillation (ENSO) in the Pacific, energy shifts in the Indian Ocean and the highly volatile circulations off the southern Antarctic Ocean. These systems interact with the continental land mass and localised landscapes to generate high climate variability in canola production regions.

Major droughts bring multiple seasons of crop failure across large areas of the canola growing regions. The Millennium drought (1997–2009) had prolonged dry periods that greatly affected the Murray–Darling Basin and almost all the southern cropping zones. The 2017–19 drought brought extremely dry seasonal conditions to northern and southern NSW and Victoria. This resulted in multiple years of low yield or failed canola crops, and the 2018–19 and 2019–20 seasons were the lowest value return from oilseed production in Australia over the decade (Dahl et al. 2023). The Bureau of Meteorology recorded rainfall deciles of below average to lowest on record (Bureau of Meteorology 2020).

Canola is also susceptible to waterlogging and high seasonal rainfall brings yield penalties. Many growers confine canola production to well drained soils on the mid to upper slopes of their farm. Three years of back-to-back La Niña conditions following the 2017–19 drought resulted in a strong industry recovery and well above average rainfall across the production zone. Yield penalties were widely reported and waterlogged soils created logistical constraints for machinery at harvest. Flooding resulted in crop damage and losses in the NSW central western plains and parts of Victoria.

Variability and risks under climate change

Climate change has reduced growing season (April to October) rainfall across southern Australia. It has reportedly decreased by 10% since the late 1990s in the south-east of Australia, and by 15% since 1970 for the south-west of Australia (Commonwealth of Australia 2022).

Across southern and eastern Australia, a further continual decline in winter rainfall is predicted. This may lead to longer dry seasonal conditions or drought periods whilst increasing the incidence of short intense heavy rainfall events (Commonwealth of Australia 2022).

The predictions are that the magnitude and potentially the frequency of extremes will likely increase in the future. Agricultural droughts might become more prolonged and intense due to changing rainfall patterns and warming temperatures influencing evaporative demand. A warming climate creates conditions where the atmosphere can hold more moisture, increasing rainfall intensity. This has potential flow on effects such as an increased incidence of crop damage, waterlogging and flooding.

Potential shifts in climate risk are some of the most difficult to detect and track but are potentially the most challenging for canola production. They can exacerbate the impacts that are already being observed under seasonal climate variability. It is important that industry and growers continue to remain vigilant and adapt to change.

More information

References relating to this chapter are listed in Appendix 1 (p. 95).

Crop limiting factors: soils

Dr. Shihab Uddin
NSW Department of Primary Industries, Wagga Wagga NSW 2650

Summary

- Soil constraints are a major limiting factor for the Australian grain industry causing an estimated yield loss of A$2 billion per annum.
- Soil constraints are often present in the subsoil below 20–30 cm across large areas of the grain growing region.
- Ameliorating soil constraints with strategic tillage and amendments (such as lime, gypsum, sulfur and organic matter) can improve productivity in canola.
- Adopting amelioration strategies is challenging with significant upfront costs and associated risks.

Introduction

Since its introduction in Australia, both production and area sown to canola is increasing annually because of its popularity as a dual-purpose (Kirkegaard et al. 2008b; Bell et al. 2015) and disease-break crop (Kirkegaard et al. 2008a). Canola has high nitrogen (N) and other plant nutrient requirements. It is best grown in fertile soil with unrestricted soil conditions for root growth. However, with the recent surge in area, canola is now being widely grown in less suitable soils with single or multiple soil constraints.

The Australian grain growing region is affected by a range of physicochemical constraints. These constraints limit root growth and reduce water and nutrient uptake, use and efficiency. On an area basis approximately 77% of Australian cropping soils have single or multiple physicochemical constraints (Bot et al. 2000) that cost Australian grain growers A$2 billion annually in forfeited grain yield (Orton et al. 2018).

Canola is susceptible to different soil constraints. For example, poor establishment is a widespread issue in Australia. This is most often associated with soil water repellence, soil water availability, transient waterlogging and soil crusting apart from agronomic practices, seed quality and genetics (McMaster et al. 2019; Davies et al. 2022; Nelson et al. 2022). Soil constraints such as poor fertility, acidity, salinity, sodicity and waterlogging significantly affect canola yield.

In an unrestricted soil environment, canola can take advantage of subsoil water and nutrients through its deep rooting system (Kirkegaard et al. 2020). Unfavourable subsoil physicochemical constraints that restrict rooting depth (Adcock et al. 2007; Azam et al. 2023) can prevent canola from using subsoil water and nutrients. This results in a yield penalty, particularly in a low rainfall year.

Different soil constraints that affect canola yield and productivity and the problems associated with them are discussed below.

Soil types

The wide distribution of canola across Australia shows that it is adapted to a wide range of soil types (Potter et al. 2009). Soils that grow high yielding canola are easily identifiable as they also grow high yielding wheat. The most suitable soils for canola are red–brown earths and clay soils that enable unrestricted root growth. These soils generally have higher organic matter and inherent fertility. Other soil types on which large areas of canola is grown include deep, leached, sandy soils in Western Australia, highly calcareous soils in South Australia, and hard setting acidic soils in New South Wales (Parker 2009b).

Paddocks with a uniform soil type will permit more even sowing depth and seedling emergence and more even crop ripening (Parker 2009a).

Soil constraints

Approximately 77% of Australian soils have single or multiple constraints both at the surface and in the subsoil, and the area affected is increasing over time (Bot et al. 2000). Subsoil constraints are any soil physical or chemical characteristics located below the topsoil that limit crop and pasture productivity. A range of subsoil constraints have been identified in Australian growing regions (Adcock et al. 2007; Orton et al. 2018) including:

- water repellence
- acidity
- compaction
- boron (B) and aluminium (Al) toxicity
- salinity
- sodicity
- nutrient deficiencies
- waterlogging.

When growing canola, constrained soils should be avoided or best management practices for those soils adopted to achieve better outcomes.

Water repellence

Water repellence is one of the major soil constraints in southern Australia. It is estimated that around 10.2 million hectares (Mha) of arable land in the south-west of Western Australia is at risk of water repellence with 3.3 Mha marked as at high risk and another 6.9 Mha at moderate risk (van Gool et al. 2008). Water repellent soils are characterised by an increased organic carbon content in the surface soil, especially in soils with low clay content (Roper et al. 2013). Agronomic practices including furrow or on-row sowing (Figure 4), and repeated application of wetting agents can temporarily treat soil water repellence. Using strategic tillage such as mouldboard ploughing and spading can be a medium-to-long term solution for treating soil water repellence, albeit at a moderate to high cost. Water repellence occurs mainly in sandy topsoils with less than 5% clay. Adding clay followed by an incorporation using strategic tillage is a longer-term solution.

Figure 4 *Canola establishment on water repellent gravel improved when sown in the previous year's crop row (left of image) compared to establishment when sown between the previous year's crop row (right of image).* Photo: © 2023 DPIRD.

Acidity

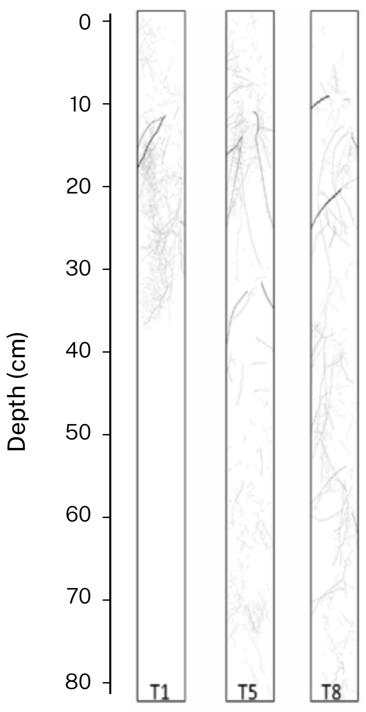
Approximately 50% of Australian agricultural land has acid (pH_{Ca} <5.5) soil of which 35 Mha is highly acidic with pH_{Ca} <4.8 (Orgill et al. 2018). Although most are naturally acidic, this acidity has been increased by agricultural practices. Low soil pH (acidity):

- decreases the availability of essential plant nutrients, such as phosphorus (P) and molybdenum
- increases the availability of some elements to toxic levels, particularly Al and manganese (Mn).

Canola is more susceptible to acidity than cereals due to its low tolerance to Al and Mn toxicities.

Aluminium toxicity affects root cell division and the ability of the root to elongate (DPIRD 2018). This results in shallow and stunted root systems that are unable to exploit soil moisture and nutrients from deeper in the soil profile. Aluminium toxicity can cause patchy areas of stunted plants and poor growth (Parker 2009b). Mild Mn toxicity causes yellowing of the leaf margins (Parker 2009b); extreme Mn toxicity causes entire leaves to become chlorotic and distorted resulting in yield loss (Hocking et al. 1999).

Liming is one of the most effective ways to ameliorate soil acidity and minimise Al and Mn toxicity (Gazey et al. 2013). Lime rates depend on the current pH, organic carbon, cation exchange capacity of the soil and the lime quality factors such as neutralising value and particle size (Condon et al. 2021). High quality lime is applied at 2–4 t/ha. Subsoil acidity is becoming more common in Australia under dryland conditions and is difficult to correct with surface liming owing to poor solubility and limited movement of lime. Research has shown that incorporating deep lime can significantly raise soil pH, lower Al toxicity, improve subsoil root growth (Figure 5) and increase canola yield within a year of application (Li et al. 2019; Azam et al. 2023).



T1 = untreated control
T5 = combined removal of soil acidity and soil compaction
T8 = combined removal of soil acidity and compaction and addition of soil organic matter.

Figure 5 *Canola root growth in unameliorated and ameliorated soils in a paddock in Meckering, Western Australia in the 2021 season.* Source: Gaus Azam, DPIRD.

Salinity

It is estimated that more than 9 Mha of Australian agricultural land is affected by salinity which leads to an annual yield loss of about A$200 million for the Australian grain industry (Orton et al. 2018). Salinity decreases plant available water (PAW) by decreasing the osmotic potential of the soil solution thereby resulting in water stress conditions. Salinity increases the concentration of certain ions (such as chloride), which is toxic for plants.

Canola is moderately tolerant of salinity, having better tolerance than wheat and field pea (Steppuhn et al. 2001) but slightly lower than barley (McCaffery 2009). Overseas published data has reported that it can tolerate soil electrical conductivity (EC) levels of 6.5 dS/m averaged across the rhizosphere (Parker 2009b). Salinity symptoms in canola vary with the salt concentration and waterlogging severity (DPIRD 2022).

Research in southern NSW has demonstrated an inverse relationship between electromagnetic (EM) survey readings indicating apparent EC, and the rooting depth of canola. Rooting depth drastically reduces with increasing salinity (Poile et al. 2012). The same study showed that in a low rainfall year with increasing soil salinity, canola biomass production and grain yield was significantly reduced. However, in a year with late spring rainfall, salinity did not affect canola biomass or yield. This indicates that the effect of subsoil salinity on canola is likely to vary with the seasonal availability of soil water.

Sodicity

Sodicity is the most important soil constraint related to yield gaps across Australian grain growing regions, causing an estimated yield loss of A$1.3 billion per annum (Orton et al. 2018). Sodic soils exhibit a range of physicochemical properties, including the presence of high subsoil exchangeable sodium (Na) concentrations, that cause:

- soil dispersion leading to poor subsoil structure
- lack of porosity
- impeded drainage
- waterlogging
- denitrification
- high soil strength.

Sodicity restricts the rooting depth and subsequent water and nutrient extraction (Adcock et al. 2007) and reduces profitability.

The most widespread traditional approach to ameliorate structural problems associated with surface sodicity is to apply gypsum. However, the effectiveness of surface-applied gypsum in ameliorating dispersive sodic subsoil is poor due to its low solubility and the large quantities required to displace significant amounts of sodium. Applying gypsum deeper into the soil profile, where the structural problem is located can help overcome this slow movement of surface-applied gypsum and result in a quick response. Research conducted by NSW DPI in a medium rainfall zone of southern NSW demonstrated that deep banding 5 t/ha gypsum (20–40 cm deep) increased canola yield by 34% during the third year of gypsum incorporation (Uddin et al. 2020).

Subsoil manuring using ripping lines for deeper placement of organic amendments can directly affect subsoil properties. The increases in crop yield in dispersive sodic subsoils following subsoil manuring have been attributed to improvements in soil:

- physical properties (structural stability, hydraulic conductivity and water retention)
- chemical properties (pH, exchangeable sodium percentage [ESP] and nutrients availability)
- biological properties (microbial diversity and function) (Sale et al. 2021).

A field experiment in a medium rainfall zone of southern NSW in 2017 evaluated a range of organic (manure, pelletised wheat and pea stubbles) and inorganic (gypsum and nutrients) amendments or their combinations. Amendments were applied either at the soil surface or incorporated in the subsoil (20–40 cm deep) as a 50 cm band. This single (once-off) application had a residual effect on grain yield in the order of 15–40% for 6 consecutive years (2017–2022). Canola was included in the rotation during 2019 and 2021. Canola yields increased by 36% in 2019 (Uddin et al. 2020, Figure 6) and by 15% in 2021 (Uddin et al. 2022).

The increases in canola yield following dispersive sodic subsoil amelioration was associated with the reduced subsoil pH and ESP and increased microbial activity. These changes improved soil aggregation, facilitating increased root growth (Figure 7) and soil water use from the deeper clay layers during the critical reproductive stages of crop development (Uddin et al. 2020).

Figure 6 *The effect of ameliorating an alkaline dispersive subsoil with organic amendments on canola productivity during the third season (in 2019) following a once-off application of amendments during the 2017 season in a medium rainfall region of southern New South Wales. Plots in comparison are unamended control (left) and amended with 15 t/ha of pea hay (pelletised) incorporated 20–40 cm deep with a band of 50 cm spacing (right).* Photo: Ehsan Tavakkoli, NSW DPI.

Figure 7 *The effects of ameliorating an alkaline dispersive subsoil with organic amendments on root proliferation of canola during the third season (in 2019) following a once-off application of amendments during the 2017 season in a medium rainfall region of southern New South Wales. Pelletised pea hay was incorporated at 15 t/ha (20–40 cm deep) with a band of 50 cm spacing. The amendment band shows a dark-coloured band in profile (a) and a friable soil structure when cored (b) at the depth of amendment incorporation. Increased canola root proliferation is evident in the cores (c) and soil mass (d) of the amendment band.* Photo: Shihab Uddin, NSW DPI.

Soil crusting

A soil crust is a thin layer of dense and tough material that forms on the soil surface due to dispersive forces in raindrops or irrigation water followed by drying (Awadhwal and Thierstein 1985). It is considerably more compacted and packed than the underlying material (Agriculture Victoria n.d.).

When a sodic dispersive soil particularly low in organic matter content gets wet, the dispersing agent (Na ions) pushes the soil particles apart. This makes soil aggregates (clumps) swell and collapse, causing the fine clay particles to disperse. Soil pores are collapsed or filled by these dispersed clay particles, resulting in surface sealing and poor infiltration. As the soil surface dries, the dispersed particles cement into a tough mass, forming a crust without or with limited pores for water, air and crop roots to move through.

Waterlogging

In Australia, waterlogging is one of the key constraints for crop production in the high-rainfall zones (Acuña et al. 2011). However, given that dispersive sodic soils with heavy clay and low infiltration rates are widely distributed (Orton et al. 2018), transient waterlogging can occur even with minimal rainfall in medium to low rainfall zones.

The degree to which waterlogging affects canola yield is related to the developmental stages at the time of waterlogging and the duration and frequency of the waterlogging (Shaw et al. 2013). Canola is most sensitive to waterlogging during germination as the lack of oxygen under waterlogged conditions hinders metabolic processes and ceases germination leading to patchy establishment (Figure 8) and stunted rooting systems (Figure 9). The effect on canola yield is greater during the rosette stage than during the grain-filling stage and the longer the period of waterlogging, the greater the impact (Edwards and Hertel 2011).

Figure 8 *Waterlogging associated with the micro-topography of this paddock resulted in the poor establishment and growth of canola in a medium rainfall region of southern New South Wales.* Photo: Mathew Dunn, NSW DPI.

Implementing different management practices such as raised bed systems, subsurface drainage, crop management and subsoil manuring can help to stabilise yield in soils prone to waterlogging (Shaw et al. 2013; Manik et al. 2019).

Soil fertility

Due to the continent's age and extensive weathering, Australia has some of the least fertile soils in the world. Total and available P and low pH (Eldridge et al. 2018) and soil organic matter (SOM), critical components of healthy soils and sustainable agricultural production, are naturally low in Australian soils. This leads to macronutrient (particularly N, P and sulfur [S]) and micronutrient (copper [Cu], zinc [Zn] and manganese [Mn]) deficiencies. Furthermore, traditional cropping reduces SOM (Dalal and Mayer 1986) which causes the natural fertility of cropped agricultural soils to decline over time.

Compared with most other grain crops in Australia, canola has a greater requirement for nutrient inputs to achieve high yields. Canola needs about 25% more N, P and potassium (K), and up to 5 times more S than wheat to balance fertiliser inputs with nutrient removal in grain (Hocking et al. 1999).

Canola's nutritional requirements will vary depending on soil type, rainfall, crop rotation and target yield. Deficiency of any of the key nutrients or trace elements will prevent canola crops from producing optimum yields. Paddock records, including yield and protein levels, fertiliser test strips, crop monitoring, and soil and plant tissue tests all help to formulate an efficient nutrition program for canola (Parker 2009b).

Figure 9 *Waterlogging resulted in stunted rooting systems of canola.* Photo: Shihab Uddin, NSW DPI.

Available soil water

Available soil water at sowing is a critical factor for successful canola germination and seedling establishment, as low soil water at this stage can reduce the germination rate and slow seedling emergence. A modelling study using APSIM-CANOLA demonstrated that available soil water at sowing (starting soil water) has a significant effect on canola yield particularly in a low-yielding environment of southern Australia (Zeleke et al. 2014). This effect is less in a high-yielding environment where in-season rainfall can be sufficient to achieve the water-limited potential yield.

Water stress during canola flowering or pod development stages causes large yield losses, especially if coinciding with high temperatures (Edwards and Hertel 2011). In south-eastern Australia winter crops commonly have enough water either from stored soil water or rainfall during the early growth stages. The reproductive phase is often affected by water stress or terminal drought.

Canola plants are efficient at using subsoil moisture provided the soil profile is free of subsoil constraints, such as hardpans and sodic subsoils (Potter et al. 2009). Shallow root depth induced by subsoil constraints and high temperatures compounds water stress effects and results in large yield losses (Edwards and Hertel 2011). Under such conditions, improving root growth in and through the constrained subsoil is key to productivity, as this enables the crop to use deep subsoil water late in the growing season. Water use at this late stage has a 2 to 3-fold greater conversion efficiency into grain yield (Kirkegaard et al. 2007) than seasonal average-based conversion efficiencies (e.g. 20–25 kg/mm versus 50–60 kg/mm).

More information

References and resources relating to this chapter are listed in Appendix 1 (p. 95).

Acknowledgement

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Crop limiting factors: weeds

Dr. Md Asaduzzaman (Asad)
NSW Department of Primary Industries, Wagga Wagga NSW 2650

Summary

- In Australia, canola (*Brassica napus* L.) production can be constrained by a wide range of weeds.
- Australian canola growers utilise a series of chemical, mechanical and cultural tactics to control crop weeds in an integrated weed management (IWM) approach in their farming systems. This approach is known as the BIG 6.
- Canola offers unique opportunities to manage weeds. Hybrids are generally more competitive against weeds than conventionally bred varieties.
- Paddock selection is important. Paddocks should be relatively free of broadleaf weeds as they are difficult to control in canola, especially charlock (*Sinapsis arvensis*), wild turnip (*Rapistrum rugosum*), wild radish (*Raphanus raphanistrum*) and other *Brassicaceae* weeds.
- When selecting paddocks for canola, care is needed to avoid the potential effects of residual herbicides applied to fallows or the previous crop. Plant back restrictions apply for Group 2 and Group 3 herbicides.

Weed spectrum and density

Canola is highly susceptible to weed competition during its early growth stages. Many weed species naturally occur in canola paddocks and cause significant yield loss (Table 1). Grasses, such as annual ryegrass (*Lolium rigidum*), vulpia (*Vulpia myuros*) and wild oats (*Avena* spp.), are the most abundant weed species in canola crops in south-eastern Australia. Annual ryegrass, vulpia and brome grass (*Bromus inermis*) also harbour cereal root diseases, which can affect subsequent cereal crops.

Changed cropping practices over the past 2–3 decades have allowed some other weed species to increase under the predominately no-till, residue retention system used for establishing canola. Examples include, 'harder to kill' weeds such as flaxleaf fleabane (*Conyza bonariensis*), windmill grass (*Chloris truncata*) and feathertop Rhodes grass (*Chloris virgata*).

Canola quality is reduced if contaminated with *Brassica* weed seeds (Table 1) (Salisbury et al. 2018). Glucosinolate and erucic acid content in Australian *Brassicaceae* weed species varies. High levels of contamination can increase the risk of erucic acid in the oil and glucosinolates in the meal, impacting canola grain quality and acceptance into the market.

Table 1 *Common weeds of Australian canola crops (GRDC 2015).*

Weed (common name)	Scientific name	High levels of glucosinolates (G) and/or erucic acid (E) **
Wild radish*	*Raphanus raphanistrum*	G (11.76%), E (6.35%)
Indian hedge mustard*	*Sisymbrium orientale*	G (17.95%), E (7.87%)
Annual ryegrass	*Lolium rigidum*	
Shepherds purse*	*Capsella bursa-pastoris*	G (29.79%)
Wild turnip*	*Brassica tournefortii*	G (13.33%), E (4.18%)
Charlock*	*Sinapsis arvensis*	G (7.78%), E (5.15%)
Paterson's curse*	*Echium plantagineum*	
Vulpia*	*Vulpia* spp.	
Wireweed	*Polygonum aviculare*	
Toad rush	*Juncus bufonius*	
Wild oats	*Avena* spp.	
Spiny emex	*Emex australis*	
Turnip weed*	*Rapistrum rugosum*	G (9.09%), E (5.49%)
Fumitory	*Fumaria* spp.	
Buchan weed	*Hirschfeldia incana*	G (9.93%), E (6.19%)
Cape weed	*Arctotheca calendula*	
Volunteer cereals		

* Weeds species that have been particularly important in restricting canola production before the introduction of triazine tolerant (TT) varieties.
** Minimum percent weed contamination to exceed the canola quality standard for glucosinolates and erucic acid (Salisbury et al. 2018).

High weed densities significantly increase weed seed banks when herbicide control is poor (Table 2). The greater the initial weed density, the higher the final weed number post control.

Table 2 *Initial weed density effect on final weed number at different rates of control (GRDC 2015).*

Initial density (plants/m²)	Final weed density (plants/m²)	
	95% control	75% control
10,000	500	2,500
1,000	50	250
100	5	25

The likelihood of selecting herbicide-resistant biotypes increases in situations where weed populations are high. Repeated use of the same mode of action (MoA) can cause herbicide resistance to evolve quicker in weed populations.

Herbicide resistance in Australian weeds

Most Australian growers have adopted minimum-till or no-till farming systems. These systems have largely relied on herbicides and crop sequences to manage weeds. This approach has contributed to widespread herbicide resistance.

Herbicide resistance now affects many weed species. Annual ryegrass (*Lolium rigidum*) is the most economically important weed in Australia (Busi et al. 2021), but resistance is also prevalent in sow thistle (milk thistle) (*Sonchus oleraceus*) and prickly lettuce (*Lactuca serriola*). It is less common in brome (*Bromus* spp.), barley grass (*Hordeum* spp.), wild oats (*Avena* spp.), wild radish (*Raphanus raphanistrum*), Indian hedge mustard (*Sisymbrium orientale*) and fleabane (*Conzya bonariensis*) (Boutsalis et al. 2023).

The major herbicide resistance problem in grass weeds in Australia is to Group 1 and Group 2 herbicides. Resistance to Group 5, 3, 12, 22 and 9 herbicides has also been documented.

Wild radish has developed resistance to Group 2, 5 and 12 herbicides. Combined with the resistance in ryegrass, this has serious implications for growers in general but particularly to those using Clearfield® and TT varieties.

Canola growers in Australia have access to a range of herbicide tolerance traits (Table 3). Together with alternative chemical options (Table 4) at sowing e.g. pre-emergent herbicides, and cultural and mechanical strategies, canola offers growers multiple weed management practices.

Table 3 *Canola herbicide tolerance systems in Australia, 2023.*

Herbicide tolerance systems	Abbreviation	Herbicide group
Conventional	CC	-
Triazine tolerant	TT	5
Clearfield® (imidazolinone tolerant)	IMI	2
Glyphosate tolerant	GT	9
Roundup Ready®	RR	9
TruFlex®	-	9
Stacked		
Glufosinate tolerant + Triazine tolerant	Glu + TT	10 + 5
Glyphosate tolerant + Glufosinate tolerant	GT + Glu	9 + 10
Glyphosate tolerant + Triazine tolerant	GT + TT	9 + 5
Glyphosate tolerant + Clearfield®	GT + IMI	9 + 2
Triazine tolerant + Clearfield®	TT + IMI	5 + 2

Table 4 *Common herbicides used in canola crops in Australia.*

Herbicide group	Herbicides
1	Diclopfop-methyl, fluazifop, quizalofop, clethodim, butroxydim, propaquizafop
2	Imazapic+imazapyr, imazamox+imazapyr (Clearfield® varieties)
3	Trifluralin, pendimethalin, oryzalin, propyzamide
4	Clopyralid, halauxifen
5	Simazine, atrazine, terbuthylazine (TT varieties)
9	Glyphosate (RR varieties)
10	Glufosinate-ammonium
13	Bixlozone
15	Metolachlor, S-metolachlor, metazachlor, triallate, napropamide
22	Diquat

WeedSmart – The BIG 6

WeedSmart is a national communications and extension team delivering science-backed weed control solutions to growers and advisors. The BIG 6 is an IWM program that growers can apply across all cropping systems. It is a diverse approach that includes several chemical and non-chemical tactics putting downward pressure on the weed seed bank and reducing the risk of weeds developing herbicide resistance.

1. Rotate crops and pastures

Add diversity to the farming system and the weed management strategies increasing the tactics available, including herbicide tolerance traits.

2. Increase crop competition

Optimise crop growth and adopt at least one competitive strategy e.g. higher plant population, uniform seed distribution, competitive crop type and variety, improved soil characteristics.

3. Mix and rotate herbicides

Rotating between herbicide MoA buys time, while mixing herbicide MoA (in a single or consecutive applications) buys applications (shots) to reduce the risk of herbicide resistance.

4. Optimise spray efficacy

Make every drop count and avoid spray drift.

5. Stop weed seed set

Aim for 100% control of weeds and monitor for survivors following each weed control activity. Implement tactics to stop seed set in late season weeds including in a pasture phase e.g. crop topping, windrowing, hay or silage or brown manure.

6. Implement harvest weed seed control

Capture weed seed survivors at harvest to prevent them adding to the weed seed bank. Tactics include the use of narrow windrow/chaff lining, chaff decks/tramlining, chaff carts, and weed seed impact mills.

The quantity of weed seed collected is determined by the proportion of weed seeds that enter the header. Harvest weed seed control is improved by optimal header setup, harvest timing and height.

Further information go to WeedSmart BIG 6.

Monitoring and site-specific weed management (SSWM)

Post treatment monitoring is critical to the success of weed management plans. This includes detecting and controlling survivors to prevent them from setting seed.

In fallow, these should then be re-treated by spot tillage, spot spraying including weed sensor spray technology, or manual removal to prevent seed set. The 'double-knock' program of applying 2 different MoA herbicides in 2 separate passes spaced 7–10 days apart is now commonly used in the leadup to sowing canola.

Remote sensing or physical monitoring can be used to detect patches followed by effective control with herbicides. Monitoring and SSWM support efficient and effective herbicide use, helping to minimise environmental risks and avoid herbicide resistance.

Future directions

Herbicide resistant weeds are promoting the rapid evolution of industry's approach and attitude to weeds. The focus has shifted to planning multiple actions to minimise weed seed production, depleting the weed seed bank, and reducing herbicide resistance risk.

Technology is developing rapidly. Breeding varieties with improved early vigour and multiple stack-herbicide traits is ongoing. Herbicide application technology advances like green-on-green, green-on-brown targets are using optical spray technologies applied to ground operated booms, drones, and swarm bots. Incorporating field mapping (boom and UAV) are in various stages of development. Subsequent prescription weed mapping and management techniques are predicted to be commercial alternatives within a few years.

Competitive crops (Figure 10) rely on a combination of agronomic practices like variety selection, seeding rate, sowing time, row spacing, crop nutrition and disease management. The legacy effects of canola and other crops and pastures in the system play an important role in managing weeds in all farming systems.

More information

References and further reading relating to this chapter are listed in Appendix 1 (p. 98).

Figure 10 *Weeds infestation in competitive (left) and non-competitive (right) canola cultivars, Wagga Wagga Agricultural Research site.* Photo: Md Asaduzzaman, NSW DPI.

Physiology, agronomy and farming systems

Dr. Rajneet Uppal[1], Mathew Dunn[1], Dr. Julianne Lilley[2] and Dr. John Kirkegaard[2]
[1] NSW Department of Primary Industries, Wagga Wagga NSW 2650
[2] CSIRO, Canberra ACT 2601

Summary

- Canola production in Australia has expanded since the 1990s from the more reliable medium to high rainfall areas of the cereal growing region to all areas except on the driest margins.
- Understanding the optimal flowering period to avoid heat, frost and drought stress has led to better matching of varietal phenology to sowing date across diverse environments to increase productivity.
- Earlier sowing systems, increased use of hybrids, improved nitrogen (N) inputs, a range of herbicide tolerant options and winter types for grazing have underpinned ongoing expansion and yield increases.

Introduction

Australian canola production systems differ from those of other major global producers. In the EU and China, production systems involve autumn-sown winter canola that becomes dormant through a cold winter followed by rapid growth in spring, while in Canada the growing season is short and spring canola is sown in spring and grows through summer. In Australia, spring canola is sown in autumn, grows vegetatively through the mild winters to flower in spring and is harvested in early summer. Under these conditions the critical climatic limits to production are:

- timing of the opening rains in autumn to allow timely sowing
- damaging spring frost on small pods and developing seeds
- terminal heat and drought during flowering and pod fill.

Ensuring that the sensitive reproductive stages avoid late frost and heat as well as drought during grain-filling is the key determinant of yield potential. Winter canola is grown as a dual-purpose (graze/grain) in the higher rainfall areas of southern Australia. Sown in February–March, its longer vegetative phase allows grazing during the vegetative period prior to bud elongation without significant impacts on grain yield.

Climate and water availability

In Australia, canola is predominately grown as a rainfed crop in areas where mean annual rainfall can vary from <325 mm to >600 mm. Only a small area of canola is grown under irrigation in Australia.

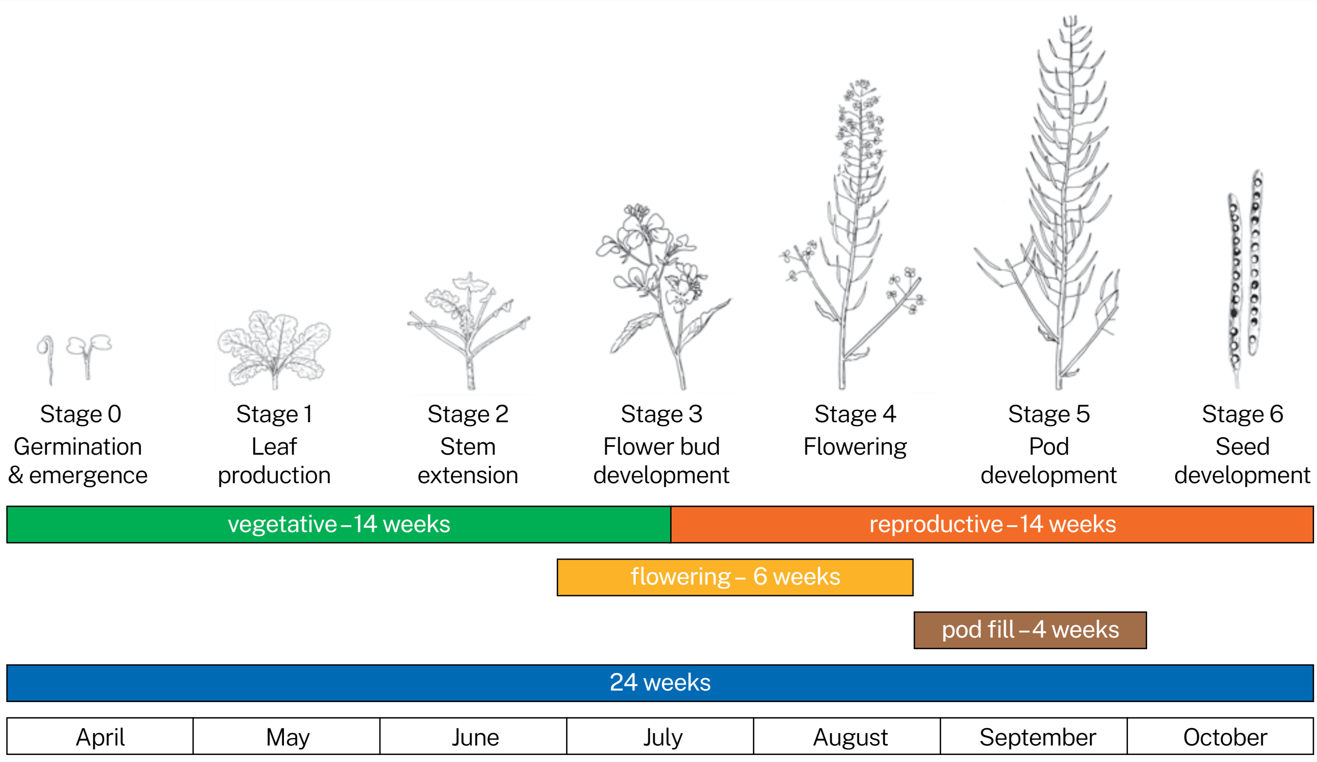


Figure 11 *Phenological development stages of canola matched to seasonal growth in Australia.*
Source: Hertel and Edwards (2011).

Back in the 1990s, canola was initially grown in the south-eastern areas with more reliable rainfall (>400 mm annually). With improvements in breeding and agronomy, canola was extended to the low rainfall areas (<325 mm) especially in Western Australia due to its rotational benefits in weed and disease control. Canola production in Australia is affected by the seasonal variability in rainfall timing and amount (mm) as well as canola prices. The seasonal variability of rainfall in Australia is large and can result in reduced crop area and production. For example, the Millennium drought period (between 1997 and 2009) experienced late breaks, low rainfall and warmer springs. More recently, the consecutive 2018–2019 drought years led to a decline in area of 15% and production of 30%, while in the past few years (2020–2022), production has increased by 27% and is at an all-time high, including an expansion in area of approximately 30%.

Variety selection

The main features to consider when selecting a canola variety include:

- maturity types that fit the growing season
- yield potential
- oil content
- herbicide tolerance
- disease resistance.

Canola varieties are categorised into 2 breeding groups:

1. hybrids
2. open pollinated (OP).

Within these breeding groups, there are 5 herbicide tolerance groups:

1. conventional
2. triazine tolerant (TT)
3. imidazolinone tolerant (IMI, Clearfield®)
4. glyphosate resistant (Roundup Ready®,RR and Truflex®)
5. stacked herbicide tolerance e.g. TT+RR, TT+IMI.

There were 60 canola varieties available for Australian growers in 2022. These varieties are organised into 4 phenological groups based on the rate of development to flowering. The 4 phenology groups include:

1. fast developing spring types which are preferred in low rainfall zones
2. fast to mid developing spring types suited to low to medium rainfall zones
3. mid to slow spring types for medium to high rainfall zones
4. slow spring to winter types for high rainfall zones and for grazing.

This wide range of phenology groups in combination with herbicide tolerance has enabled the wide adaptation of canola across diverse cropping environments and farming systems in Australia.

Physiology

Canola development and drivers of development

Canola development stages include:

- seed germination
- vegetative development (leaf production and stem elongation)
- reproductive development (floral initiation, bud emergence, flowering, pod formation, grain-filling and oil deposition and seed maturation)
- plant senescence.

Phase duration from emergence to floral initiation; floral initiation to bud emergence; bud emergence to flowering and flowering to maturity are determined by thermal time. Canola is a long-day plant so increasing photoperiod can reduce thermal time to flowering. Vernalisation (exposure to cool temperature) can also reduce the thermal time requirement of the emergence to floral initiation phase in some varieties.

Canola varieties vary in the extent of sensitivity to vernalisation and photoperiod and consequently in rates of phenological development in response to environment. In Australia, varieties range from winter types which have obligate vernalisation requirements and are slow to develop, through to spring types with little or no vernalisation or photoperiod requirement and that develop rapidly in response to thermal time.

Accurate prediction of timing of the bud-visible and flowering stages is important for various crop management practices such as optimal N application timing, grazing period timing and length in a dual-purpose cropping system or variety choice in new environments.

Crop growth rate is closely related to the amount of solar radiation captured by the leaves. Depending on variety and sowing date, the plant produces between 6 leaves for fast-developing spring varieties under long days and near-optimal temperature to over 30 leaves in slow-developing winter varieties under cool temperatures and short days. The rate that light interception increases depends on plant density, N supply and temperature during the early growth period. Canopy size is often measured in terms of green area index (GAI), including green leaves, stems and pods and typically reaches between 0.5 and 2.0 by the start of stem extension and a maximum of between 2.0 and 7.0 by flowering. A GAI of about 4.0 is required for the crop canopy to intercept about 90% of the incoming solar radiation. Leaves senesce and are shed rapidly from late flowering onwards. At full flower, the canopy of flowers can intercept or reflect up to 60% of the incoming radiation, causing potential shortages of photosynthate to the early developing pods underneath. After flowering, a dense layer of green pods provides a photosynthetic canopy.

Roots reach maximum depth late in the flowering phase. In the absence of significant soil constraints, the leading roots will penetrate downwards through the soil at about 1–2 cm per day and have been reported at depths below 3 m in unconstrained soils. Typically, about two-thirds of the total root system length is found in the top 30 cm of the soil profile.

Dry matter production and yield components

Dry matter accumulation in canola shoots is initially slow, but once canopy closure is reached a period of rapid growth ensues reaching a maximum before slowing as leaves senesce during pod filling. At flowering approximately 60% of the shoot dry matter is in the leaves and 40% in the stems. The green pod walls and stems photosynthesise actively, although not as efficiently as leaves, as stomatal density is not as high. The radiation-use efficiency (RUE) of canola before flowering ranges from 1.2 g/MJ to 1.7 g/MJ of total solar radiation and has been reported to be 8% greater in hybrid canola relative to OP varieties. RUE is known to be 30% lower in TT varieties due to an inefficiency in photosystem II linked to the herbicide-tolerance trait.

Canola yield is related to biomass production. Harvest index (the ratio of grain dry weight to above-ground dry weight at harvest maturity) of Australian canola crops typically varies between 0.25 and 0.35. In stressful situations the harvest index can be substantially lower, due to poor pod set. Harvest indices of canola are similar to other grain crops, when account is made for the higher energy content of canola grain (oil containing about 2.5 times as much energy as carbohydrate, as in cereals).

Yield is poorly related to biomass at the start of flowering, and a stronger relationship exists between yield and biomass at maturity. A range of abiotic and biotic stresses can affect final seed number and size, causing considerable variation in yield. Yield potential is more closely related to biomass accumulation during the critical period when final grain number is determined, which is the major driver of yield in canola. Grain-filling is dependent on post flowering biomass accumulation, with only approximately 10% of assimilates utilised from pre-flowering reserves. Water soluble carbohydrates accumulated in the pre-flowering period contribute more to yield in dry years (10–22%) than in average (3–9%) or above average rainfall years (7–12%).

Seed number/m^2 is determined by pods/m^2 and seeds per pod. Pods/m^2 is more strongly associated with yield than seeds per pod. Potential pod number is determined by flower number and pod abortion during flowering and grain-filling. Pod number is influenced by number of leaves and potential branches, while the ability of canola to compensate for low plant density through more branching can increase pod number. While yield is strongly correlated to grain number, canola has the capacity to compensate yield through an increase or decrease in seed size. Seed size varies between 2.5 mg and 5 mg per seed.

While grain yield under dryland conditions generally varies between 0.5 t/ha and 3 t/ha, more than 5 t/ha has been recorded in favourable situations with a long, cool growing season and adequate moisture.

Oil and protein accumulation

Almost half of the final weight of canola seed is oil accumulated in lipid bodies or oleosomes. A trade-off between protein content and oil content has been consistently demonstrated in canola seed. Increasing N supply can increase seed protein content and decrease seed oil concentration. Most of the protein in canola seed is accumulated during the first half of grain-filling, while most of the oil content is accumulated during the second half of grain-filling. Thus, stress during early grain-fill might not affect oil content as much as later stress. Any factors that curtail the grain-filling period prematurely (e.g. premature windrowing, high temperatures) tend to have a disproportionately large effect on oil content. Research has shown that for every 1 °C rise in the temperature during grain-filling oil content declined by 1.5–2.7%.

Water use efficiency

The ability of crops to access soil moisture is critical for crop productivity and yield potential, especially in rainfed agriculture. A meta-analysis of 42 experiments with crop simulation reported canola water use efficiency for grain of 11 kg/ha/mm, with the most efficient crops achieving 15 kg/ha/mm. A recent trend of sowing earlier in the season and widely adopted use of hybrids has consistently improved water use efficiency by reducing the evaporative losses during early vegetative stages and utilising water during the critical period.

In canola growing regions, the grain-filling period often coincides with high crop transpiration, increased soil evaporation and dry conditions. Crops rely on accessing stored soil moisture through deep root systems. Early sown crops (April) in southern Australia can develop root systems up to 3.5 m in deep red loam soils compared with 2 m from later sowing in May. Deeper roots were associated with an extra 33 mm of water uptake below 2 m during a terminal drought in 2018, leading to an additional yield of 1.2 t/ha and water use efficiency of the deep stored water was 36 kg/ha/mm.

Heat stress

Canola is sensitive to heat stress at temperatures greater than 29.5 °C during reproductive development. Canola yield losses of 0.3 t/ha in Australia were expected for every 1 °C increase in mean daily post-anthesis temperature. Short periods of high temperature at reproductive development induce floret sterility and abortion, seed abortion and disrupt pod and seed development, resulting in reduced pod number, seeds per pod and seed yield. Research in controlled environments has shown that female reproductive organs are most sensitive to heat stress 7 days before and after the start of flowering. Other research which deployed portable heat chambers to simulate heat stress in the field demonstrated that mid flowering to end of flowering was the phenological stage most sensitive to heat stress and yield was reduced by 40–56%.

Frost stress

Open flowers and developing pods and seeds are most susceptible to frost damage. Due to its indeterminate nature, canola flowers over a 30- to 40-day period. It can compensate from early flowering frost stress by producing more flowers when soil moisture is not limiting. In the event of late season spring frosts coinciding with pod development and grain-filling, plants are unable to produce more flowers or pods. These frosts can reduce grain yield and oil quality.

Frost risk is highly variable across the Australian cropping region and from year to year. It can cause significant crop losses. For example, it is estimated that in 2017 frost reduced canola yield in NSW by approximately 0.3 t/ha, a total of 120,000 tonnes valued at A$63 million.

Damage to canola crops from frosts can be highly variable within a paddock. The extent of damage will depend on factors such as temperature, soil type, soil moisture, cloud cover, wind speed, position in the landscape, crop development stage, crop nutrition and crop density. Generally, low-lying paddocks with light coloured soils are more prone to frost risk.

Frost symptoms at reproductive development can range from bud discolouration to white, twisting inflorescence, floret abortion, pod abortion, discolouration of pods to pale yellow and blistered surface and seed death leading to gaps in the pods. Damage during grain-filling is particularly evident after a severe late frost when developing grain turns into a mushy green mass that dries into a small black or brown speck.

The extent of damage can be assessed by opening pods and checking for healthy and damaged seed. Symptoms of frost damage might not be obvious until 5–7 days after the frost. Identifying frost affected crops is important to allow timely management decisions such as options including cutting for hay, sacrificial grazing or reducing further investment by minimising inputs.

Critical period for yield development

The critical period for yield determination is the period in which abiotic stresses have the greatest impact on grain yield. To identify the critical period for canola, field experiments using discrete periods of shade from the vegetative stage through to maturity to limit the photosynthetic assimilates, mimicked the effects of abiotic stresses.

The experiments determined:

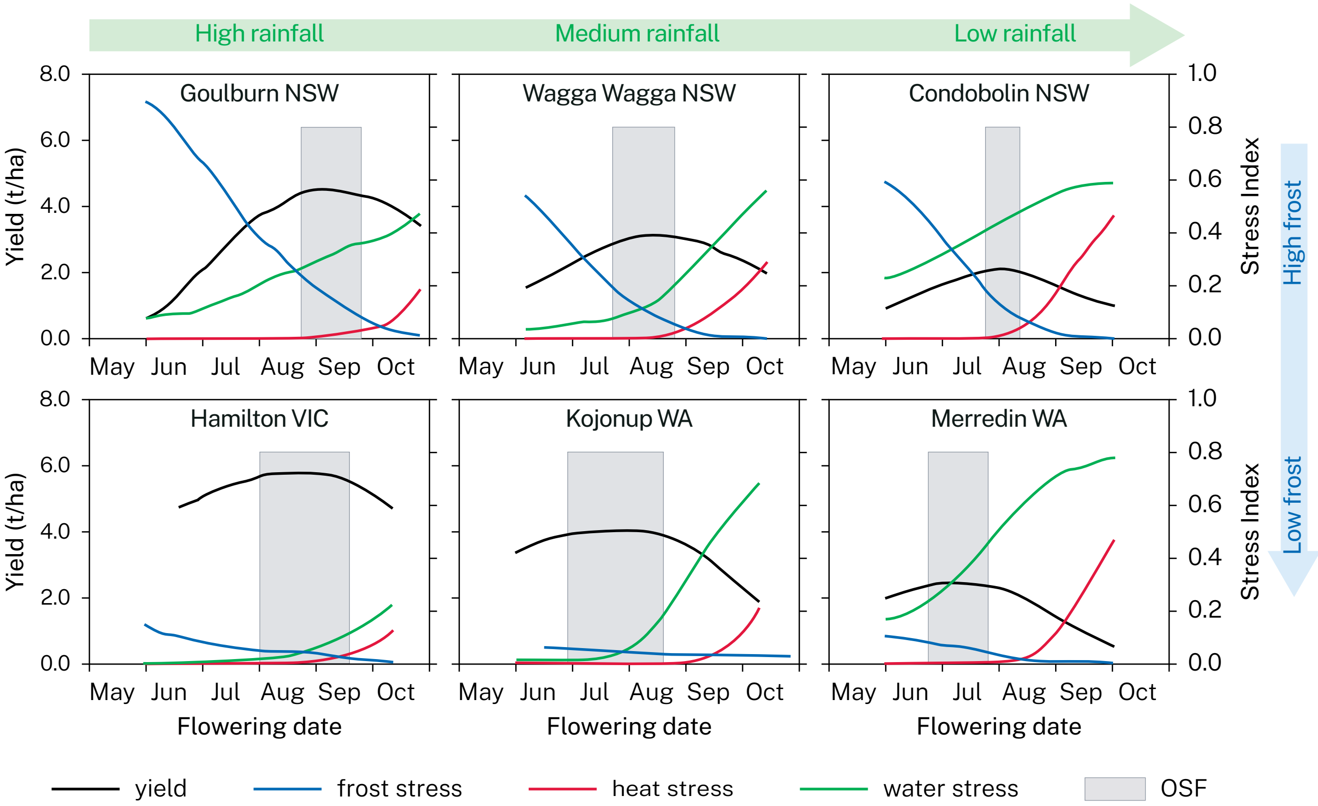
- The critical period of canola extends from 100 °Cd to 400 °Cd after the start of flowering, centring around 300 °Cd after flowering.
- Stress during the critical period, reduced seed number with pods/m^2 more sensitive in the early part of the period and seed per pod more sensitive in the later part.
- Seed size increased but did not fully compensate for the reduction in seed number and yield was reduced. These trends were similar on the lateral branches and main stem and were linked to the timing of their development.
- Seed oil content also declined in response to stress during the critical period however a trade-off between seed oil content and protein content resulted in increased protein content.

Optimum start of flowering

Researchers have used multi-location field experiments and simulation studies to understand the interaction between sowing date and phenology to determine the optimum flowering period across diverse Australian cropping regions. Simulation studies found that the relative importance of seasonal water supply and extremes of temperature varied with environment and these defined the optimal flowering windows (Figure 12).

In canola, the optimal start of flowering (OSF) period is defined as the range of flowering dates when yield is at least 95% of the maximum long-term average yield. Achieving flowering during the OSF period minimises the risk of abiotic stress (frost, heat, drought) during the critical period for yield development. In the Australian cropping region, the duration of the OSF period is shorter (19–35 days) in low rainfall environments and longer (30–52 days) in high rainfall environments.

Sowing date recommendations vary for varieties with different phenological development patterns and growing environments. Understanding the OSF in various cropping regions allows breeders to develop varieties with appropriate phenology for specific environments and underpins variety choice for growers seeking to minimise production risk. A range of tools are under development to identify the optimal sowing date for the range of canola varieties available to growers.



Graphs show the long-term average yield, frost stress, heat stress and water stress indices associated with a range of start of flowering dates, simulated with the APSIM (Agricultural Production Systems sIMulator) model at each location. The OSF period is shown where the yield is at least 95% of the maximum yield. Source: Lilley et al. (2019).

Figure 12 *Optimal start of flowering period for canola at 6 diverse locations in the Australian cropping regions.*

Agronomy

Sowing date

Grain yield is maximised when sowing date and variety combinations result in a start of flowering time that coincides with the OSF period for the specific location. Recent research has identified OSF periods for locations across Australia which have then been used to classify optimum canola sowing dates.

Winter canola varieties are generally grown in higher rainfall areas to provide grazing forage for livestock in autumn and early winter before being locked up in July for grain harvest. These varieties have a vernalisation requirement that results in late flowering times irrespective of sowing time. February–March sowing dates are recommended to maximise both forage potential and grain yield.

Slow spring canola varieties are vernalisation responsive however, unlike winter varieties do not have an obligate vernalisation requirement. They tend to have a very stable flowering window regardless of sowing date and therefore are well suited to take advantage of full soil water profiles following wet summers with early sowing dates. Mid March through to mid April sowing dates are recommended.

Mid spring varieties are only weakly vernalisation responsive. As a result, they are generally slower in warm autumn conditions than fast spring varieties however, at later sowing dates the vernalisation response is met quickly allowing more rapid development. Sowing dates from the second week in April through to early May are recommended.

Fast spring varieties have little or no vernalisation responsiveness. They have little flexibility in their optimum sowing window and as a result early sowing can cause significant yield penalties. Fast spring varieties are best suited to situations where later sowing dates are expected and lower rainfall environments. Late April through to early May sowing dates are recommended.

Sowing rate

Canola sowing rates in Australia vary widely depending on the situation with a common range of 1.5 kg/ha to 4 kg/ha. Excessively high plant density can often result in tall, thin and weak stems that are more susceptible to lodging, while excessively low plant density can limit yield potential, increase crop vulnerability to diseases, pests, weed competition and environmental stresses. Sowing rate decisions are governed by target plant density, seed size and the proportion of seeds expected to establish.

Rainfall zone and variety are commonly considered factors when determining target plant density. Ideal plant populations in the low rainfall zones range from 20 plants/m² to 40 plants/m², compared with 30 plants/m² to 60 plants/m² in the high rainfall zones. Hybrids are often targeted at the lower end of the ideal plant population range due to the increased vigour associated with these varieties. High target plant densities can also be used as a weed management tactic to increase crop/weed competition.

Seed size is essential when determining sowing rate. It can vary widely depending on the seed crop performance, seed processing/grading, and variety. A range of 150,000–200,000 seeds/kg for hybrids and 250,000–350,000 seeds/kg for OP varieties is common.

Canola establishment can be highly variable with the conditions, equipment and equipment setup at sowing commonly contributing to the proportion of canola seeds established. Conditions that reduce seedling establishment include cold temperatures, low/variable soil moisture, high stubble loads, fertiliser toxicity, disease infection and insect/mollusc attack. Under reasonable to excellent sowing conditions an establishment percentage of between 60% and 80% can be expected.

Sowing depth

A sowing depth of 15 mm to 30 mm into a firm, moist seedbed is generally considered ideal across Australia's canola growing environments. Deeper seed placement (30–60 mm) increases the risk of failed emergence, however it can be used successfully in some situations where the soil surface has dried and soil moisture is located further down the soil profile. Success with deeper sowing often depends on the soil type, soil structure, the amount and timing of rainfall received following sowing. Deeper sowing results in elongated hypocotyl (the shoot that emerges from the seed) length, depleting seed reserves and leading to thinner/weaker hypocotyls. This results in reduced seedling vigour that can be compounded by low temperatures.

Seed quality can have a significant effect on the likelihood of achieving adequate establishment under deeper sowing conditions. Large sized seed with strong seed vigour is best suited to deeper sowing conditions.

Drilling seed to a constant depth is the widely preferred sowing method. Seed broadcasting with or without incorporation often results in unreliable and staggered germination. The use of disc seeders has become more common in recent years in retained stubble systems. Satisfactory results rely on effective equipment setup to achieve consistent sowing depth.

Canola can be dry sown successfully on suitable soil types in reliable rainfall environments with follow up rainfall triggering seed germination. Under dry sowing conditions seed depth should be reduced to 15–20 mm and pressure on closing wheels should be minimised.

Establishment

Canola establishment can be difficult due to its small seed size, typically ranging between 2.5 mg/seed and 5 mg/seed. Adequate and even establishment is critical to optimising canola grain yields (Figure 13, Figure 14, Figure 15). Important factors influencing canola establishment include:

- seed quality
- hypocotyl elongation
- root and shoot growth
- sowing date, depth and rate
- seedbed preparation (moisture content, cloddiness, soil-seed contact, competing weeds)
- nutrient availability.

Figure 13 *Canola seedlings emerging in a minimum tillage retained stubble system in southern NSW.* Photo: John Kirkegaard, CSIRO.

Canola exhibits epigeal germination, which restricts the sowing of seed to depths not exceeding the maximal length of the hypocotyl. The short hypocotyl of canola varieties reduces seedling emergence and seedling vigour when seeds are sown below soil depths of 15–30 mm. Current research is focused on genetic solutions to develop varieties with better establishment through improved early vigour and long hypocotyl and the capacity to develop longer cotyledons to improve emergence from deep sowing.

Figure 14 *Canola in Australia is commonly grown in no-till, stubble-retained systems in rotation with wheat.* Photo: Greg Condon, Grassroots Agronomy.

Figure 15 *Canola sown inter-row in standing wheat stubble.* Photo: Greg Condon, Grassroots Agronomy.

Harvest

Most canola in Australia is currently windrowed (swathed) before harvest, however direct-harvesting is used in many circumstances. The method chosen generally depends on the availability/cost of windrowing equipment/contractors and the risk of adverse weather conditions for the location. Each method has its own advantages and disadvantages. Windrowing is generally favoured due to the improved uniformity of crop ripening, increased seed dry-down speed, reduced risk of wind and hail losses and reduced shattering during harvest. Direct-harvesting is generally favoured in lower biomass crops where crop maturity is consistent across a paddock and green weeds within the crop are low.

Windrowing canola too early can result in lower yields and oil concentrations, while windrowing too late can lead to increased shattering losses. The current recommended method for assessing canola maturity for optimum windrow time includes assessing both the main stem and branches, acknowledging that the branches can contribute up to 80% of total grain yield. Canola crops should be windrowed when 60–80% of seed sampled from the middle third of the main stem and branches has changed colour from green to red, brown or black.

Windowed canola crops are ready for harvesting once the grain moisture drops to 8% or less. This generally occurs within 5–14 days of windrowing, depending on weather.

Farming systems

Benefits of canola in the crop rotation

Canola is one of the most important and effective broadleaf break crops in cereal rotations. In general, yield benefits from rotation are mostly attributed to reduced incidence of disease, pests and weeds, although they can also be related to N and/or water supply. Numerous reviews have highlighted canola’s effectiveness in breaking the disease cycles for major soil-borne and foliar pathogens of cereal crops. Due to the widespread release of various herbicide tolerant varieties, canola has become a major weed management tool within farming systems.

In Australia, the canola area expanded rapidly after the release of TT varieties in 1993 which facilitated the management of intractable weeds such as wild radish (*Raphanus rapistrum*). Since then, hybrids resistant to imidazolinone (Clearfield®) and glyphosate (Round-up Ready®) have been released and their use is growing. Recently, 'stacked' herbicide tolerant varieties resistant to combinations of 2 or 3 classes of herbicides have been released, and adoption is likely where grass weeds such as annual ryegrass have developed resistance to major herbicides. The ongoing issues of herbicide resistance will mean careful stewardship and the integration of non-herbicide methods (e.g. crop vigour, rotation, harvest weed seed management [HWSM], tillage) will be a necessary part of future canola farming systems.

Historically it was recommended to grow canola around one year in every 4 to avoid breakdown in disease resistance that can significantly reduce canola yield, however the high market value of canola has resulted in an increase in the frequency of its use in the rotation in some areas. Overall, intense crop rotations are not completely compensated with agricultural inputs, but the value of canola makes short rotations more profitable under current price-to-cost ratios. Sustaining productivity improvements in canola in the longer term will require a balance between the use of sufficiently diverse rotations, and the careful use of disease resistant varieties and agricultural inputs.

Recent opportunities for improved production

Early sown canola

Recent research highlights earlier sowing of canola can improve productivity and reduce the economic risk if the crop flowers during the appropriate window. Earlier sowing has logistical benefits for farm operations and has been key to maintaining yield under seasons with reduced rainfall, warmer springs and more rapid onset of drought. A yield decline of 5–12% per week delay in sowing after mid April has been shown in several studies. In high-rainfall environments, early sowing provides the opportunity to gain additional income from grazing. In the low-rainfall environment of southern Australia, an opportunity to sow canola early enables the crop to capture more water and convert this to yield. To maximise grain yield from early sowing dates, it is important for growers to sow varieties with slower development rates to target flowering in the optimal window in their environment to minimise production losses due to abiotic stress. Knowing the optimal flowering time for a location will allow breeders to develop varieties with appropriate phenological characteristics for target environments.

Dual-purpose canola

The development of dual-purpose canola systems, where the crops are sown earlier than normal for forage production and development is slowed by defoliation to maintain suitable flowering windows for seed production, has provided further novel options to adapt canola to new growing environments. Crops are grazed by sheep or cattle during the vegetative period (Figure 16). It is important to cease grazing of the crop before bud-elongation to avoid damage to the developing reproductive structures and consequent reduction in grain yield.

Dual-purpose cropping of canola is now practiced across 200,000 ha annually, delivering additional benefits to industry of over A$200 million per annum. The strategy provides substantial benefits: weed and disease control in cereal crops, perennial pasture establishment and higher farm stocking rates, risk mitigation and increasing enterprise resilience. Research has focused on understanding variety × sowing date interactions and refining grazing and livestock management strategies to maximise grazing value while protecting subsequent grain yield.

Figure 16 *Dual-purpose canola being grazed in southern NSW.* Photo: John Kirkegaard, CSIRO.

Hyper yielding canola

Recent research has focused on understanding management factors such as variety choice, nutrition, fungicide, and canopy management to achieve a yield of 5 t/ha in canola and to understand genotype × environment × management (G × E × M) interactions. In multi-location field experiments, different phenology groups, spring and winter types were grown in low, medium and high input management systems. The experiment reported a significant effect of location ranging from 0.5 t/ha to 1 t/ha and a small response from management with 0.3 t/ha difference in high input compared with low and medium input systems. Variety choice and crop nutrition are important factors driving canola yield in high yielding environments.

Irrigated canola

Recent research has focused on understanding yield and profitability of irrigated canola in response to a range of management options including plant population, N rates and timings, and application of plant growth regulators. Yield benefits from applying high N rates and high plant populations with surface irrigation were demonstrated, however applying too much N in irrigated systems does not always provide a yield advantage.

The decisions around how often and when to irrigate canola are complex and highly dependent on a range of factors including the season, soil water status, rainfall, waterlogging potential as well as irrigation method, water availability and water cost. Fully irrigated crops can require up to 4 spring irrigations in order to maximise grain yield. In drier seasons with limited irrigation water availability, one irrigation applied at early flowering is likely to provide the best return on investment.

Hybrids

Open pollinated varieties have traditionally been favoured in the low to mid rainfall canola growing regions of Australia however, in the last 10 years the adoption of hybrids throughout these regions has been rapid and widespread. Hybrids have a considerably higher seed cost compared with OP varieties, yet they have consistently higher yield potential and increased crop vigour across Australia's rainfed environments. These benefits combined with other superior traits (e.g. herbicide tolerance, disease resistance) have resulted in their rapid adoption.

Future directions

Maintaining recent increases in production requires ongoing research to close yield gaps, maintain genetic gain and adaptative management in existing environments in the face of climate change. Where feasible, this may include expansion into new environments.

Current research projects are working to improve crop simulation models by improving estimation of damage caused by frost and heat stress. Coupled with mapping of temperature extremes across the cropping region, this will enable prediction of risk of damage from temperature stress and near real-time reporting of crop damage which can assist grower decision-making. Crop improvement projects are focusing on genetic solutions to increase frost and heat stress tolerance.

Other research is providing phenological information for varieties as they are released to the market and developing tools to predict optimal sowing date and variety combinations to minimise production risks associated with environmental stresses across the canola growing regions of Australia.

Research is also focusing on developing genetic and management solutions to increase establishment in more challenging conditions associated with exposure to higher temperatures and more marginal moisture due to climate change and early sowing strategies. A [G × E × M] approach is being employed to ensure that OP and hybrids with a range of phenology and management decisions are available across the Australian cropping region to refine and operationalise opportunities to improve crop productivity. At the same time there is a need to maintain grain quality attributes and consider greenhouse gas emissions from the production systems to ensure access to international export markets.

Potential areas for future research include a focus on genotypic variation in yield development during the grain-filling phase and improved understanding of sensitivity to a range of stresses in the critical period. Particularly, the phase duration, efficiency and rate of pod photosynthesis, and allocation to grain versus structural organs.

More information

References, further reading and resources relating to this chapter are listed in Appendix 1 (p. 99).

Nutrition

Dr. Rob Norton[1], Mathew Dunn[2] and Dr. John Kirkegaard[3]
[1] School of Agriculture, Food and Ecosystem Sciences, The University of Melbourne, Melbourne VIC 3010
[2] NSW Department of Primary Industries, Wagga Wagga NSW 2650
[3] CSIRO, Canberra ACT 2601

Summary

- Nitrogen (N) is the major nutrient that canola requires to achieve water limited yields, with rate generally more important than timing or N source.
- The increased use of early sown winter types of canola for grazing requires different N strategies.
- Phosphorus (P) strategies for wheat are generally appropriate for canola, but sulfur (S) fortified P sources can also support the high S demand of canola.
- Diagnostic soil testing for critical values for P and potassium (K) on heavier soil types in high rainfall regions are lacking.

Introduction

Canola is widely adapted and grown commercially on a wide range of soils that include:

- deep, leached sands in Western Australia
- highly calcareous soils in South Australia
- alkaline self-mulching clays in Victoria
- acidic red duplex soils in central New South Wales.

Inherent infertility means each soil type has particular needs for additional macronutrients (N, P, K and/or S) and/or micronutrients (copper [Cu], manganese [Mn], boron [B] and zinc [Zn]).

In most situations, one or more of these nutrients will limit the crop's ability to achieve its water-limited yield potential, and care must be taken to diagnose situations where an economic response is likely to occur. Soil type, paddock history and soil tests can all help with the diagnosis, but in most situations, under appropriate agronomic practice, attention should focus on getting the macronutrients 'right', before addressing any potential micronutrient issues.

Nutrient best management practices

Nutrient best management practices (BMPs), for canola or any other crop, can be described as applying the Right source (or product) at the *R*ight rate, *R*ight time and *R*ight place. Linking source, rate, time and place sits within effective agronomic practice, such as weed, pest and disease control, and timely crop establishment. Under the Global '4R' Nutrient Stewardship Framework developed in 2007, the four 'Rights' (4R) convey how nutrient management, including fertiliser and manure use, can be managed to achieve economic, social and environmental goals. These 4R's have become a guiding principle for canola nutrient management.

While economic goals may dominate many of our production systems, other aspects such as managing nutrient run-off or restricting nitrous oxide losses can moderate the optimum source, rate, time, place combination. The higher yield potential of recently released canola varieties and changes in the frequency of pasture and grain legumes has placed larger demands on nutrient supply, especially N. In addition, where soil organic matter is relatively low and there has been a long history of crop production, supply from the soil is rarely sufficient to meet crop demand.

Compared with most other grain crops in Australia, canola has a greater requirement for nutrient inputs to achieve high yields (Table 5). In general, canola yields are usually between 50% and 65% of wheat yields, so under similar growing conditions, a 2.5 t/ha canola crop removes about 25% more N, P and K, and over twice the amount of S than a 4.0 t/ha wheat crop. Fine-tuning N and P management to canola is fundamental to sustainable and profitable crop production. Other nutrients can be important in certain regions, so developing a balanced nutrition program depends on understanding soil properties and the effects of seasonal conditions.

There has been interest in cutting canola crops for hay or silage, particularly where spring conditions are unfavourable to harvesting the crop for grain. Canola fodder is readily palatable to cattle but can be prone to high levels of nitrate leading to potential animal toxicity. Removals of K and S are higher where crops are cut for forage rather than left for grain, so nutrient budgets need adjustment.

For example, if a canola crop was cut for hay, a 2.5 t/ha yield will remove around 65 kg N, 8 kg P, 15 kg S, 85 kg K. If left for grain, a 0.6 t/ha yield could be expected, which would remove 18 kg N, 3 kg P, 3 kg S, 6 kg K.

Common nutrient deficiencies and constraints

Macronutrients

Nitrogen

Nitrogen management is a key part of achieving water limited canola yields. As a general rule, if canola follows a long legume-based pasture phase, soil mineral N levels will be high but even so, additional N is often required. Canola is commonly part of a continuous cropping system dominated by cereals, so compared with recommendations from the 1990s, higher N application rates are now used to support the lower organic soil N supply.

While there have been regionally specific N decision support tools developed, most growers would now base N rates on a nutrient budget. The overall N rate can be assessed based on the yield potential, estimated soil nutrient supply and the expected nutrient use efficiency. Yield potential can be set based on previous experience, using the water use efficiency guide example given in Table 6 or tools such as Yield Prophet®. Yield Prophet® uses the crop simulation model APSIM (Agricultural Production Systems siMulator) to assist growers with key decisions around growth, phenology, yield potential and water use.

The basis of this budget approach is that each tonne of canola grain requires 80 kg N supply, which is twice the expected grain removal. There may be some N losses through denitrification, volatilisation or leaching, and around 20 kg N per tonne of grain will be present as organic N in crop residues. It is also clear that where transfer processes are not active, spared N can carry through to the following crop. In the calculation in Table 6, in-crop mineralisation of N from organic residues can be included, but growers are increasingly aware that including this as part of the N supply is running down soil organic matter.

Research has identified that the critical period for yield formation is between 100 to 500 degree-days after the first flower appears on 50% of plants. Efficient N management aims to ensure that N is not limiting during this period. Provided supply is adequate at this critical period, the actual timing between sowing and early flowering seems less important than the rate.

Care needs to be taken with canola and fertiliser placement at sowing. Seedlings can be damaged by both salt and ammonia as they develop. The largest impact occurs on dry coarse textured soils with wide sowing rows and minimal soil disturbance. Under these conditions rates as low as 5 kg N/ha can reduce stand establishment unless seed and fertiliser is separated by 2–3 cm. Current sowing equipment is capable of this separation, preferably placing fertiliser between or to the side of the seeding rows.

Experience over the past 25 years suggests that there is little or no yield penalty from split N fertiliser applications to canola and there is little distinction among different N sources such as granular or liquid urea, ammonium sulfate and urea/ammonium nitrate liquids, as well as blends of these products. Granular ammonium nitrate is not available to growers in Australia and there is limited availability of anhydrous ammonia.

Grower strategy to meet peak N demand varies with rainfall and soil type. In drier regions, more N is often applied at or near sowing, because of the fewer opportunities for in-crop rainfall to wash fertiliser N into the root zone. In regions where N losses are likely due to leaching in light-textured soils or waterlogging leading to denitrification, deferring some N supply until stem elongation does not result in significant yield penalties. This improves the efficiency of N fertiliser use.

In general, 40–50 kg N (top 60 cm) from soil and fertiliser is adequate during vegetative growth, with additional N top-dressed or inter-row drilled as the season unfolds to help match supply with the yield potential demand. It is important to 'read' the crop during this stage, taking note of paling of the older leaves (Figure 17), which is a sign the crop is limited by N. Variable rate N application is currently used on 11% of crops, with a range of assessment methods available.

Active and passive canopy sensors have been developed in Europe to help diagnose N deficiencies, but their adoption in Australia has been low. Similarly, whole plant N analysis and petiole nitrate testing are available, but paddock test strips are commonly used to assess N status visually using optical sensors or plant analysis.

With the development of dual-purpose (graze/grain) canola sown in early autumn or with true winter types sown in the prior spring, the early N requirement is likely to be up to 150 kg N/ha to support forage production. Nitrogen should not be applied within 2–3 weeks of grazing due to the risk of nitrate poisoning of grazing ruminants.

Table 5 *Nutrient removal (kg/ha) in grain of a 2.5 t/ha canola crop compared with a 4.0 t/ha wheat crop. The nutrient concentrations in typical canola hay are also given.*

Crop	Yield	Nutrient removal (kg/ha)			
		N	P	K	S
Canola grain	kg/t	40	6	8	4
	2.5 t/ha	100	15	20	10
Canola hay	kg/t	30	3	35	8
Wheat grain	kg/t	21	3	3.5	1
	4.0 t/ha	84	12	14	4

Table 6 *An example of a balance sheet approach to estimating crop N demand and soil supply, and therefore additional nutrient to be added to meet yield potential.*

N demand estimate	N supply estimate
A Stored soil water at sowing measured = 100 mm	A Soil mineral N at sowing measured = 50 kg N/ha
B Estimated seasonal rainfall = 300 mm	B In crop mineralisation = organic C (%) × seasonal rainfall ÷ 6 = 1 × 300 ÷ 6 = 50 kg N/ha
C Water use efficiency (WUE) = 10–12 kg/ha/mm	C N supply = A + B = 50 + 50 = 100 kg N/ha
D Non-productive water use (e.g. evaporation and drainage) SE = 120–170* mm	**Additional N required to support a 2.8 t/ha canola crop = 224 – 100 = 114 kg N/ha**
E Yield potential WUE × (A + B – SE) = 10 × (100 + 300 – 120) = 2800 kg/ha = 2.8 t/ha	
F N demand = yield (t/ha) × N content (%) ÷ use efficiency = 2.8 × 40 ÷ 0.50 = **224 kg N/ha**	

* Use lower water use efficiency with higher non-productive water and vice-versa.

Split N applications on canola are useful if N fertiliser rates need to be varied according to seasonal conditions on difficult soil types. Typically, as soil moisture availability rises, additional N can be supplied to match the water limited yield potential. Another benefit from delaying N is spreading the investment to later in the season when there is greater confidence in the yield potential. The wide response window for canola allows strategies to be tailored to seasonal conditions.

While there is little evidence of any 'haying-off' in canola – where excess vegetative growth reduces seed size and grain fill in dry springs – crops supplied with excessive amounts of N during early growth stages can grow tall and risk lodging. This creates poor machine efficiency at harvest as well as an increased risk of diseases in the canopy such as sclerotinia and blackleg. Lodged crops can also result in uneven maturity. This causes difficulty with harvesting and possible risks of green seed lowering oil quality.

Moderate rates of N fertiliser usually have little effect on seed oil concentration, although high rates might increase seed protein and therefore reduce the oil concentration. Even though oil concentration might decline, the increased grain yield due to N fertiliser usually more than compensates for any decrease in oil concentration. Seed fatty acid profile and glucosinolate contents of modern varieties are largely unaffected by nutrition.

Enhanced efficiency fertilisers (EEF) with inhibitors and coatings have been evaluated in a range of crops in Australia and internationally. In general, where the EEF addresses the operating loss pathway, there are improvements in N use efficiency, including reduced nitrous oxide emissions. Combining EEFs with appropriate tactical management and continuing with genetic approaches to improve N acquisition and translocation in the plant offers a suite of opportunities to improve N use efficiency in canola.

Phosphorus

For much of the cropping zone, P is a cornerstone of current nutrient management. Applying P fertiliser to crops, including canola, is routine. The application rate for canola varies from 10–15 kg P/ha in lower rainfall regions where yield expectations are 1.0–1.5 t/ha, to 20–25 kg P/ha in higher rainfall regions where yields of 2.5–3.5 t/ha are expected. Soils with a higher phosphorus buffering index (PBI) will require more applied P to raise the Colwell P test value. High PBI values are generally associated with heavy textured highly alkaline soils such as in the Victorian Mallee or the Eyre Peninsula of South Australia, or on acid soils with high levels of iron (Fe) and aluminium (Al).

The critical range for 0–10 cm Colwell P for canola is 20–27 mg/kg, although the data used to define this limit is predominantly from Western Australia. This is lower than the critical range for wheat; canola is more efficient than wheat at accessing soil P reserves. This lower critical value could be due to the organic acids secreted from canola roots which dissolve some of the P 'fixed' in calcium phosphates, making it available for plant uptake. Experiments in the Victorian and South Australian high rainfall zones suggest there are significant crop responses to P when soil test values are above the critical soil test value. It is unclear if P demand and the critical soil P test value differ with higher N application rates. There is evidence that while canola can efficiently extract P, there appears to be a high P demand for wheat following canola.

Using the Colwell soil test, or any single assessment, may not be the best way to determine P application rate. Soil tests used over time in conjunction with nutrient application and product removal (balance method) might be a better strategy to judge crop P requirements. After initial testing, Colwell P can be used to estimate P levels for the next 4–5 years. After this time, it is best to re-test the paddock.

Early in growth and season, when soils are cold the older leaves can appear purple particularly on the tips and margins suggesting a P deficiency (Figure 18), but this transient effect generally resolves when root exploration enables access to soil and fertiliser P.The most used P fertiliser is mono-ammonium phosphate (MAP). Rates >15 kg MAP/ha can result in seed damage due to the ammonium component. When using any N source, separation of seed and fertiliser is recommended. Phosphorus fertiliser applied at commercial rates does not appear to have any effect on canola oil concentration.

Potassium

Canola has a high K demand, although only modest amounts are removed in grain. The nutrient content of canola hay is 4 times the grain K content. Nutrient removal can be 10 times higher if a canola crop is cut for hay compared with being harvested for grain. Improved canola growth under previous crop windrows or header residue trails, due to the deposition of high K residues, can be a sign of low soil K. Tissue testing within and between the windrows can help confirm K status.

Figure 17 *Nitrogen deficiency symptoms in canola. Yellowing of the older leaves.* Photo: Rob Norton.

Figure 18 *Phosphorus deficiency symptoms in canola. Marginal reddening of older leaves.* Photo: International Plant Nutrition Institute.

Low soil K levels occur where there have been large removals of K, and particularly on light-textured soils under high rainfall conditions where K can be leached. There is little evidence of K deficiency in eastern Australian canola crops, although K deficiency has been reported in Western Australia. The critical soil test value for Colwell K for canola (43–54 mg/kg) is similar to the range for cereals, although the data set used to derive the canola value was small and largely derived from Western Australian experiments on tenosols. Preliminary research suggests that the critical value for canola grown on heavier soils such as vertosols, is similar to a pasture critical value of approximately 90 mg/kg. Deeper soil sampling (0–30 cm), compared to shallow (0–10 cm) sampling has been shown to give a better estimate of K fertiliser response in Western Australia.

Experiments in Western Australia demonstrated that canola required more applied K than wheat on very low K soils. Where K levels were low to moderate, canola has been shown to have a greater ability to take up K compared with wheat. In south-eastern NSW, under high rainfall conditions, canola has been shown to be less responsive to K than wheat, possibly a consequence of canola accessing K from deeper in the profile than wheat. Fertiliser K had no significant effect on oil concentration in canola grain or protein concentration in both canola and wheat grain.

Most soils are well supplied with K. Potassium deficiency (Figure 19) in canola is only likely when it is grown on deep sandy acid soils in high rainfall regions, particularly if a heavy hay crop has been removed the previous season. As cropping moves into the high rainfall zones, which generally have lower soil K levels than many of the lower rainfall areas, it is appropriate to consider K as part of a balanced nutrition program. When applied at sowing compared with in-crop topdressing, significantly lower rates of K in the form of potassium chloride (KCl) can be used, a consequence of the low mobility of the K^+ cation. Foliar application of K generally cannot supply adequate nutrient to overcome severe deficiency and can also scorch the leaves.

Figure 19 *Potassium deficiency symptoms in canola. Interveinal scorching or firing along leaf margins of older leaves.* Photo: International Plant Nutrition Institute.

Sulfur

Early research in NSW identified S deficiency as a significant limitation to canola production (Figure 20). Deficiencies were linked to the higher S removal in canola compared with wheat and the trend to use ammoniated phosphates (1% S) rather than single superphosphate (11% S). Recently, these previously responsive areas were re-visited and responses were less common, possibly due to the change to using gypsum as a soil ameliorant, coupled with residue retention and minimum tillage preserving some organic S sources. It is also likely, but largely speculative, that high glucosinolate canola varieties might have had a larger S demand than the current varieties.

Figure 20 *Sulfur deficiency symptoms in canola. Yellowing initially seen in the younger leaves.* Photo: International Plant Nutrition Institute.

Like N, S in soil is present as the plant available form (sulfate), although most is present in organic matter. Sulfate, like nitrate, leaches down the profile with water movement. Sulfur deficiencies are likely on soils with low organic matter, light texture and under high rainfall (or flooding). Deficiency can occur where a paddock has had an adequate superphosphate history. Deficiencies of S are not common in irrigated farming systems, where irrigation water often contains significant amounts of sulfate.

The right S rate will balance the soil supply with crop demand. Soil tests give an estimate of soil supply on which to base fertiliser decisions. Two topsoil mineral S tests include using either mono-calcium phosphate (MCP) or warm potassium chloride (KCl-40). Both give a guide to the sufficiency of S. Current critical values for canola are 7–8 mg/kg, somewhat higher than the value for wheat, reflecting the higher demand by canola. Because S is mobile, a deeper sample (0–10, 10–30, 30–60 cm) will give better information about the presence of deep S that might meet the demand despite a low topsoil value.

Sulfur demand is closely linked to N demand. Sulfur removal is about one seventh of N removal. A budget approach similar to N can be used, taking into account soil mineral sulfate content and balancing that with expected S removal. Removal can be estimated as one seventh the amount of N, so an N removal of 112 kg suggests an S removal of 16 kg S. The supply from the soil plus fertiliser should at least balance that S removal.

Ammonium sulfate has become a popular S source (24%) in lower rainfall areas. It supplies some additional N (21%) and can be blended with urea to increase the amount of N supplied relative to S. Sulfur fortified MAP (10–15% S) has also become popular, with a balance of relatively slow-release elemental-S and readily available sulfate-S co-granulated with MAP.

Calcium

Many Australian agricultural soils contain considerable amounts of calcium (Ca). A useful estimate is that each cmol(+) of exchangeable Ca is equivalent to 400 kg/ha to a depth of 15 cm. Soil pH generally provides an assessment of Ca levels in soils. Alkaline soils contain more Ca than acid soils. In soils where Ca is present as deposits of gypsum (calcium sulfate) or limestone (calcium carbonate), some of the Ca from these compounds will be available to the crop. High Ca levels can react with P or Mn to form insoluble products which reduces the availability of P to the crop.

Figure 21 *Calcium deficiency symptoms in canola (tipple top). Collapse of tip of flowering raceme.* Source: Don McCaffery, NSW DPI.

Symptoms of Ca deficiency occur occasionally in Australian canola during early spring, particularly on acidic soils. The deficiency usually occurs when plants are waterlogged, and weather conditions are cold and cloudy, even with adequate Ca in the soil. The main symptom of the disorder (called 'withertip' or 'tipple top') is the collapse of the inflorescence stalk tissue and subsequent withering of the flower head (Figure 22). The disorder is usually transient and its incidence patchy within a paddock and is considered to be of low economic significance. Liming to raise the pH_{Ca} to above 5.0 will increase Ca availability and help reduce the incidence of 'withertop'. Supplementary Ca applied to the foliage has not shown yield responses.

Magnesium

Tissue testing has diagnosed Mg deficiency in some canola crops during early growth. Symptoms are generally transient, disappearing once the root system reaches deeper into the subsoil where there is usually adequate Mg. If canola is planned to be grown on low Mg soils, the application of dolomitic limestone before sowing is recommended. For a tactical response, several foliar Mg products are available. Data from replicated field experiments is lacking for these products.

There is no evidence that adjusting the ratio of Ca to Mg will have any effect on soil physical, biological or chemical fertility. It is important to have the soil levels above sufficiency rather than try to change their ratio.

Micronutrients

Micronutrients are critical to strong growth and yield. It is only where their availability is restricted that they become limiting. Yields will increase if the correct diagnosis is made and addressed. There are many products on the market used by growers, but little data on canola response to supplementary micronutrients. Additional micronutrients applied tactically as foliar sprays might not be a large investment, but unless reliably diagnosed will be uneconomic.

There are reports of deficiencies for B, Mn and molybdenum (Mo), and suggestions that Cu, Fe and Zn may also be issues in particular situations. Trace elements are often chemically similar to other elements and so there can be interactions among nutrients – where an excess of one will induce a deficiency of another. Well documented examples are between P and Zn, and between S and Mo.

Despite the complexity of nutrient interactions, soil conditions can be a guide to the potential for low availability of certain micronutrients. Soil pH is important. It affects the plant availability of many nutrients. Waterlogging and drought, soil texture and organic matter content also affect potential micronutrient availability. Table 7 provides a summary of micronutrient availability under various soil and environmental conditions.

Soil tests for Zn, Cu and B are available but the caution with these tests (other than chemistry) is that often subsoil nutrient supplies can be greater than topsoil, particularly with mobile nutrients such as B. Copper and Zn are usually tested using the DTPA extractions method but the critical values for Cu vary for different species. Boron is tested from hot water or KCl extracts.

There is no Australian data for soil test calibrations for Mo or Mn status for any crop. For all tests, often soil pH, organic carbon (C) levels and clay contents might need to be included to assess the likelihood of deficiencies from a soil test.

Zinc

Canola is moderately susceptible to Zn deficiency; however, it is rarely seen probably because growers have used fertilisers containing Zn in the past and often use compound fertilisers that contain low levels of Zn. Where Zn deficiency is suspected, diagnosis by tissue tests using the youngest emerged blade approximately 40 days after emergence is reliable and provides an opportunity for a foliar application of Zn.

Manganese

The most widely reported micronutrient deficiency in canola is Mn, particularly on soils where calcium carbonate levels are greater than 30% such as on the Eyre Peninsula of South Australia. In highly alkaline soils (pH >7.5), Mn availability can be low because Mn ions (Mn^{2+}) tend to form insoluble compounds with other elements in the soil, such as Ca, Mg and Fe. High soil pH can increase the production of hydroxide ions (OH^-) in the soil, which can react with Mn^{2+} ions to form Mn hydroxides. These are insoluble and not available to plants.

Management of Mn status involves foliar applications of approximately 1 kg Mn/ha, usually as Mn sulfate. Often a follow-up application 3–4 weeks later is required. Soil applications are mostly ineffective, except where 4–5 kg Mn/ha as sulfate is blended with acidifying fertilisers and banded in the root zone at sowing.

Table 7 Soil factors affecting micronutrient availability. + indicates the factor increases plant availability, and – indicates the factors reduces plant availability.

Soil factors	Micronutrient availability					
	Cu	Fe	Mn	Zn	B	Mo
pH >7.0	– – –	– – –	– –	– – –	++	++
pH <5.5	++	+++	+++	+	– –	– –
Waterlogged soil	+	+	+	+	–	–
Drought	– – –	– – –	– – –	–	– – –	– –
High organic C content	– – –	++	++	++	++	–
High P content	–	– – –	–	– – –	–	+++
Sand	– – –	– – –	– –	– – –	– –	–
Compaction	+	++	+	+	+	+

On very acidic soils Mn can become toxic, and canola is highly sensitive. Factors that can contribute to Mn toxicity in canola include acidic soils with low Ca levels, high levels of Mn in the soil, and waterlogging or poor drainage. While there is some genetic variation in current and older canola varieties for Mn tolerance, the responses are generally within the range of the Mn-susceptible wheat variety Janz.

Boron

Canola is significantly more susceptible to B deficiency than wheat. Boron is highly mobile; deficiencies are likely on light-textured, acid soils in wet years, and can occur following liming. Foliar application of 1 kg B/ha provides adequate nutrition for the crop. Even on low B soils, B drilled with seed at sowing has been shown to induce toxicity in canola.

There are differences among canola varieties for B efficiency, but there is little information on current varieties with respect to their capacity to tolerate low B soils.

Boron can be present at toxic levels in some soils especially those formed from marine or wind-blown sediments that have an alkaline sodic subsoil. Boron toxicity is more prevalent in dry seasons and in years with mid season drought when crops rely on deep subsoil moisture.

Salinity and subsoil constraints

Generally, canola is considered moderately salt-tolerant, and can tolerate soil salinity levels up to 4–6 dS/m without significant yield reductions. There are 3 elements to a soil salinity response by any crop:

- sodium (Na) toxicity
- chloride (Cl) toxicity
- osmotic effects.

Canola is a sodium-excluder and so is relatively tolerant of Na levels in the soil. High exchangeable sodium levels can cause soil dispersion. Using gypsum (calcium sulfate) can displace Na with Ca and restore some soil structural stability.

Canola is less tolerant of Cl than wheat or barley. Soil water supply and soil texture play a role in reducing the risk of losses due to toxicity.

In addition to any specific ion imbalances, canola can still be affected by sub-soil salinity due to restricted water availability to the crop. This occurs because of restrictions on root growth and the increased osmotic pressure from the soil solution. In general, canola varieties that are more tolerant of saline soils are also likely to be more tolerant of Na toxicity. Some breeding programs have been working to develop canola varieties specifically bred for improved tolerance of high-sodium soils.

High levels of B occur in some soils across south-eastern Australia, often with saline and sodic subsoils. There is little that can be done to ameliorate high subsoil B levels (>2 mg/kg hot water-soluble B) other than to avoid those areas of the landscape. While there are variety differences in B tolerance noted for cereals and some pulses, the current canola variety guide gives little guidance on any differences for B tolerance.

Soil acidity and liming

Canola is generally not very tolerant of highly acid soils. The ideal soil pH_{Ca} range for canola is between 6.0 and 7.5, however it can still grow reasonably well in slightly acidic soils with a pH_{Ca} range of 5.5–6.0 if other soil factors, such as nutrient availability are not limiting.

Where soil pH_{Ca} is less than 5.0, aluminium (Al) and Mn toxicity can occur. This can be rectified by liming to raise the soil pH_{Ca} above 5. Lime rates depend on the pH to depth and the cation exchange capacity of the soil. Microfine lime is usually applied at 2.5–4.0 t/ha. Shallow incorporation of lime is sufficient to ameliorate surface soil acidity, but deep ripping is required to incorporate the lime, reduce soil strength and improve drainage where there are serious subsoil acidity problems. Deep ripping and other mechanical interventions such as claying, deep ploughing and spading to mix acidic subsoil with less compromised topsoil and subsoil has transformed yield potentials on those soils.

Liming reduces the potential for Mo deficiency, but it can raise the potential for B deficiency. In many respects, the sensitivity of canola to soil acidity has had beneficial spin-offs. It has encouraged Australian growers to implement liming programs before their soils became too acidic for less sensitive crop and pasture species.

The nutrition chapter of *Canola in Australia: the first thirty years* (1999), proposed that genetic engineering of canola will play an important role in developing new Australian varieties for increased tolerance of specific nutritional conditions such as high Al in acid soils, and greater tolerance of both high and low levels of micronutrients such as B and Mn. This opportunity has yet to be realised.

Decision support tools for canola nutrition

Growers have access to high quality crop simulation models through Yield Prophet®. Once calibrated for specific soil types, the simulation model can provide growers with predicted phenology and yield potentials under a range of potential climatic scenarios.

Soil and tissue testing

Soil testing, both shallow (0–10 cm) and deep (0–60 cm) is a common practice used by growers to estimate fertiliser requirements for canola. Paddock cropping history, balance sheets based on nutrient removal and test strips in fields, all assist growers to determine nutrient requirements. These tools are best used in combination rather than in isolation to develop a nutrient management plan for a high yielding canola crop. Plant tissue tests are available for canola but are mostly used for nutrient deficiency diagnosis rather than determining fertiliser rates.

Interpreting soil tests is quite difficult because of low absolute values, sampling errors and analytical reliability. For example, the critical soil test value for Zn is 0.75 mg/kg in alkaline soils, and while this can be accurately measured in the laboratory, the critical values are at the lower levels of confidence for predicting responses. In some cases, such as B, the deficiency value is not very different to the toxicity value. As with all soil testing, it is important to use nationally accredited laboratories for assessing nutrients – these tests are ones that have critical values established for Australian conditions.

Interpreting tissue concentrations requires an understanding of the nature of the tissue content and yield relationship, and sometimes low tissue concentrations are a consequence of 'yield dilution'. Another major caution with tissue testing relates to sampling time, as other reserves (e.g. deeper in the soil) might not yet be accessed and so results might indicate a 'false' low tissue concentration.

Significant research developments

The most significant change in canola farming systems in recent years has been a shift towards earlier sowing and dry sowing systems driven by increasing farm size and earlier optimum flowering periods associated with climate change. As sowing dates move earlier into potentially warmer and drier soils, appropriate nutritional packages to ensure successful establishment under more challenging conditions are required. Suitable approaches to plant nutrition at sowing will need to go hand-in-hand with the emerging genetic and management solutions to ensure successful crop establishment.

Another significant change has been the shift to grow hybrids which generally have a higher yield potential meaning higher nutrient requirement. Hybrids can be more efficient in nutrient uptake due to the increased vigour of the root systems during early growth. Nutrient management guidelines may need refining to ensure that the greater demand and uptake efficiency are considered with new hybrids.

Precision and digital agriculture innovations targeting fertiliser inputs are rapidly developing. They will provide further opportunities for more precise fertiliser placement and more frequent in-crop assessment of crop needs using various sensing approaches. These are currently in their infancy but are evolving quickly and will enable growers to respond with more precisely timed and positioned delivery of nutritional products.

Future directions

Suggested areas for future N research on canola include developing:

- tools that can assess in-crop N status
- N management guidelines for grazed canola
- guidelines to identify, and then address, particular N loss pathways using enhanced efficiency fertilisers.

There are also likely trade implications due to the potential environmental impact of the greenhouse gas nitrous oxide on the use of N on canola and other crops. The emissions intensity of canola farming systems will be under increasing scrutiny.

Fertiliser inputs and use efficiency will be areas for focused improvement.

Current critical soil test values for both P and K need to be refined, particularly in the high rainfall areas where canola is rapidly expanding and where dual-purpose (graze and grain) canola are likely to become more common.

There is some information about genetic differences among canola varieties to nutritional and other edaphic stresses. Identifying these traits in commercial varieties will allow a wider adaptation of canola where these types of limitations occur.

More information

Further reading and resources relating to this chapter are listed in Appendix 1 (p. 100).

Breeding

Dr. Harsh Raman[1], Kate Light[2] and Justin Kudnig[3]
[1] NSW Department of Primary Industries, Wagga Wagga NSW 2650
[2] Nutrien Ag Solutions, Horsham VIC 3400
[3] Advanta Seeds Pty Ltd, Highett VIC 3190

Summary

- High yielding, blackleg resistant, herbicide tolerant and improved adapted open-pollinated (OP) varieties and hybrids have increased both canola growing area and productivity in Australia.
- Private companies play a significant role in developing new OP varieties and hybrids, accessing novel traits such as pod shatter resistance, high vegetative grazing biomass in winter varieties and specific end-use oil quality.
- Herbicide tolerance, especially in genetically modified (GM) canola, including dual-herbicide stacks, has provided more options to sow canola in predominantly cereal growing areas.
- Improved phenotyping and genetic selection tools play critical roles in canola breeding programs.

Introduction

Canola breeding programs have been the backbone of the Australian canola industry since 1970, when the first public breeding program was initiated in Victoria. New South Wales and Western Australian programs followed in 1973.

In the early years, canola breeding programs focused on *Brassica rapa* (common mustard, AA genome, 2n = 2x = 20), *Brassica napus* (rapeseed/canola, 2n = 4x = 38) and *Brassica juncea* (Indian mustard, AABB genome, 2n = 4x = 36). Varieties of *B. rapa* and *B. juncea* were targeted for low rainfall areas. Recently, genetic improvements have been made in *Brassica carinata* (Ethiopian mustard, also called Abyssinian mustard, BBCC genome, 2n = 4x = 34).

The first private breeding program in Australia was initiated in 1980 by Pacific Seeds (now Advanta Seeds Pty Ltd), followed by AgSeed Research Pty Ltd (now part of NuSeed Pty Ltd). Both public and private breeding programs supported the fledging canola industry. Approximately 329 canola-quality varieties and hybrids were released between 1980 and 2022, 327 of these were *B. napus*.

Non-herbicide resistant (conventional) canola first established the industry. However, triazine tolerant (TT) followed by imidazolinone (IMI) tolerant and then glyphosate resistant canola types grew the industry to over 3.5 million hectares (Mha). Glufosinate resistant hybrids and multi-herbicide tolerant types (stacks) are now also important integrated weed management (IWM) tools.

Australian canola breeding programs use all available technologies to improve efficiencies, stay ahead of blackleg disease, and continue to drive yield gains. The industry continues to innovate and release varieties that meet grower needs, fitting into different:

- farm management systems (herbicide tolerance)

- regions (maturity)
- markets (specialty or canola quality, GM or non-GM)
- budgets (OP varieties versus hybrids).

Australian canola breeding participants

The Australian canola breeding landscape significantly changed in the late 1990s when public canola breeding ceased.

The original public breeding programs in Victoria and NSW continued to provide pre-breeding research services to private breeding companies via the *National Brassica Germplasm Improvement Program* (NBGIP). The program ran from 1992 to 2017, in partnership with Grains Research and Development Corporation (GRDC). NBGIP focused on pre-breeding activities including:

- identifying novel and existing genetic resistance to blackleg (causal fungal agent *Leptosphaeria maculans*)
- oil quality attributes
- pod shatter resistance
- drought tolerance
- heat tolerance.

Several private breeding companies accessed germplasm, phenotypic and genetic data that the NBGIP generated.

In 2023, 7 established private canola breeding programs operate in Australia. They include:

- Advanta Seeds Pty Ltd
- Australian Grain Technologies (AGT)
- BASF
- Corteva AgriScience
- NPZ Lembke (in partnership with the University of Western Australia – UWA)
- NuSeed Pty Ltd
- Nutrien Ag Solutions Ltd.

All programs except AGT are actively breeding and releasing canola hybrids (5 Ogura based and one the NPZ Lembke MSL system). They continue to develop inbred material that could be released as OP varieties. Overseas programs not actively breeding in Australia but are, or have, marketed canola varieties in specific regions of Australia include RAGT and AGF Seeds.

Australian breeding programs have successfully released varieties with different:

- maturities (early, mid and late)
- disease resistance
- agronomic traits
- herbicide tolerances
- oil/seed quality parameters.

Selecting for these traits has led to material adapted to diverse regions from south-eastern Australia to Western Australia. Current breeding efforts are focused on extending canola cultivation and its related species to the hotter and drier climates of northern NSW and Queensland.

Breeding methods – achieving high yield

Originally, the Australian canola industry was based on pedigree breeding methods of selection for developing OP, non-herbicide tolerant and TT canola varieties. Multiple traits in the same generation were selected using tandem and simultaneous selection. Some programs also used index selection as a part of their breeding pipeline, although no formal data was published in the literature.

In 1988, Pacific Seeds released the world's first canola hybrids in Australia. Grower uptake of hybrids was slow compared with Canada, as they initially baulked at the increased seed cost and not being able to retain harvested seed for the next cropping season. This changed with the release of the first IMI (Clearfield®) tolerant hybrids in 2005 and a conventional hybrid in 2007 (Table 8: p. 52). Yield gains were quickly realised by growers. From 2014 to 2023, more than 90% of all canola varieties released in Australia have been hybrids (83 hybrids, 9 OP varieties). Hybrids have higher:

- yield potential
- plant vigour
- response to nitrogen
- resistance to lodging.

Hybrids also provide broader herbicide tolerance options. Canola yields have improved by 5–7% every 2 years since hybrids were introduced, and this growth is not slowing down.

Australian canola breeding companies are early adopters of new plant breeding technologies that help to improve selection efficiency, such as:

- using near-infrared red (NIR) calibrations to predict seed and oil quality attributes
- doubled haploid (DH) production

- reduced generation time in greenhouses
- molecular marker development and marker-assisted selection strategies
- biometrics – the deployment of statistical designs, modelling and data analytic methods to increase the efficiency and accuracy of general combining ability (GCA) predictions
- overseas seed and contra-season production (largely in Chile)
- genomic selection and associated modelling
- drones for large-scale field experiment phenotyping and plot integrity analysis.

It is now common to use DH technology to develop both male and female hybrid parental pools where possible and pedigree selection where necessary. Depending on the target herbicide tolerance group, forward breeding (including backcrossing), trait introgression, or a combination of both, are used to develop hybrid parents.

Many Australian canola breeding programs are owned and operated by global breeding companies. These companies are well supported by their overseas colleagues to carry out these activities.

Australian biometricians, under the leadership of Professor Brian Cullis (firstly at NSW DPI and later at the University of Wollongong), have radically improved statistical design and analysis techniques. These developments cannot be underestimated when considering improvements to varietal performance. As Australian programs moved towards hybrid breeding, the value of advancements like partial replication, spatial correction and the use of pedigree to calculate GCA of parental lines were quickly recognised.

iClasses is becoming increasingly popular with some breeding organisations and is also being used in technical development trials to accurately compare statistical results across all varieties and all herbicide technologies. These innovations have resulted in improved efficiency and accuracy and greatly improved estimates of GCA, all of which drive the genetic gain in any breeding program.

Blackleg resistance

Australia has the highest blackleg resistance levels in spring canola varieties/hybrids worldwide. Canola cannot be grown for commercial production in Australia without some level of effective blackleg resistance. Blackleg-susceptible varieties collapsed the local industry in the early 1960s. The fungal causal agent *Leptosphaeria maculans* is endemic in Australian soils. It has high evolutionary potential as it undergoes both sexual and asexual reproduction. There is clear host resistance-pathogen virulence gene-for-gene interaction. Canola sowing and early establishment times in Australia coincide perfectly with major *L. maculans* ascospore release events, so crop infection without effective host resistance is highly probable.

Consequently, blackleg resistance has become a major breeding objective of all canola breeding programs. Initially, Australian breeders relied on French winter and Japanese donor sources of resistance, e.g. 'Jet Neuf' and 'Norin 20'. A large collection of diverse accessions of *B. rapa* subspecies, especially *Sylvestris*, *B. napus*, *B. juncea*, *B. carinata* and wild crucifers and identified accessions of interest were evaluated. Introgression of resistance genes from *B. carinata* (especially from the B subgenome) and wild crucifers into canola germplasm has been challenging due to sexual incompatibility barriers. Several blackleg-resistant varieties derived from crosses between *B. napus* and *Sylvestris* were developed and released by Pacific Seeds in the early 2000s. Later, these varieties were used as disease-resistance gene donors by other Australian programs.

The Australian canola industry is a world leader in developing traditional in-field-phenotyping methods and knowing how to combine these with new phenotypic and molecular marker methodologies to determine qualitative (major, race-specific) resistance.

Selection of blackleg-resistant germplasm in disease nurseries under field conditions, comprising stubbles from previous crops, is commonplace in Australia (Figure 22). This technique has been instrumental in maintaining the still elusive quantitative blackleg resistance (minor, non-race specific). In the early 2000s, the canola industry worked across disciplines to develop a coordinated national blackleg rating system (NBRS). The NBRS rates variety resistance on a scale of 1–9 (Potter et al. 2007) and is based on overall plant survival in disease nurseries across Australia. This system is still used today.

With the support of pre-breeding and blackleg research initiatives, Australia has also pioneered new phenotypic and molecular marker methodologies. The University of Melbourne and Marcroft Grains Pathology (MGP), in collaboration with the INRA (Institut national de la recherche agronomique, France), developed a differential set of isolates that recognises individual blackleg resistance genes (Marcroft et al. 2012). Differential isolate screening is used to classify commercial canola varieties into blackleg resistance groups based on genetic resistance type. It is constantly built upon as new resistance types are identified. There are now 8 resistance groups (A to H) and combinations of the same. As molecular markers are developed, they replace/complement the characterisation of certain resistance genes by the differential isolate set.

Figure 22 *Field phenotypic blackleg resistance screening: Infection of a susceptible breeding line at the cotyledon stage in a field blackleg nursery grown on stubble from a previous year's crop (Nutrien Ag Solutions disease nursery, Toolondo Victoria, 2023).* Photo: Kate Light, Nutrien Ag Solutions.

Blackleg resistance group classifications were first released to growers in 2011 and are now updated twice annually. Molecular markers for certain genes and differential isolate set testing have been used extensively within breeding programs to assist with selection strategies at earlier generations.

Large-scale glasshouse-based phenotypic screening for qualitative resistance to blackleg, ascospore shower (also called 'tub test') and disease nurseries for quantitative screening are well developed. These tests:

- characterise germplasm and commercial varieties for resistance conferred by known qualitative genes, *Rlm* (*Rlm1*, *Rlm2*, *Rlm3*, *Rlm4*, *Rlm6*, *Rlm7*, *Rlm9*, and *LepR1* and *LepR3*)
- discover new qualitative genes that confer resistance
- are used to investigate quantitative trait loci associated with resistance, including for upper canopy infection (Light et al. 2011; Raman et al. 2011; Marcroft et al. 2012; Raman et al. 2016a; Van de Wouw et al. 2021; Raman et al. 2020a; Raman et al. 2021).

Australian research has also shown that the durability of blackleg resistance in varieties depends on the blackleg pathogen's population structure. For example, the breakdown of *Sylvestris* resistance derived from *B. rapa* due to virulent isolates against *Rlm1* and *LepR3* genes (Li and Cowling 2003; Sprague et al. 2006; Larkan et al. 2013) reinforced the need to breed varieties with alternative qualitative and quantitative resistance sources. It was anticipated that combining quantitative and qualitative resistance genes would improve the durability of resistance.

Recent Australian studies have shown that the durability of gene stacks for race-specific genes and race-specific plus non-race-specific genes can be ineffective in conferring blackleg resistance under certain conditions (Raman et al. 2020a). This is because matching genes for virulence in *L. maculans* may be present and will result in the breakdown of the blackleg resistance in canola varieties.

To-date, Australian canola breeders have continually kept ahead of the blackleg pathogen. As new resistance sources (or resistance combinations) are released in commercial varieties, the industry learns how the resistance genes work and how to manage them.

In addition to deploying blackleg-resistant varieties, the canola industry also manages disease by following appropriate crop rotation and fungicide spray schedules (including seed dressing, treatment of fertiliser and foliar fungicides) under accepted industry stewardship guidelines.

Blackleg resistance will always be a shifting target for Australian canola breeders as the pathogen continues to overcome new genetic resistance sources and growers continue to tighten canola cropping rotations.

Breeding for sclerotinia resistance

Compared with blackleg, Australian canola breeding programs have made limited genetic progress on sclerotinia stem rot resistance. Nevertheless, breeding programs are accumulating favourable alleles for resistance. Progress on developing and evaluating selection methods and genetic analysis of resistance genes has been made in pre-breeding programs (Garg et al. 2008; Newman et al. 2023). Presently there is no standard system of phenotyping sclerotinia resistance or significant variation for resistance in the current germplasm.

Specialty canola breeding

Since double low (low erucic acid and low glucosinolate) varieties were first discovered and developed in Canada, Australian breeders have used those donor sources to develop canola quality rapeseed (*B. napus*), *B. rapa* and *B. juncea* varieties (Table 8: p. 52).

Several different specialty *Brassica* varieties for specific end uses have also been developed in the past. AgSeed Research and Agriculture Victoria developed higher erucic acid rapeseed (HEAR) types (*B. napus*), and biofumigant mustards (*B. juncea*). This joint program and the CSIRO also developed condiment mustards (*B. juncea*). Due to limited market uptake, breeding of these specialty lines ceased in 2008.

The most successful specialty canola type developed in Australia is the high oleic low linolenic (HOLL) canola. AgSeed Research began developing HOLL varieties in the early 1990s with a fatty acid profile approximating 67% oleic and 4% linolenic. This program is now part of NuSeed Pty Ltd and forms their Monola line of HOLL varieties. Cargill Seeds market several HOLL hybrids, and Corteva AgriScience (formerly the Dow AgroSciences program) are now pursuing the HOLL market in Australia. Current Cargill and NuSeed HOLL specialty products in Australia have all been selected for blackleg resistance, maturity, adaptation, and herbicide tolerance. The Australian HOLL area is upwards of 60,000 ha annually.

Herbicide tolerance systems

Conventional or non-herbicide tolerant canola

Conventional canola OP varieties were developed and released in Australia until 2011. These varieties had tolerance to grass-selective herbicides. The last conventional hybrid was released in 2017.

The area sown to conventional canola in Australia has dramatically decreased since the 1990s when 5 herbicide tolerance systems became available:

- triazine tolerant (TT)
- imidazolinone tolerant (IMI, Clearfield®)
- glyphosate resistant (Roundup Ready® and TruFlex®)
- glufosinate resistant (Liberty Link®).

Herbicide tolerant varieties gave canola growers and agronomists more options for efficient and effective integrated weed management (IWM).

Triazine tolerant

Triazine tolerant canola varieties comprise over 40% of the annual Australian canola area. Despite recognition of the inherent yield penalty related to the triazine tolerance mutation, TT canola fulfills a key role in many IWM systems. The area sown to TT canola is split evenly between OP varieties and hybrids.

The first TT hybrids were the Ogura cytoplasmic male sterility (CMS) system (Pacific Seeds) and the NPZ Lembke MSL system (NPZA), released in 2009 (Table 8: p. 52). Within a few seasons, it was clear that whilst TT hybrids had significantly improved yield compared with OP varieties (+10–15%), they still lagged behind the yield of hybrids with other herbicide tolerance systems.

TT Ogura CMS paved the way for the stacking of herbicide tolerances. However, TT stacks inherit the yield penalty associated with the TT mutation. Some recently released TT hybrids show significant genetic yield gain and in-cross technology analysis shows equivalent yields to technologies such as Roundup Ready® (RR) or Clearfield®.

Imidazolinone tolerant

Imidazolinone (IMI) tolerant OP canola was first released in Australia in 2000 by Pioneer Hi-Bred Australia Pty Ltd, offering an alternate herbicide system for Australian canola growers. When the first hybrids were developed and released in 2005 by Pioneer the yield benefit over TT and flexibility offered by the system was realised.

Since 2010 all IMI tolerant varieties have been hybrids. Cereal grain crops in Australia are now also available with IMI tolerance. As the summer months are often very dry, crops following IMI tolerant cereals, such as canola, need to have a tolerance to any potential IMI residue. This led to the stacking of IMI tolerance with other herbicide tolerance systems.

The Clearfield® hybrid system enables herbicide tolerant stacks to be created. Growers have the flexibility to sow a glyphosate/IMI tolerant hybrid stack to avoid soil residue issues from previous IMI use and/or manage resistant weed populations.

Glyphosate resistance

It was anticipated that glyphosate resistant canola in Australia (Monsanto's Roundup Ready®) would be commercially released by 2002. However, due to state moratoria and the extended regulatory approval process, this was delayed until 2008. Nuseed Pty Ltd, Advanta Seeds Pty Ltd and Pioneer Hi-Bred Australia Pty Ltd, all released Roundup Ready® varieties that year (Table 8: p. 52). Glyphosate resistant hybrids are now estimated to comprise 35–40% of the entire Australian canola crop acreage.

TruFlex® canola was first released in 2018, both globally and in Australia by Advanta Seeds Pty Ltd.

Corteva AgriScience's Optimum *GLY*® trait was granted regulatory approval in 2023, with commercial release of a Pioneer Opt imum *GLY*® canola hybrid planned for 2024.

Glufosinate resistance

The first hybrid stacked with glufosinate resistance and triazine tolerance was released in 2021 by BASF. A stacked hybrid with both glufosinate and glyphosate resistance is due to be released commercially in Australia in 2024.

Herbicide stacks

TT and Clearfield® hybrid systems allowed herbicide tolerant stacks to be created. This has given Australian growers the flexibility they were seeking to manage soil herbicide residue and multiple weed resistances in IWM systems. In recent years TT/RR, TT/Clearfield® and TruFlex/Clearfield®, and Liberty/TT stacks have all been released to Australian growers.

Dual-purpose canola

In the past decade, a market has developed in the medium to high-rainfall cropping regions for dual-purpose (graze/grain) varieties. These varieties are not bred in Australia – they are winter oilseed rape (WOSR) varieties licenced from mainly European breeding programs. They account for approximately 200,000 ha in Australia, fulfilling graze and grain, grazing only or grain only purposes, depending on specific agronomic and feed gap requirements in mixed farming businesses.

Other *Brassica* species

Brassica juncea

Breeding for Indian mustard commenced in the 1970s in Australia. The aim was to develop varieties for hotter, drier, low rainfall areas. The research organisations involved at the time included CSIRO, Agriculture Western Australia (AgWA) and Agriculture Victoria. The CSIRO and AgWA programs ceased by the turn of the century, and the breeding material was incorporated into the Agriculture Victoria breeding program. This program became part of the NBGIP and began to focus on developing canola-quality *juncea*. The first of these varieties was released in 2007 (Dune), and 2 IMI tolerant canola quality *B. juncea* varieties followed in 2009 (Table 8: p. 52). Viterra (now Nutrien Ag Solutions) continued the breeding program from 2011 to 2014 with support from the GRDC. The first hybrid *juncea* varieties were developed, but were not commercialised in the Australian market.

Brassica carinata

Australian breeding programs and pre-breeders have evaluated Ethiopian mustard accessions for blackleg and pod shatter resistance, flowering time, grain yield and other agronomic traits. Research has identified considerable genetic variation for these traits. Research continues in Australia at a pre-breeding level to explore the possibility of exploiting these traits in Australia, whereas they have been commercialised in other locations worldwide.

Significant research developments

Significant investment in research and development has resulted in continuous innovation and technological improvements in Australian canola breeding across several areas.

Gene characterisation

Characterising genetic variation for priority traits and trait marker discovery in partnership with the GRDC and other organisations, for:

- blackleg resistance (MGP, NSW DPI and CSIRO)
- heat tolerance (UWA and NSW DPI)
- tolerance to acid soils due to aluminium, manganese and proton toxicities (NSW DPI and DPIRD)
- phenology (CSIRO and NSW DPI)
- pod shatter resistance (NSW DPI)
- drought tolerance (NSW DPI)
- oil quality (NSW DPI and CSIRO).

Genetic marker technologies

Different marker technologies such as single sequence repeat (SSR), single nucleotide polymorphism (SNP), genotyping-by-sequencing (GBS), and skim sequencing were used:

- to characterise canola germplasm and construct linkage maps
- for genetic analysis using interval mapping, genome-wide association analysis, and haplotype analysis, high-resolution mapping in Australian canola pre-breeding germplasm.

More recently, a DNA resequencing-based approach has been used for genome-wide association studies (GWAS) analyses in Australian germplasm.

Reference and pan-genomes

Australian researchers collaborated internationally and contributed to developing *B. rapa*, *B. oleracea*, *B. napus* and *B. carinata* reference and pan-genome assemblies. These resources are crucial for pinpointing genes and understanding the genetic architecture of important agronomic traits and for trait enhancement.

Artificial intelligence and data mining

Artificial intelligence is being exploited to select traits and make 'ideal' crosses in breeding programs. Breeding programs use drone sensor technologies to assess trials. This technology played a significant role during the COVID pandemic (2020–22) when travel restrictions and state border bans existed in Australia.

Gene engineering and editing

Extensive progress has been made in genetic engineering and gene editing technologies in Australia and overseas. For example, CSIRO and NuSeed Pty Ltd have developed transgenic canola with an omega fatty acid biosynthesis gene. The Australian Research Council supported Australian Training Centre on Future Crops (led by the Australian National University and supported by NSW DPI, CSIRO, the University of Adelaide [UA], and Australian and international industry research partners), is focusing on genetic engineering and gene editing approaches to develop canola with improved resistance to blackleg, pod shatter and photosynthesis efficiency. This research is being done in collaboration with Australian canola breeding companies, NSW DPI and CSIRO.

Agronomic interventions

Research on agronomic interventions with spray-on technologies has shown promising results in switching genes on and off 'at will' in crop plants. This technology has potential in managing diseases such as blackleg and sclerotinia and optimising plant development/physiological processes that negatively affect canola yield and quality.

Future directions

High-yielding, blackleg-resistant, herbicide tolerant varieties or hybrids with improved adaptation have built the Australian canola industry to what it is today. The Australian industry is relatively small compared with Canada, China and India and is largely dependent on international export demand, especially in Europe, for the biodiesel market.

Australian canola breeding programs must continue to embrace new technologies and seek partnerships that foster new scientific discoveries such as phenomics, genomics and artificial intelligence technologies. Incorporating these new endeavours into breeding programs will inform and improve efficiencies and continue to drive improvement.

Further research and development is needed to develop super-high-yielding hybrids by consolidating new heterotic patterns. Phenotypic and genomic tools need to be developed to accelerate genetic gains in canola for high productivity and physiological efficiency (e.g. photosynthesis, water use).

Genetic technologies such as plant transformation and gene editing protocols that are agnostic to varieties are being developed in Australia. These technologies, together with breeding programs, will play an important role in developing next-generation canola varieties that meet future industry needs such as:

- resilience to environmental and biotic stresses
- ability meet growing demands for food, feed and industrial applications.

Table 8 *List of rapeseed and canola varieties released for commercial cultivation in Australia.*

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
1978	Rapeseed	Wesreo	Conv.	First variety	OP	AgWA	
1979	Rapeseed	Wesway	Conv.		OP	AgWA	
1980	Canola	Marnoo	Conv.	First canola quality	OP	AgVic	
1980	Rapeseed	Wesbell	Conv.		OP	AgWA	
1980	Canola	Wesroona	Conv.	First canola quality	OP	AgWA	
1982	*B. rapa*	Jumbuck	Conv.		OP	NSW DPI	
1984	Canola	Wesbrook	Conv.		OP	AgWA	
1986	Canola	Tatyoon	Conv.		OP	AgVic	
1987	Canola	Wesbarker	Conv.		OP	AgWA	
1988	Canola	Maluka	Conv.	First canola quality low gluc	OP	NSW DPI	
1988	Canola	Shiralee	Conv.		OP	NSW DPI	
1988	Canola	Nindoo	Conv.		OP	AgVic	
1988	Canola	Taparoo	Conv.		OP	AgVic	
1988	Canola	Hyola 30	Conv.		Hybrid	Pacific Seeds	
1988	Canola	Hyola 40	Conv.		Hybrid	Pacific Seeds	
1989	*B. juncea* condiment	Siromo	Conv.		OP	CSIRO	
1989	Canola	Eureka	Conv.		OP	NSW DPI	
1990	Canola	Barossa	Conv.		OP	NSW DPI	
1990	Canola	Yickadee	Conv.		OP	NSW DPI	
1990	Canola	Hyola 41	Conv.		Hybrid	Pacific Seeds	
1991	Canola	Narendra	Conv.		OP	AgWA	
1991	Canola	Hyola 42	Conv.		Hybrid	Pacific Seeds	
1992	Canola	Oscar	Conv.		OP	NSW DPI	BLN500
1993	Canola	Rainbow	Conv.		OP	AgVic	RE9
1993	Canola	Dunkeld	Conv.		OP	AgVic	RF3
1993	Canola	Siren	TT	First OP TT variety	OP	AgVic/AgSeed	
1995	Canola	Karoo	TT		OP	AgVic	TI7
1995	Canola	TI 10	TT		OP	AgVic	TI10
1996	Canola	Scoop	Conv.		OP	NSW DPI	BLN877
1996	Canola	Grouse	Conv.		OP	NSW DPI	BLN884
1996	Canola	Monty	Conv.		OP	NSW DPI	BLN900
1996	Canola	Drum	TT		OP	NSW DPI	BLN971
1996	Canola	Clancy	TT		OP	NSW DPI	BLN973
1996	Canola	Pinnacle	TT		OP	AgVic	TI1
1996	Canola	Range	Conv.		OP	AgSeed	
1996	High erucic acid rapeseed	Hemola 7	Conv.	First high erucic	OP	AgVic/AgSeed	
1996	High erucic acid rapeseed	Hemola 9	Conv.	First high erucic	OP	AgVic/AgSeed	
1997	Canola	Charlton	Conv.		OP	AgVic	R125
1997	*B. juncea* condiment	Muscon M-973	Conv.		OP	AgVic/AgSeed	

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
1997	*B. juncea* biofumigant	Fumus F-E71	Conv.	First biofumigant mustard	OP	AgVic/AgSeed	Fumus E71
1997	*B. juncea* biofumigant	Fumus F-E75	Conv.	First biofumigant mustard	OP	AgVic/AgSeed	Fumus E75
1998	Canola	Mystic	Conv.		OP	AgVic	RK7
1998	HOLL Canola	Monola L-711	Conv.	First HOLL	OP	AgSeed	
1998	HOLL Canola	Monola L-712	Conv.	First HOLL	OP	AgSeed	
1999	Canola	Hylite 200TT	TT	Apetalous type	OP	Advanta Seeds	PAC N151
1999	Canola	Insignia	Conv.		OP	AgSeed	AGA97.06
1999	Canola	Pioneer 44C71	IMI	First IMI OP	OP	Pioneer	NS2743
1999	Canola	46C01	Conv.		OP	Pioneer	NS2596
1999	Canola	Pioneer 46C03	IMI	First IMI OP	OP	Pioneer	NS22784
1999	Canola	47C02	Conv.		OP	Pioneer	NS2585
1999	Canola	Purler	Conv.		OP	NSW DPI	BLN1216
1999	Canola	Surpass 400	Conv.	*Sylvestris* resistance	OP	Advanta	PAC141
1999	Canola	Surpass 600	Conv.	*Sylvestris* resistance	OP	Advanta	PACN142
1999	Canola	Surpass 600 TT	TT	*Sylvestris* resistance	OP	Advanta	PACN148
1999	Canola	Trooper	TT		OP	AgSeed	AGA97.14
2000	Canola	AG Emblem	Conv.		OP	AgSeed	AGA98.07
2000	Canola	AG Outback	Conv.		OP	AgSeed	AGA99.04
2000	Canola	ATR Grace	TT		OP	AgSeed	TM4
2000	Canola	ATR Hyden	TT		OP	AgSeed	AGR99-27
2000	Canola	Bugle	TT		OP	AgSeed	AGA99.22
2000	Canola	Ripper	Conv.		OP	NSW DPI	BLN1400
2001	Canola	AG Castle	Conv.		OP	AgSeed	AGC110
2001	Canola	ATR Eyre	TT		OP	AgSeed	TO003
2001	Canola	AV Fortress	Conv.		OP	AgVic	AGC11
2001	Canola	Georgie	Conv.		OP	AgSeed	BLN1239
2001	Canola	Hyola 60	Conv.		Hybrid	Advanta	PACN168
2001	Canola	Pioneer 44C73	IMI		OP	Pioneer	NS3752
2001	Canola	Pioneer 46C74	IMI		OP	Pioneer	NS03729
2001	Canola	Surpass 300 TT	TT		OP	Advanta	PACN164
2001	Canola	Surpass 402 CL	IMI		OP	Advanta	PACN176
2001	Canola	Surpass 603 CL	IMI		OP	Advanta	PACN178
2002	Canola	ATR Beacon	TT		OP	AgSeed	TN4
2002	Canola	AV Sapphire	Conv.		OP	AgVic	RO011
2002	Canola	Lantern	Conv.		OP	Canola Alliance	BLN1981
2002	Canola	Pioneer 45C05	Conv.		OP	Pioneer	NS4377
2002	Canola	Pioneer 45C75	IMI		OP	Pioneer	NS3741
2002	Canola	Pioneer 46C04	Conv.		OP	Pioneer	NSO4376
2002	Canola	Rivette	Conv.		OP	Canola Alliance	BLN1999
2003	Canola	AG Spectrum	Conv.		OP	AgSeed	AGC111
2003	Canola	ATR Stubby	TT		OP	AgSeed	AGT103
2003	Canola	Hyola 43	Conv.		Hybrid	Advanta	H1012
2003	Canola	Pioneer 44C11	Conv.		OP	Pioneer	P98125
2003	Canola	Pioneer 46C76	IMI		OP	Pioneer	NS4397
2003	Canola	Surpass 404 CL	IMI		OP	Advanta	J1318
2003	Canola	Trigold	TT		OP	NPZA	CBWA002
2003	Canola	Trilogy	TT		OP	NPZA	CBWA003
2004	Canola	AG Comet	Conv.		OP	AgSeed	AGC103
2004	Canola	AG Drover	Conv.		OP	AgSeed	AGC114
2004	Canola	BravoTT	TT		OP	Canola Alliance	BLN2893TT
2004	Canola	Hyola 61	Conv.		Hybrid	Advanta	H1480

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
2004	Canola	Kimberley	Conv.		OP	Canola Breeders International Ltd	RGAAS0205
2004	HOLL Canola	MC201	Conv.		OP	AgSeed	MC201
2004	HOLL Canola	MC202	Conv.		OP	AgSeed	MC202
2004	Canola	Rocket CL	Conv.		OP	Advanta	J9747
2004	Canola	Skipton	Conv.		OP	Canola Alliance	BLN2677
2004	Canola	Thunder TT	TT		OP	Advanta	T2062
2004	Canola	Tornado TT	TT		OP	Advanta	T2015
2004	Canola	Tranby	TT		OP	DAFWA	DB150.98W5
2004	Canola	Tribune	TT		OP	NPZA	CBWA004
2005	Canola	ATR Banjo	TT		OP	AgSeed	AGT346
2005	Canola	ATR Summitt	TT		OP	AgSeed	TP004
2005	Canola	AV Jade	Conv.		OP	AgVic	RR013
2005	Canola	AV Opal	Conv.		OP	AgVic	RR002l
2005	Canola	AV Ruby	Conv.		OP	AgVic	RQ011
2005	Canola	CB Boomer	TT		OP	NPZA	CBTT-026
2005	Canola	Hyola 45	Conv.		Hybrid	Advanta	H4481
2005	Canola	Hyola 75	Conv.		Hybrid	Advanta	CBI4407
2005	Canola	Pioneer 44Y06	Conv.		Hybrid	Pioneer	02N708C
2005	Canola	Pioneer 45Y77	IMI	First IMI hybrid	Hybrid	Pioneer	03N734I
2005	Canola	Warrior CL	IMI		OP	Canola Alliance	BLN2867CL
2006	Canola	AG Muster	Conv.		OP	AgSeed	AGC323
2006	Canola	ATR Barra	TT		OP	AgSeed	TN4*207
2006	Canola	ATR Signal	TT		OP	Nutrihealth	NMT052
2006	Canola	CB Tanami	TT		OP	NPZA	CBTT-061
2006	Canola	Flinders TTC	TT		OP	AgSeed	ATR438
2006	HOLL Canola	Monola 130CC	Conv.		OP	Nutrihealth	NMC-130
2006	HOLL Canola	Monola NMT311	TT	First TT HOLL	OP	Nutrihealth	NMT-311
2006	Canola	Pioneer 46Y78	IMI		Hybrid	Pioneer	03N733I
2006	Canola	Rottnest TTC	TT		OP	AgSeed	ATR501
2007	Canola	ATR Cobbler	TT		OP	Nuseed	NMT040
2007	Canola	ATR Marlin	TT		OP	AgSeed	ATR423
2007	Canola	ATR409	TT		OP	AgSeed	ATR409
2007	Canola	AV Garnet	Conv.		OP	Nuseed	RT125
2007	Canola	CB Argyle	TT		OP	NPZA	
2007	Canola quality *B. Juncea*	Dune	Conv.		OP	AgVic	JR055
2007	Canola	Hyola 50	Conv.		Hybrid	Advanta	CBI4403
2007	HOLL Canola	Monola NMC115	Conv.		OP	Nutrihealth	NMC115
2007	HOLL Canola	Monola 131CC	Conv.		OP	Nuseed	NMC131
2007	Canola	Tarcoola	Conv.		OP	NSW DPI	BLN2026 *SL902
2008	Canola	GT61	Gly.	First RR OP	OP	Nuseed	GT61
2008	Canola	Hurricane TT	TT		OP	Advanta	T2202
2008	Canola	Hyola 502RR	Gly.	First RR hybrid	Hybrid	Advanta	M8032
2008	Canola	Hyola 571CL	IMI		Hybrid	Advanta	K9209
2008	Canola	Hyola 601RR	Gly.	First RR hybrid	Hybrid	Advanta	M8265
2008	Canola	Hyola 76	Conv.		Hybrid	Advanta	CBI6654
2008	HOLL Canola	Monola 66TT	TT		OP	Nuseed	NMT310

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
2008	HOLL Canola	Monola 75TT	TT		OP	Nuseed	NMT320
2008	HOLL Canola	Monola 76TT	TT		OP	Nuseed	NL042
2008	HOLL Canola	Monola 77TT	TT		OP	Nuseed	NL045
2008	Canola	Pioneer 43C80	IMI		OP	Pioneer	NS6108BI
2008	Canola	Pioneer 44C79	IMI		OP	Pioneer	NS6082BI(1)
2008	Canola	Pioneer 46Y20	Gly.	First RR hybrid	Hybrid	Pioneer	Z03N741R
2008	Canola	Pioneer 46Y81	IMI			Pioneer	Pioneer 05N289I
2008	Canola	Storm TT	TT		OP	Advanta	T2203
2008	Canola	Tawriffic TT	TT		OP	Canola Alliance	BLN3697TT
2008	HOLL Canola	Victory V3001	Conv.	First hybrid HOLL	Hybrid	Cargill	06H932
2009	Canola	CB Jardee HT	TT	First TT hybrid (Lembke)	Hybrid	NPZA	TTRIUMPH Jardee
2009	Canola	CB Mallee HT	TT	First TT hybrid (Lembke)	Hybrid	NPZA	TTRIUMPH CHYB-157
2009	Canola	CB Scaddan	TT		OP	NPZA	06S159
2009	Canola	CB Tumby HT	TT	First TT hybrid (Lembke)	Hybrid	NPZA	TTRIUMPH CHYB-125
2009	Canola	Hyola 751TT	TT	First TT hybrid (Ogura)	Hybrid	Advanta	T2475
2009	Canola	Lightning TT	TT		OP	Advanta	T2196
2009	Canola	Pioneer 45Y82	IMI		Hybrid	Pioneer	Pioneer 06N785I
2009	Canola	Pioneer 46Y83	IMI		Hybrid	Pioneer	Pioneer 06N788I
2009	Canola quality *B. Juncea*	Sahara CL	IMI		OP	Nutrien	J05Z-08960
2009	Canola	Telfer	TT		OP	NPZA	N03D-0369
2009	Canola quality *B. Juncea*	Xceed Oasis CL	IMI		OP	Nutrien	J05Z-08920
2010	Canola	CB Agamax	Conv.		Hybrid	NPZA	
2010	Canola	CB Eclipse RR	Gly.		Hybrid	NPZA	CHYB-166
2010	Canola	CB Junee HT	TT		Hybrid	NPZA	CHYB-127
2010	Canola	Crusher TT	TT		OP	Advanta	T2206
2010	Canola	Fighter TT	TT		OP	Advanta	T2181
2010	Canola	GT Cougar	Gly.		OP	Nuseed	NG0028
2010	Canola	GT Mustang	Gly.		OP	Nuseed	NG0157
2010	Canola	GT Scorpion	Gly.		OP	Nuseed	NG0195
2010	Canola	Hyola 404RR	Gly.		Hybrid	Advanta	M8534
2010	Canola	Hyola 433	Conv.		Hybrid	Advanta	H4722
2010	Canola	Hyola 444TT	TT		Hybrid	Advanta	T98002
2010	Canola	Hyola 505RR	Gly.		Hybrid	Advanta	M8535
2010	Canola	Hyola 555TT	TT		Hybrid	Advanta	T2522
2010	Canola	Hyola 575CL	IMI		Hybrid	Advanta	K9317
2010	Canola	Hyola 606RR	Gly.		Hybrid	Advanta	M8430
2010	Canola	Hyola 676CL	IMI		Hybrid	Advanta	K9356
2010	Canola	Pioneer 44Y84	IMI		Hybrid	Pioneer	Pioneer 06N784I
2010	Canola	SARDI515M	Conv.		Hybrid	Canola Breeders International Ltd	
2010	Canola - winter	CB Taurus	Conv.	First winter type	Hybrid	NPZA	
2011	Canola	ATR Gem	TT		OP	Nuseed	NT0107

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
2011	Canola	ATR Snapper	TT		OP	Nuseed	NT049
2011	Canola	ATR Stingray	TT		OP	Nuseed	NT045
2011	Canola	AV Zircon	Conv.		OP	Nuseed	RT123
2011	Canola	Bonanza TT	TT		OP	Advanta	T2414
2011	Canola	CB Frontier RR	Gly.		Hybrid	NPZA	CHYB-1721 RR
2011	Canola	CB Henty HT	TT		Hybrid	NPZA	CHYB-148 HT
2011	Canola	GT Cobra	Gly.		OP	Nuseed	NG0517
2011	Canola	GT Taipan	Gly.		OP	Nuseed	NG298
2011	Canola	GT Viper	Gly.		OP	Nuseed	NG0520
2011	Canola	Hyola 474CL	IMI		Hybrid	Advanta	K9319
2011	Canola	Jackpot TT	TT		OP	Advanta	T2447
2011	HOLL Canola	Monola 506TT	TT		OP	Nuseed	NL0437
2011	HOLL Canola	Monola 603TT	TT		OP	Nuseed	NL110
2011	HOLL Canola	Monola 605TT	TT		OP	Nuseed	NL0305
2011	HOLL Canola	Monola 704TT	TT		OP	Nuseed	NL120
2011	HOLL Canola	Monola 707TT	TT		OP	Nuseed	NL0587
2011	Canola	Pioneer 45Y21	Gly.		Hybrid	Pioneer	Pioneer 08N021R
2011	Canola	Pioneer 45Y22	Gly.		Hybrid	Pioneer	Pioneer 08N020R
2011	Canola	Thumper TT	TT		OP	Advanta	T2214
2011	HOLL Canola	Victory V3002	Conv.		Hybrid	Cargill	08H5061C
2011	HOLL Canola	Victory V3003	Conv.		Hybrid	Cargill	08H5067C
2011	HOLL Canola	Victory V5001RR	Gly.	First RR HOLL	Hybrid	Cargill	07H5000
2011	HOLL Canola	Victory V5002RR	Gly.		Hybrid	Cargill	08H5052
2012	Canola	Archer	IMI		Hybrid	Seedmark	SMPTHC105
2012	Canola	Carbine	IMI		Hybrid	Seedmark	SMHC111CL
2012	Canola	CB Nitro HT	TT		Hybrid	NPZA	CHYB1380
2012	Canola	CB Status RR	Gly.		OP	NPZA	CBWA-134RR
2012	Canola	CB Tango C	Conv.		Hybrid	NPZA	CHYB-187
2012	Canola	Hyola 559TT	TT		Hybrid	Advanta	T98060
2012	Canola	Hyola 656TT	TT		Hybrid	Advanta	T98022
2012	Canola	IH50 RR	Gly.		Hybrid	BASF	AN10R5001
2012	HOLL Canola	Monola 413TT	TT		OP	Nuseed	NL0606
2012	HOLL Canola	Monola 513GT	Gly.		OP	Nuseed	NP0549
2012	Canola	Nuseed GT-41	Gly.		Hybrid	Nuseed	HC1088
2012	Canola	Nuseed GT-50	Gly.		Hybrid	Nuseed	HC1050
2012	Canola	Pioneer 43Y23	Gly.		Hybrid	Pioneer	Pioneer 10N589R
2012	Canola	Pioneer 43Y85	IMI		Hybrid	Pioneer	Pioneer 08N102I
2012	Canola	Pioneer 45Y86	IMI		Hybrid	Pioneer	Pioneer 07N406I
2012	Canola	Pioneer Atomic TT	TT		Hybrid	Pioneer	CHYB1368
2012	Canola	Pioneer Sturt TT	TT		OP	Pioneer	CBWA-106
2012	Canola	VT 525 G	Gly.		Hybrid	Nutrien	08H5052
2013	Canola - Winter	Hyola 930	Conv.		Hybrid	Advanta	W8002

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
2013	Canola - Winter	Hyola 971CL	IMI		Hybrid	Advanta	W80006CL
2013	Canola	ATR Bonito	TT		OP	Nuseed	NT0183
2013	Canola	ATR Wahoo	TT		OP	Nuseed	NT0184
2013	Canola	Hyola 400RR	Gly.		Hybrid	Advanta	M95199
2013	Canola	Hyola 450TT	TT		Hybrid	Advanta	T18097
2013	Canola	Hyola 500RR	Gly.		Hybrid	Advanta	M95027
2013	Canola	Hyola 525RT	Gly. TT	First RR TT stack	Hybrid	Advanta	M17072
2013	Canola	Hyola 577CL	IMI		Hybrid	Advanta	K10050
2013	Canola	Hyola 650TT	TT		Hybrid	Advanta	T18098
2013	Canola	IH30 RR	Gly.		Hybrid	BASF	AN11R5181
2013	Canola	Nuseed Diamond	Conv.		Hybrid	Nuseed	HC1203
2013	Canola	Pioneer 44Y24	Gly.		Hybrid	Pioneer	Pioneer 10N523R
2013	Canola	Pioneer 44Y87	IMI		Hybrid	Pioneer	Pioneer 09N121I
2013	Canola	Pioneer 45Y88	IMI		Hybrid	Pioneer	Pioneer 09N146I
2014	Canola	DG 550RR	Gly.		Hybrid	Nutrien	VT-WZ 11-2685
2014	Canola	Hyola 600RR	Gly.		Hybrid	Advanta	M46652
2014	Canola - Winter	Hyola 970CL	IMI	First IMI winter	Hybrid	Advanta	X3721
2014	Canola	Hyola 635CC	Conv.		Hybrid	Advanta	I8802
2014	Canola	Hyola 725RT	Gly. TT		Hybrid	Advanta	M47001
2014	Canola	IH51 RR	Gly.		Hybrid	BASF	Bayer AN13R9003
2014	Canola	IH52 RR	Gly.		Hybrid	BASF	Bayer AN11R5201
2014	HOLL Canola	Monola 314TT	TT		OP	Nuseed	NL0769
2014	HOLL Canola	Monola 515TT	TT		OP	Nuseed	Monola 415TT
2014	Canola	Pioneer 44Y26	Gly.		Hybrid	Pioneer	PHR-1311
2014	Canola	Pioneer 44Y89	IMI		Hybrid	Pioneer	PHI-1305
2014	Canola	Pioneer 45Y25	Gly.		Hybrid	Pioneer	PHR-1306
2015	Canola	ATR Mako	TT		OP	Nuseed	NT0252
2015	Canola	Banker CL	IMI		Hybrid	Barenbrug	PHI-1401
2015	Canola	BASF 3000 TR	Gly. TT		Hybrid	BASF	PJTT1
2015	Canola	DG 460RR	Gly.		Hybrid	Nutrien	SN3
2015	Canola	DG 560TT	TT		Hybrid	Nutrien	SFR65-008TT
2015	Canola	Hyola 504RR	Gly.		Hybrid	Advanta	M26120
2015	HOLL Canola	Monola 416TT	TT		OP	Nuseed	NL0852
2015	HOLL Canola	Monola G11	Gly.		Hybrid	Nuseed	Monola 515HGT
2015	Canola	Nuseed GT-42	Gly.		Hybrid	Nuseed	NCH13G055
2015	Canola	Pioneer 45T01TT	TT		Hybrid	Pioneer	CB1302TT
2015	Canola	Rimfire CL	IMI		Hybrid	Barenbrug	HSHC133 (CL)
2015	Canola	SF Turbine TT	TT		Hybrid	RAGT	SFR65-009TT
2015	Canola	Yetna	TT		OP	Agronomy for Profit	
2016	Canola	InVigor R 5520P	Gly.		Hybrid	BASF	Bayer AN14R9012
2016	Canola	InVigor T 4510	TT		Hybrid	BASF	PJTT3
2016	Canola	Nuseed GT-53	Gly.		Hybrid	Nuseed	NCH13G046
2016	Canola	Pioneer 44T02 TT	TT		Hybrid	Pioneer	PHT-1504
2016	Canola	Pioneer 44Y90	IMI		Hybrid	Pioneer	PHI-1502
2016	Canola	Pioneer 45Y91	IMI		Hybrid	Pioneer	PHI-1402

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
2016	Canola	SF Ignite TT	TT		Hybrid	RAGT	SFR65-014TT
2016	HOLL Canola	VICTORY V5003RR	Gly.		Hybrid	Cargill	10H4061
2017	Canola	DG 408RR	Gly.		Hybrid	Nutrien	11H4054
2017	Canola	DG 670TT	TT		Hybrid	Nutrien	SFR65-013TT
2017	Canola	Hyola 350TT	TT		Hybrid	Advanta	T48481
2017	Canola	Hyola 506RR	Gly.		Hybrid	Advanta	M95168
2017	Canola	HyTTec Trophy	TT		Hybrid	Nuseed	NCH15T085
2017	Canola	InVigor R 3520	Gly.		Hybrid	BASF	Bayer AN15R5537
2017	Canola	Nuseed Quartz	Conv.		Hybrid	Nuseed	NCH14C047
2017	Canola	Pioneer 43Y92	IMI		Hybrid	Pioneer	PHI-1601
2017	Canola	Pioneer 44Y27	Gly.		Hybrid	Pioneer	PHR-1605
2017	Canola	Saintly CL	IMI		Hybrid	Barenbrug	PHI-1503
2017	HOLL Canola	VICTORY V7002CL	IMI	First IMI HOLL	Hybrid	Cargill	
2018	Canola - Winter	RGT Nizza CL	IMI		Hybrid	RAGT	
2018	Canola - Winter	Phoenix CL	IMI		Hybrid	AGF Seeds	
2018	Canola	ATR Flathead	TT		OP	Nuseed	NT0218
2018	Canola	Hyola 410XX	Gly.	First TruFlex® hybrid	Hybrid	Advanta	M65041
2018	Canola	Hyola 530XT	Gly. TT	First TruFlex® TT stack	Hybrid	Advanta	M67279
2018	Canola	Hyola 550TT	TT		Hybrid	Advanta	T68001
2018	Canola	Hyola 580CT	IMI TT	First IMI TT stack	Hybrid	Advanta	T61001
2018	Canola	InVigor R 4020P	Gly.		Hybrid	BASF	AN16R9438
2018	Canola	InVigor T 3510	TT		Hybrid	BASF	CHYB2124TT
2018	Canola	Pioneer 43Y29 RR	Gly.		Hybrid	Pioneer	PHR-1703
2018	Canola	Pioneer 45T03 TT	TT		Hybrid	Pioneer	45T03
2018	Canola	Pioneer 45Y28 RR	Gly.		Hybrid	Pioneer	PHR-1702
2018	Canola	Pioneer 45Y93 CL	IMI		Hybrid	Pioneer	PHI-1706
2018	Canola	SF Spark TT	TT		Hybrid	RAGT	SFR65-023
2019	Canola	Hyola 540XC	Gly.	First IMI Truflex® stack	Hybrid	Advanta	M64001
2019	Canola	HyTTec Trident	TT		Hybrid	Nuseed	NCH15T103
2019	Canola	InVigor R 4022P	Gly.		Hybrid	BASF	AN17R9107
2019	Canola	Nuseed Raptor TF	Gly.		Hybrid	Nuseed	NCH15G290
2020	Canola	Hyola Blazer TT	TT		Hybrid	Advanta	ADV-Excite
2020	Canola	Hyola Enforcer CT	TT		Hybrid	Advanta	CT90008
2020	Canola	Hyola Garrison XC	Gly.		Hybrid	Advanta	XC90010
2020	Canola	HyTTec Trifecta	TT		Hybrid	Nuseed	NCH16T324
2020	Canola	InVigor R 4520P	Gly.		Hybrid	BASF	AN18R9002
2020	Canola	InVigor T 6010	TT		Hybrid	BASF	CHYB3668TT
2020	HOLL Canola	Monola 420TT	TT		OP	Nuseed	NL1015
2020	HOLL Canola	Monola H421TT	TT		Hybrid	Nuseed	NMH18T446
2020	Canola	Nuseed Condor TF	Gly.		Hybrid	Nuseed	NCH18Q421
2020	Canola	Pioneer 44Y94 CL	IMI		Hybrid	Pioneer	PHI-1904
2020	Canola	Pioneer 45Y95	IMI		Hybrid	Pioneer	PHI-1804
2020	Canola	SF Dynatron TT	TT		Hybrid	RAGT	CHYB3688TT
2020	HOLL Canola	VICTORY V75-03CL	IMI		Hybrid	Cargill	16MH6004
2021	Canola - Winter	Hyola Feast CL	IMI		Hybrid	Advanta	CL82005
2021	Canola	AFP Cutubury	TT		OP	Agronomy for Profit	

Year of release	Quality type	Variety name	Herbicide category[1]	First landmark variety	Breeding method[2]	Breeding program[3]	Other code
2021	Canola	ATR Bluefin	TT		OP	Nuseed	NT0289
2021	Canola	DG BIDGEE TT	TT		OP	Nutrien	DG1903TT
2021	Canola	DG Bindo TF	Gly.		Hybrid	Nutrien	DG2102XX
2021	Canola	DG Lofty TF	Gly.		Hybrid	Nutrien	DG2101XX
2021	Canola	DG MURRAY TT	TT		OP	Nutrien	DG1902TT
2021	Canola	Hyola Battalion XC	Gly.		Hybrid	Advanta	XC91402
2021	Canola	Hyola Equinox CL	IMI		Hybrid	Advanta	CL90009
2021	Canola	InVigor LT 4530P	Gluf. TT	First glufosinate hybrid	Hybrid	BASF	AN20LT001
2021	HOLL Canola	Monola 422TT	TT		Hybrid	Nuseed	NL1131
2021	Canola	Nuseed Emu TF	Gly.		Hybrid	Nuseed	NCH18Q567
2021	Canola	Pioneer 44Y30 RR	Gly.		Hybrid	Pioneer	WW1739R
2021	Canola	RGT Capacity TT	TT		Hybrid	RAGT	SFR65-028TT
2022	Canola	ATR Swordfish	TT		OP	Nuseed	NT0504
2022	Canola	Bandit TT	TT		OP	AGT	AGTC0006
2022	Canola	DG Hotham TF	Gly.		Hybrid	Nutrien	DG2103XX
2022	Canola	DG Torrens TT	TT		Hybrid	Nutrien	DG1924TT
2022	Canola	Hyola Regiment XC	Gly.		Hybrid	Advanta	PS-21XC316
2022	Canola	Hyola Solstice CL	IMI		Hybrid	Advanta	PS-21CL208
2022	Canola	HyTTec Velocity	TT		Hybrid	Nuseed	NCH19T588
2022	Canola	InVigor T 4511	TT		Hybrid	BASF	CHYB4372TT
2022	Canola	Nuseed Eagle TF	Gly.		Hybrid	Nuseed	NCH20Q732
2022	Canola	Nuseed Hunter TF	Gly.		Hybrid	Nuseed	NCH20Q733
2022	Canola	PY520TC	IMI TT		Hybrid	Pioneer	AA0419E
2022	Canola	Renegade TT	TT		OP	AGT	AGTC0034
2022	Canola	RGT Baseline TT	TT		Hybrid	RAGT	SFR65-059TT
2022	HOLL Canola	VICTORY V55-04TF	Gly.		Hybrid	Cargill	19TH6009
2023	Canola - Winter	RGT Clavier CL	IMI		Hybrid	RAGT	SFR65056CL
2023	Canola - Winter	Captain CL	IMI		Hybrid	AGF Seeds	AGFCA014120
2023	Canola	InVigor LR 4540P	Gluf. + Gly.	First Glufosinate + Glyphosate hybrid	Hybrid	BASF	AN22LR008

1 Herbicide category: Conv. = conventional; TT = triazine tolerant; IMI = imidazolinone tolerant; Gly. = glyphosate resistance; IMI TT = imidazolinone + triazine tolerant; Gluf. TT = glufosinate resistance + triazine tolerance; Gluf. + Gly. = glufosinate + glyphosate resistance.

2 OP = open pollinated

3 Advanta = Advanta Seeds Pty Ltd
AGT = Australian Grain Technologies Pty Ltd
AgWA = Agriculture Western Australia, now Department of Primary Industries and Rural Development
AgSeed = Ag-Seed Research Pty Ltd, now NuSeed Pty Ltd
BASF = BASF Australia Ltd
NSW DPI = NSW Agriculture and NSW Department of Primary Industries
Nutrien = Nutrien Ag Solutions Ltd
Pacific Seeds, now Advanta Seeds Ltd
Pioneer = Pioneer Hi-Bred Australia Pty Ltd, now Corteva AgriScience

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More information

References and further reading relating to this chapter are listed in Appendix 1 (p. 100).

Transgenic canola

Dr. Carl Ramage[1], Dr. Raymond Cowley[2] and Kate Light[3]

[1] Rautaki Solutions Pty Ltd, Mitcham VIC 3132
[2] Corteva AgriScience, Wagga Wagga NSW 2650
[3] Nutrien Ag Solutions, Horsham VIC 3400

Summary

- The introduction of genetically modified (GM) canola into Australia was challenging. Despite regulatory approvals demonstrating food, feed and environmental safety, the commercial cultivation of GM canola was significantly delayed by state and territory moratoria banning cultivation.
- Grains industry leadership developed a national framework for the pathway to market of GM crops. It provided a unified approach to ensure quality supply chain management, market choice and market access. The result was a gradual lifting of moratoria across states and territories.
- Despite a strong domestic pathway to market, the introduction of GM canola can be slow as food/feed regulatory approvals are required in Australia's key export markets.
- Industry continues to engage domestically and internationally with regulators and supply chain advocacy groups to ensure that Australian growers continue to have access to new trait opportunities.
- GM and non-GM canola are segregated at delivery points to enable identity preservation in downstream markets.

Introduction

Achieving approvals to release a GM trait in Australian canola varieties has been very difficult. Before 2000, Australia did not have a formal regulatory system to assess and approve GM products and relied on a voluntary process (O'Sullivan et al. 2022). Not having a regulatory system was considered prohibitive to a pathway to market for GM canola. This was further complicated by each state and territory holding differing positions on the commercial cultivation of genetically modified organisms (GMOs) *per se*. Additional approvals, such as a food approval from Food Standards Australia New Zealand (FSANZ), are also required before commercialisation. Despite these challenges, since implementing the National Regulatory Scheme for Gene Technology in 2001, there have been 10 GM canola traits approved for commercial release in Australia.

Approval for commercial cultivation of GM crops is a Federal process. However, through an inter-governmental agreement individual states and territories may impose their own restrictions on commercial cultivation of a transgenic canola trait, in their jurisdiction, if they believe the product could compromise market and trade. Further, considerations such as regulatory approvals for food, feed and or processing in export markets also influence the practical cultivation of specific transgenic canola types at a given time.

In 2004, despite regulatory approvals, states and territories recognised a disconnect along the grains supply chain. They held significant concerns that introducing GM canola would impact grain exports and so imposed moratoria on commercial cultivation. The moratoria were allowed to lapse in 2008 in both New South Wales and Victoria owing to the Australian grains industry's significant efforts to demonstrate supply chain alignment. The moratorium in Western Australia ended in 2010 and more recently the moratorium in South Australia ended in 2021. Moratoria remain in place in Tasmania and certain parts of South Australia (i.e. Kangaroo Island).

Transgenic canola was first cultivated in Australia in 2008. Since then, it is estimated that 30–35% of the total area sown to canola in Australia annually is transgenic. This percentage continues to increase each season. To preserve certain markets, Australian canola is segregated at the grain silo receival points into GM and non-GM canola. Identity preservation is maintained through downstream canola processing.

Whilst most transgenic traits currently released are production traits (i.e. hybrid system and/or herbicide tolerances), output traits are starting to progress through the regulatory approval process. The first one was approved in 2018.

Regardless of the hurdles and timeframes involved, Australia now has a well-established regulatory framework and grower adoption of currently cultivated transgenic canola proves the traits developed and regulated for their use are valued.

Australia's National Gene Technology Scheme

Australia's National Gene Technology Scheme (the Scheme) is a national cooperative of all state, territory and Commonwealth governments, set out in the intergovernmental Gene Technology Agreement 2001 (the Agreement). The Scheme includes:

- the Agreement
- the *Gene Technology Act 2000* (Cth) (GT Act, Commonwealth of Australia 2000)
- the *Gene Technology Regulations 2001* (Cth) (the Regulations, Commonwealth of Australia 2001)
- corresponding state and territory legislation.

The Scheme is highly regarded, both domestically and internationally. It is designed to protect the health and safety of people, and the environment, from risks associated with gene technology processes.

The Legislative and Governance Forum on Gene Technology (LGFGT) oversees the regulatory framework and provides guidance on matters of policy that underpin the legislation. The forum comprises ministers from the Commonwealth and each state and territory. It is supported by the Gene Technology Standing Committee, comprising senior officials from all jurisdictions.

The Scheme also works in conjunction with, and complements, other regulatory frameworks that deal with GM products (Thygesen 2019). In Australia, GM products are regulated by a range of agencies with the appropriate expertise to assess any associated risks (Table 9).

The Act provides for the independent appointment of a Gene Technology Regulator (the Regulator) with administration provided by the Office of the Gene Technology Regulator (OGTR). These Commonwealth and state laws provide national coverage for regulating GMOs.

The Act is the primary piece of legislation regulating GMOs and aims to:

> 'Protect the health and safety of people, and to protect the environment, by identifying risks posed by or as a result of gene technology, and by managing those risks through regulating certain dealings with GMOs.'

The Act regulates gene technology processes rather than the products themselves (*cf* Canadian novel foods regulations, Ellens et al. 2019). Case by case assessment is required as the processes and outputs/products that might be covered by the Act is vast.

Organisations and their partners/representatives must meet several regulatory milestones to handle ('conduct dealings' with) GM plant products in Australia. This applies from time of development through to eventual commercial release. These regulatory milestones include:

- Approval as an 'Accredited Organisation' under the Act.
- Establishing or gaining access to an Institutional Biosafety Committee (IBC) to oversee GM product regulatory activities.

- Obtaining a notifiable low risk dealing (NLRD) and access to certified physical containment level 2 facilities for laboratory and glasshouse dealings with GM plants (as required).
- Preparing and submitting a DIR license application to allow limited and controlled field experiments of GM plants.
- Gathering a dossier of biosafety information to support the submission of a DIR license application for commercial release.

When assessing applications for an intentional release license the OGTR is required to consult and liaise with the public as well as other government agencies. Comprehensive information on the scheme, processes for certifying and maintaining physical containment facilities, making license applications and a list of all approved GMOs is publicly available on the OGTR website (www.ogtr.gov.au). Collectively, this ensures a transparent and coordinated decision-making process.

Under the national scheme, all states and territories recognise GMO approvals by the Regulator with respect to potential harm to human health and safety and the environment. However, under an intergovernmental agreement, states and territories reserved the ability to legislate with respect to market and trade. In 2003 and 2004, most state governments in Australia implemented various bans on the commercial cultivation of GM crops, more specifically GM canola varieties. Thereafter numerous reviews of state legislation, driven by strong advocacy from the grains industry (Grain Trade Australia 2019) have subsequently led to wider commercial GM canola production.

The Australia New Zealand Food Standards Code (the Code) is a collection of enforceable food standards. Supplying food that does not comply with the Code is prohibited by law in Australia and New Zealand. Any agency, body or person can apply to vary the Code.

In contrast to OGTR, FSANZ assesses the final product for safety rather than the process itself, though the assessment does consider the process of product development. Further, the definitions that FSANZ are guided by differ from those of the OGTR. Current FSANZ definitions are:

- *food produced using gene technology* means a food which has been derived or developed from an organism which has been modified by gene technology
- *gene technology* means recombinant DNA techniques that alter the heritable genetic material of living cells or organisms.

Table 9 *Regulatory agencies with responsibilities for the regulation of GM products in Australia.*

Agency	Products regulated	Relevant legislation/agreements
Office of the Gene Technology Regulator (OGTR)	All 'dealings' with GMOs	*Gene Technology Act 2000* *Gene Technology Regulations 2001* *Gene Technology Agreement 2001*
Food Standards Australia New Zealand (FSANZ)	Food for human consumption	*Food Standards Australia New Zealand Act 1991* *Food Standards Australia New Zealand Regulations 1994* *Imported Food Control Act 1992* *Food Standards Code*
Therapeutic Goods Administration (TGA)	Human therapeutic goods	*Therapeutic Goods Act 1989* *Therapeutic Goods Regulations 1990*
Australian Pesticides and Veterinary Medicines Authority (APVMA)	Agricultural chemicals and veterinary medicines	*Agricultural and Veterinary Chemicals (Administration) Act 1992* *Agricultural and Veterinary Chemicals Code Act 1994.*
Australian Industrial Chemicals Introduction Scheme (AICIS)	Industrial chemicals	*The Industrial Chemicals Act 2019*
Department of Agriculture, Forestry and Fisheries (DAFF)	Import and export	*Biosecurity Act 2015*

Selling GM food in Australia or New Zealand is illegal unless expressly permitted. All GM foods intended for sale must undergo a pre-market assessment under *Standard 1.5.2 – Food Produced Using Gene Technology* contained in the Code. In some circumstances, proponents might also need to apply to amend *Standard 1.5.1 Novel Foods*. The Standards have two provisions:

- mandatory pre-market approval (including a food safety assessment)
- mandatory labelling requirements.

The Standards ensure that only assessed and approved GM foods enter the food supply. Guidance documents detailing the safety assessment process as well as how to apply to amend the Code are available (FSANZ 2005; 2019). Approved products are listed in Schedule 26 of the Code (Food produced using gene technology).

FSANZ will not approve a GM food unless it is safe to eat. Therefore, if the OGTR determine a product has been developed using gene technology and requires regulation, then typically FSANZ will also need to consider whether a change to the Code is required. In many cases the data requirements provided to each authority are similar. Importantly, whilst there is no specific animal feed approval, GM crops grown for feed cannot be grown in Australia or New Zealand unless they have been approved for human consumption.

Australian grains industry leadership

In 2003, the OGTR approved Bayer CropScience's InVigor® GM canola and Monsanto Australia's Roundup Ready® GM canola for commercial release.

In 2004, the Victorian Government concluded that the timing was not appropriate for the full commercial release of GM canola, due to '*divisions and uncertainty within industry, the farming sector and regional communities about the impact of GM crops on markets*' (Office of the Premier 2004). The Minister for Agriculture issued an Order declaring a moratorium on the commercial cultivation of GM canola in Victoria. All other states and territories, except Queensland and the Northern Territory also introduced moratoria on GM canola, or more broadly, GM crops.

State and territory moratoria were imposed for trade and market access reasons. This reasoning extended to the potential for the unintended presence of GM canola in other key export grains such as wheat and barley, potentially jeopardising valuable markets. Further, there was uncertainty as to how the grains industry could manage the costs and potential liability that might be imposed on GM and non-GM growers to segregate GM from non-GM crops when supplying GM sensitive markets.

The industry responded to the moratoria through several initiatives.

Firstly, Single Vision Grains Australia (SVGA) facilitated a process that encouraged supply chain participants to help develop a national framework for GM crops in the Australian grains industry. This allowed the industry to identify the key elements required when introducing a GM crop that would minimise grain supply chain disruption.

Secondly, SVGA developed a pathway to market package for grains industry stakeholders (including governments). The package demonstrated how the Australian grains industry would ensure market choice and market access for all canola products and grains following the introduction of GM canola.

Collectively, these initiatives aimed to deliver market choice for the Australian canola industry and resulted in a Market Choice Framework (Grain Trade Australia 2019).

The framework incorporates the elements required when introducing a GM crop that are least disruptive to the Australian grain supply chain. It includes stewardship, domestic and international regulatory requirements, and processes for managing planting seed and grain along the supply chain where GM and non-GM products coexist.

The framework sets out 3 key elements in the delivery of market choice. These are the ability of any supply chain participant to:

1. source product that meets a pre-determined set of specifications
2. supply product that meets a pre-determined set of specifications
3. manage their area of the production, processing, manufacturing, and delivery of product to a predetermined set of specifications.

Importantly, the framework requires:

- a market risk assessment to identify key countries of production and import before the commercialisation of any new GM crop
- the GTA Plant Breeding Innovation Committee agree with the supply chain where food, feed and processing approvals are required

- the technology provider, together with the industry, develop and implement stewardship programs that are appropriate for the nominated GM crop. The stewardship program must be sufficient to prevent the GM trait from becoming present above established threshold levels in the non-GM stream.

Transgenic canola in Australia

Currently 10 GM canola events have been approved for commercial cultivation in Australia (Table 10)

Of these:

- 9 involve herbicide tolerance (input traits), 5 also include a hybrid breeding system (production trait)
- one is related to a modified oil quality profile (output trait).

An additional event received commercial cultivation approval in 2016 (Pioneer Hi-Bred's Optimum *GLY*®). However, due to delays in receiving approvals in export markets this event will not be available to Australian growers until 2024, 8 years after commercial release was granted in Australia.

There are currently 4 regulated dealings with the OGTR that are under limited and controlled intentional release directions (Table 11).

Future directions

New breeding technologies continue to receive significant attention and have been the subject of recent regulatory reforms (Jones et al. 2022). A summary of the regulatory reviews on new breeding technologies in Australia was recently published (Entine et al. 2021). The Australian grains industry continues to consult domestically and internationally on these opportunities. The industry has also contributed to:

- a technical review of the Gene Technology Regulations
- reviews of the National Gene Technology Scheme
- FSANZ consultations on new breeding technologies.

It is important that, as new GM traits are developed in canola globally, the Australian industry continues to offer growers the choice of using available traits in their production system. For this to occur, the industry must continue to work with the regulatory system on the commercial release of GM traits in canola so that Australian growers do not miss opportunities to potentially improve their long-term profitability or access new canola markets.

Table 10 *Canola GM regulated dealings.*

Licence number	Link to Licence details	Project title	Organisation	Release	Issue date	Licence status
DIR 188	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-188	Limited and controlled release of canola and Indian mustard genetically modified for altered oil content and herbicide tolerance	Nuseed Pty Ltd	Limited and controlled	8 Jun 22	Current
DIR 164	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-164	Limited and controlled release of canola genetically modified for herbicide tolerance	Monsanto Australia Limited	Limited and controlled	21 Nov 18	Current
DIR 163	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-163	Limited and controlled release of canola genetically modified for altered oil content and herbicide tolerance	Nuseed Pty Ltd	Limited and controlled	6 Sep 18	Current
DIR 149	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-149	Limited and controlled release of Indian mustard (*Juncea* canola) genetically modified for altered oil content	Nuseed Pty Ltd	Limited and controlled	14 Feb 17	Current

Table 11 *GM Canola events approved for commercial cultivation in Australia.*

Licence number	Link to Licence details	Project title	Organisation	Release	Issue date
DIR 190	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-190	Commercial release of Indian mustard genetically modified for herbicide tolerance (RF3)	BASF Australia Ltd	Commercial	13 Oct 22
DIR 178	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-178	Commercial release of canola genetically modified for herbicide tolerance and a hybrid breeding system (MS11× RF3 and MS11 × RF3 × MON 88302)	BASF Australia Ltd	Commercial	16 Sep 21
DIR 175	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-175	Commercial release of canola (*Brassica napus*) genetically modified for herbicide tolerance and a hybrid breeding system (MS11)	BASF Australia Ltd	Commercial	12 May 21
DIR 155	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-155	Commercial release of canola genetically modified for omega-3 oil content (DHA canola)	Nuseed Pty Ltd	Commercial	13 Feb 18
DIR 139	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-139	Commercial release of canola genetically modified for herbicide tolerance	Pioneer Hi-Bred Australia Pty Ltd	Commercial	29 Mar 16
DIR 138	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-138	Commercial release of canola genetically modified for dual herbicide tolerance and a hybrid breeding system	BASF Australia Ltd	Commercial	22 Mar 16
DIR 127	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-127	Commercial release of canola genetically modified for herbicide tolerance	Monsanto Australia Ltd	Commercial	21 Nov 14
DIR 108	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-108	Commercial release of canola genetically modified for herbicide tolerance and a hybrid breeding system	BASF Australia Ltd	Commercial	2 Dec 11
DIR 021/2002	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-0212002	Commercial release of canola genetically modified for herbicide tolerance and a hybrid breeding system for use in the Australian cropping system	BASF Australia Ltd	Commercial	25 Jul 03
DIR 020/2002	https://www.ogtr.gov.au/gmo-dealings/dealings-involving-intentional-release/dir-0202002	General release of Roundup Ready® canola (*Brassica napus*) in Australia	Monsanto Australia Ltd	Commercial	19 Dec 03

More information

References relating to this chapter are listed in Appendix 1 (p. 103).

Independent variety testing in Australia: 1999–present

Katherine Hollaway[1], Sean Coffey[2] and Neale Sutton[2]
[1] Astute Ag, Horsham VIC 3400
[2] Grains Research and Development Corporation, Canberra ACT 2600

Summary

- The Grains Research and Development Corporation (GRDC) National Variety Trials™ (NVT) program combined multiple state-focused variety evaluation programs into a world leading nationally coordinated independent variety performance program.
- The program evaluates around 100 canola varieties each year at 66 locations across Western Australia, New South Wales, Victoria and South Australia.
- Consistent national trial protocols, innovative analysis and sophisticated online tools provide detailed insights into future variety performance.

Introduction

While breeding to improve yield, quality and disease resistance are the cornerstones of the success of canola over the past 25 years, it is independent variety testing that gives growers the confidence to adopt a new variety.

The GRDC's NVT program, established in 2005, is the largest independent coordinated trial network in the world. It brought multiple state-focused variety trial programs together into a single entity that has evolved (Table 12) into a world-leading variety evaluation program. NVT now conducts a wide range of grains research and works with around 30 Australian-based breeding programs. International breeding programs can also participate. Over 650 trials are conducted at over 300 locations each year (Figure 23).

The program is managed and funded by the GRDC. In addition to canola, it evaluates wheat, barley, oats, chickpea, faba bean, field pea, lentil, lupin and sorghum.

The program aims to improve grower profitability by providing independent information that enables growers to match varieties to their needs and growing conditions. Trials are conducted on grower properties to reflect regionally representative conditions.

Establishing an independent service in parallel with the shift from public to private breeding was essential to maintain confidence in variety claims. On behalf of growers, the program's original brief was to test:

- commercial varieties with ongoing relevance to industry
- advanced breeding lines within 2 years of commercial release.

In 2023, canola variety trials were located at 66 locations across Western Australia (27), New South Wales (16), Victoria (12) and South Australia (11). The 164 trial blocks were subdivided into glyphosate resistant (54), imidazolinone tolerant (44) or triazine tolerant (66) in 1 or 2 maturity groups – low to medium-rainfall (55) and medium to high-rainfall (109). The number of varieties tested each year is typically around 100 but has been as high as 188.

This is a big change from 1983 when the first advanced breeding lines were evaluated in state-based testing programs run by state government departments (Potter et al. 1999). At the time, often fewer than 10 lines were tested each year, different maturities were combined, and geographic spread was limited to around 14 locations.

Table 12 *The development timeline of today's NVT program.*

Leadership	Year	Event
Up to 1997 State-based variety trials.	1993	• State-led testing expanded and split into 4 categories – early, mid and late maturity plus triazine tolerant canola (Potter et al. 1999). • An increased number of lines evaluated – up to 33 breeding lines in each category – at 10 to 12 sites in southern Australia.
1997 to 2005 State-based trials with GRDC-funded ACAS* coordination and verification.	1997	• The Australian Crop Accreditation System (ACAS) was established by GRDC as an independent body to verify variety information using scientific protocols (Potter et al. 1999). • An oilseeds committee oversaw voluntary submission of canola and mustard varieties by breeders.
	2000	• ACAS incorporated as ACAS Limited to manage variety trials on behalf of GRDC. • Work started to build a database to consolidate trial protocols and results across state trial programs.
2005 to 2017 Nationally coordinated trials managed by ACAS with GRDC investment.	2005	• National independent field evaluation of cereal, pulse and canola varieties started as the NVT program replaced state-based testing under the leadership of Alan Bedggood. • Canola disease trials evaluated by Marcroft Grains Pathology. • NVT website established allowing registered users to access results online.
	2008–09	• 11 advisory committees established to seek grower perspectives on trial locations, management protocols and variety inclusion. • Google map interface added to website and login requirement removed to improve public access to results.
	2013–14	• Future variety performance predictions expanded from regional to local (town based) and better access was provided via the website's *Long Term Yield Reporter*.
2017 to date GRDC-managed national trial program with focus on enabling new opportunities.	2017	• NVT management transferred from ACAS to GRDC.
	2018	• *NVT Disease Ratings* tool added to website.
	2020	• Inaugural 2019 NVT *Harvest Report* published.
	2022	• GRDC introduce the *Future NVT Initiative* to allow the grains industry to leverage GRDC's investment in NVT to improve the long-term sustainability and value of the program by providing NVT resources to grains industry researchers.

*ACAS = Australian Crop Accreditation System

Herbicide tolerant canola

Canola trials have been adjusted in response to the release of herbicide tolerant varieties.

Triazine tolerant canola was released in 1993 and imidazolinone tolerant in 2000. Each was initially sown alongside conventional varieties until there were enough to segregate into separate blocks. Genetically modified glyphosate resistant canola was added to trials in:

- New South Wales and Victoria in 2008
- Western Australia in 2009 – a year before release to growers
- South Australia in 2021.

Herbicide tolerant stacked canola varieties were first released in 2013 and are included in the program. Due to declining interest conventional canola was last sown in NVT in 2020.

The NVT canola trial program will continue to evolve in line with demand for different types of canola.

Blackleg resistance ratings

Blackleg disease screening had been coordinated by Marcroft Grains Pathology (MGP) since 2000, with ratings initially based on data supplied by state canola breeding programs. GRDC established independent field screening conducted by MGP when NVT trials began in 2005 and now classifies varieties by their type of genetic resistance to blackleg (Idnurm et al 2022).

Blackleg ratings are updated twice a year via the *NVT Disease Rating* tool and the *Blackleg Management Guide*. The autumn guide updates ratings for commercial varieties, and the spring guide adds recently released varieties.

Communication

Growers, agronomists and breeders have access to a detailed variety analysis using a range of tools and resources on the NVT website including the *Long Term Yield Reporter* (LTYR) and the *NVT Disease Ratings* tool.

Annual field experiment reports are available via the interactive map-based *NVT Trial Results* tool.

Static resources include regional *Harvest Reports*, state sowing guides and the *Blackleg Management Guide*.

Updates are available via the GRDC NVT twitter account @GRDC_NVT, or by subscription notification services covering NVT communications and trial notifications.

Figure 23 *NVT canola variety trial at Spalding, South Australia, 2021.* Photo: Trevor Garnett.

Expanding horizons

With 74% of growers (GRDC 2021) now actively using NVT data to make better variety decisions, GRDC is pursuing opportunities to leverage the existing investment in trial infrastructure to deliver greater value to Australian growers through the *Future NVT Initiative*. This includes the *Pre-commercial Purchasing* and *NVT Resource Sharing* models.

The Pre-commercial Purchasing model has removed constraints on the number of pre-commercial entries available to breeders while also allowing international breeders to enter the program for the first time. This will promote better access to future varieties for Australian growers. In addition, breeders now have increased access and licence to use the extensive NVT dataset in their programs.

The NVT Resource Sharing model has increased the program's value to the grains industry by providing other research projects with access to NVT resources (data, trials, and harvested grain). As a result, it has become an enabling platform for a wide range of research that benefits the Australian grains industry.

More information

References and resources relating to this chapter are listed in Appendix 1 (p. 103).

Acknowledgements

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Diseases

Dr. Susan Sprague[1], Dr. Kurt Lindbeck[2] and Dr. Barbara J Howlett[3]

[1] CSIRO Agriculture and Food, Canberra ACT 2604

[2] NSW Department of Primary Industries, Wagga Wagga NSW 2650

[3] School of Biosciences: The University of Melbourne, Melbourne VIC 3010

Summary

- Canola production in Australia has expanded dramatically during the last 2 decades and has brought significant disease control challenges.
- Canola can be infected by several root, foliar and vascular pathogens throughout its development from germination to maturity. Blackleg disease caused by the fungus *Leptosphaeria maculans* continues to be the most economically important biotic constraint, but other fungi such as *Sclerotinia sclerotiorum* are also important.
- Research, particularly on blackleg, including crop management practices, exploitation of resistance genes and fungicide use, is discussed. Findings from this research have been incorporated into an integrated disease management (IDM) approach to help prevent and manage these diseases.

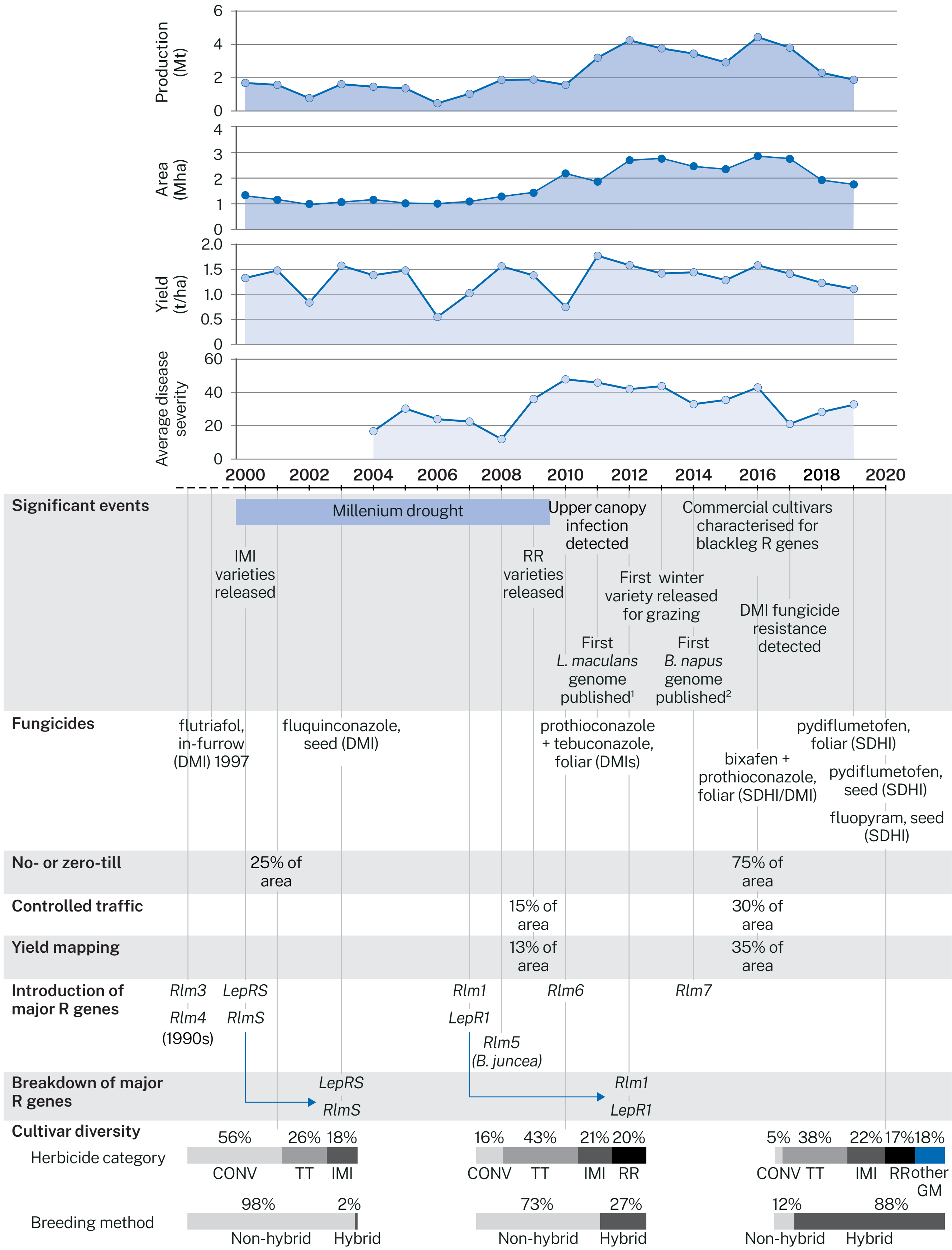
Introduction

Australian canola crops can be infected by a range of pathogens during development from germination to maturity. Blackleg (*Leptosphaeria maculans*) is the most important followed by sclerotinia stem rot (SSR, *Sclerotinia sclerotiorum*). Other diseases are present sporadically depending on seasonal conditions, regional differences and crop management decisions.

Canola production in Australia has expanded rapidly in the past 2 decades and farming practices have changed significantly in response to increased climate variability. These changes, underpinned by technological and scientific advances, have influenced the prevalence and epidemiology of canola diseases.

Australian growers have increasingly adopted conservation agricultural practices such as zero-till and controlled traffic which has resulted in crop residues being retained and carryover of stubble-borne disease inoculum (Figure 24). Canola in crop rotations (canola-wheat-canola) has increased in many regions, and both sowing and optimal flowering times are now earlier in response to climate drivers and the availability of adapted canola varieties with herbicide tolerance (Kirkegaard et al. 2016; Lilley et al. 2019; Van de Wouw et al. 2021). Winter varieties were introduced in 2013 as dual-purpose crops providing both forage for livestock during the vegetative period and grain production (Kirkegaard et al. 2008; Sprague et al. 2015).

Significant events in canola crop management and breeding over the last 20 years are described by Van de Wouw et al. (2021) and summarised in Figure 24. The prevalence and epidemiology of canola diseases are discussed in the context of the rapid expansion of canola in Australia and the significant changes in farming practices over the last 2 decades.



[1] Rouxel et al. 2011 [2] Chalboub et al. 2014 Reproduced with permission from Van de Wouw et al. 2021

Figure 24 Summary of significant events in Australian canola production including the introduction of new technologies, changes in farming practices and variety diversity. Lower production in the early 2000s reflects the Millennium drought. R, resistance; IMI, Clearfield®; RR, glyphosate resistant; CONV, conventional; TT, triazine tolerant; GM, genetically modified.

Blackleg disease

In Australia, blackleg can be more devastating than in other countries. Temperate conditions over winter favour infection and fungal growth, and crop residues which support sexual crossing over summer persist in the Mediterranean climate creating a high inoculum load. *L. maculans* can infect all above and below-ground parts of the canola plant. Airborne sexual ascospores released after rainfall land on the crop, germinate and then invade the plant. Traditionally, yield loss has been associated with infection during the seedling stage causing crown cankers. In the last decade, infection during crop reproductive stages has become more prevalent with lesions on flowers, peduncles, upper stems and pods causing similar yield loss to crown canker (Sprague et al. 2017a). Collectively, these symptoms are termed upper canopy infection (UCI) and have been a focus for recent blackleg research in Australia.

Host genetic resistance

Varieties with high blackleg resistance levels underpin disease control in Australia. Resistant varieties were crucial to re-establishing the industry following decimation by blackleg in the late 1960s when susceptible Canadian rapeseed varieties were first introduced. Resistance is conferred by both major and minor genes. Major genes provide protection throughout plant development. All Australian varieties are released with a blackleg resistance rating (susceptible to resistant) and since 2016 have been classified into resistance groups based on their complement of major genes. These genes are identified phenotypically by a differential set of *L. maculans* isolates and more recently by genetic markers (Marcroft et al. 2012; Van de Wouw et al. 2022a).

New major resistance genes have been regularly introduced into Australian varieties, however, the gene-for-gene interaction and high evolutionary potential of *L. maculans* has meant that many of these genes have been overcome (Sprague et al. 2006; Van de Wouw et al. 2014; 2022b). The temporal and spatial scale of the breakdowns reflects the popularity and uptake of varieties harbouring these genes.

Regional information about resistance gene efficacy is based on blackleg severity monitoring in representative varieties from each blackleg resistance group sown at sites across canola-producing regions. Data is provided to growers online via the GRDC National Variety Trials™ website (https://nvt.grdc.com.au/). Introducing novel major resistance genes presents an opportunity to limit blackleg severity by rotating genes. However, as most modern varieties contain ≥2 resistance genes with ineffective major genes present, the efficacy of this strategy is limited.

Quantitative resistance is considered a more durable solution for blackleg control as there are numerous genes involved. Quantitative resistance controls crown canker and UCI, with recent research indicating the same genes likely act to limit both infection types (Marcroft and Sprague personal communication, 22 June 2023). Quantitative resistance expression is masked when effective major genes are present. The interaction between host and pathogen genotypes is complex, with a strong environmental influence.

Quantitative resistance in the Australian context is important. Consequently, research efforts are focused on developing novel approaches to improve phenotyping methods to help identify quantitative trait loci (QTL) markers for breeding. Extremely sensitive molecular markers unique to *L. maculans* can detect the presence of resistance long before the onset of visual symptoms (Schnippenkoetter et al. 2021) and machine learning is being applied to images to replace visual disease scores.

Fungicides

Fungicides are an integral part of blackleg control strategies in modern farming systems in many regions of Australia. Expanding canola production, tighter rotations and increasing retention of diseased canola residue means that it is not possible to isolate new crops to avoid ascospore inoculum. Fungicides are registered for use:

- at sowing on seed and fertiliser
- for foliar application at the seedling stage to control crown canker
- during flowering for UCI.

Fungicide use in the last 20 years has increased substantially. More than 90% of surveyed growers applied fungicides in 2020 compared to 52% in 2000. The number of growers using multiple fungicides in the same season has also increased (Van de Wouw et al. 2021).

Before 2016, all fungicides for blackleg control were demethylation inhibitors (DMIs); the first global detection of resistance came from Australian populations. Resistance to DMIs was detected in 18% of blackleg populations across Australia but the resistance level and relevance for field efficacy is unknown (Van de Wouw et al. 2021).

Recently, the succinate dehydrogenase inhibitor (SDHI) and quinone outside inhibitor (QoI) classes of fungicides became available either alone or in mixtures with DMIs. Although resistance to SDHIs and QoIs is yet to be detected in blackleg populations, they are a medium–high risk of developing resistance.

Blackleg management in the farming system

The significant canola production system changes described above have had a large impact on blackleg epidemiology and management (Figure 24) (Van de Wouw et al. 2021). Increased stubble retention has increased total inoculum loads resulting in higher disease pressure and consequently greater reliance on host genetics and chemical options. Ascospore development is delayed in standing stubble, extending the period of ascospore release (McCredden et al. 2018). Initially, this was considered the factor driving UCI. Recent research has concluded that earlier flowering which aligns to conducive infection conditions and longer times for blackleg to colonise plants and affect yield, is the main factor (Sprague et al. 2017a; 2017b). In contrast, sowing canola earlier to maximise yield potential has reduced seedling exposure to infections which cause damaging levels of crown canker, thereby reducing the need for fungicides at sowing.

Dual-purpose canola has been widely adopted in some regions. Crops are grazed in autumn and winter which coincides with ascospore release and conducive infection conditions. The damage by grazing causes increased crown canker severity compared with an ungrazed crop. Increased disease is restricted by using varieties with high blackleg resistance levels (Sprague et al. 2010; 2013).

There is a strong focus on sharing new knowledge with growers and advisers on variety selection and management practices. This is mostly via information days, the annually updated Blackleg Management Guide (https://grdc.com.au/resources-and-publications/all-publications/factsheets/2023/blackleg-management-guide) and social media. Current research outcomes and industry issues are presented and discussed with breeders, researchers and the broader canola industry via an annual canola pathology workshop (www.australianoilseeds.com/conferences_workshops/canola_pathology_workshops).

Digital tools incorporating variety resistance levels, crop management practices and economics have also been developed. These tools are used to identify blackleg risk and support pre-season and in-season decisions to control both blackleg crown canker (BlacklegCM) and UCI (UCI BlacklegCM) (Diggle et al. 2018). As these tools continue to evolve, they will be supported by more sophisticated modelling approaches that integrate disease lifecycle and farming system crop models (Bondad et al. 2023).

Sclerotinia stem rot

The second most important canola disease in Australia is sclerotinia stem rot (SSR) caused by *Sclerotinia sclerotiorum*. This disease was once considered to occur sporadically, but changes to farming systems and crop rotations in the last decade have increased the frequency of disease outbreaks. In high rainfall cropping regions, managing this disease is now considered to be as important as blackleg.

Most of the *S. sclerotiorum* lifecycle is spent in soil as sclerotia; hard, black survival structures that allow *Sclerotinia* species to survive for 5–10 years under adverse conditions. Sclerotia soften in early–mid winter and produce mycelium, apothecia or both. Mucilage-covered ascospores released from apothecia adhere to plants and with adequate moisture, spores germinate and colonise senescent tissue (petals and leaves), using them as a food source. Petals generally senesce and fall into the canopy after 5–7 days, lodging against stems, branches, branch junctions and lower leaves. This spreads the infection into the crop canopy. Infection from ascospores can form lesions that cause yield loss from premature death of plants and branches.

Yield loss can also result from direct myceliogenic infection of plants via sclerotes in soil. This infection pathway was once considered rare in Australia, but with more frequent SSR outbreaks and subsequent increases in sclerotia populations in soils, direct plant infection via soilborne mycelium commonly occurs.

There is no genetic resistance to SSR in commercial Australian canola varieties. Growers largely rely on fungicides to protect crops. Using registered foliar fungicides to manage SSR provides protection for periods between 2 and 6 weeks. Their use has increased significantly in the last decade.

Industry investment in canola pathology research has greatly increased understanding of key SSR development drivers. In most canola growing regions, applying foliar fungicide during early flowering (20–30% bloom stage with 15–20 open flowers off the main stem) protects early petals and allows fungicide penetration into the lower crop canopy.

The Department of Primary Industries and Regional Development (DPIRD) in Western Australia recently developed the SclerotiniaCM app (Diggle et al. 2018). The app uses data from disease experiments and surveillance activities across Australia to assess disease risk and yield loss from SSR. This gives growers and agronomists an economic framework for decision-making.

Other diseases

Other diseases occur periodically in Australian canola crops. Generally, these rarely have an economic impact, although some have increased incidence and severity at a localised level or cause sporadic economic losses (Van de Wouw et al. 2016).

Damping-off (a complex of *Pythium* spp., *Fusarium* spp. and *Rhizoctonia* spp.)

Disease impact varies with seasonal conditions and tillage systems. Direct drilling and use of disc seeders favours disease development. Sub-optimal soil moisture conditions, either soil saturation or marginal moisture, that delay seedling emergence also favour disease development. The disease causes poor emergence in establishing canola crops, or premature seedling death within 4–6 weeks of sowing. New generation seed-applied fungicides containing metalaxyl are effective at reducing disease severity.

White leaf spot (*Mycosphaerella capsellae*)

This stubble-borne disease has increased significantly over the last decade due to increased canola production and stubble retention. The disease is commonly observed in canola crops at the seedling and vegetative stage, often in combination with blackleg. Under cool, wet conditions, distinct leaf lesions quickly form and can coalese and colonise older senescent leaves. Rain splash can spread the pathogen onto newly emerged leaves. The fungus can move up plant canopies during stem elongation and continue to form lesions on leaves. It is not clear whether these infections result in yield loss as disease development into spring is rare. The broad-spectrum foliar fungicides registered to manage blackleg and SSR are effective against white leaf spot.

Alternaria spot (*Alternaria* spp.)

Disease outbreaks and severity are driven by late winter and spring rainfall patterns, which promote pod infection resulting in small, shrivelled grain or discoloured grain that can be downgraded at delivery. Seed infected by *Alternaria* spp. can also have poor vigour and result in development of seedling blight. Options to manage alternaria spot are limited, with late fungicide applications prohibited due to maximum residue limits (MRLs) for possible fungicide residues in harvested grain.

Downy mildew (*Peronospora parasitica*)

This disease is commonly observed in vegetative canola crops. The lowermost leaves, in contact with the soil surface develop the typical grey, fluffy mycelia on the underside, while the top side of leaves develop yellow necrotic patches. The disease is most damaging when it infects cotyledons and first true leaves; this can quickly defoliate seedlings and cause plant death. Long periods of cool, wet weather favour disease development and spread. Warmer, drier conditions quickly slow down disease progression and allow plant recovery. Seed-applied fungicides containing metalaxyl can help reduce disease severity.

Powdery mildew (*Erysiphe* spp.)

Powdery mildew tends to be more severe in the northern production regions. Mild daytime temperatures and cool, dewy nights favour disease development. Symptoms include the formation of powdery mycelia over all aerial parts of the plant. In northern NSW and southern Queensland, powdery mildew occurs in early–mid spring and can cause yield loss. The thick mycelial layer impacts windrowing and spray operations. In southern production regions, powdery mildew tends to develop on canola in late spring, shortly before physiological maturity, but does not affect yields. Foliar fungicide effectiveness is limited due to the rapid generation times of the pathogen, poor canopy penetration by fungicides and lack of product registration.

White rust or staghead (*Albugo candida*)

This disease is observed during flowering when canola inflorescences become distorted and covered in white pustules (often called stagheads). Disease incidence and severity is generally very low and not thought to cause yield loss in Australia. The common weed, shepherds' purse (*Capsella bursa-pastoris*), readily hosts the pathogen between seasons.

Club root (*Plasmodiophora brassicae*)

Clubroot outbreaks in Canada in the last decade have increased awareness of this disease in Australia. To date, disease outbreaks are rare and often restricted to areas where canola is grown under irrigation, or in paddocks with a production history that includes other *Brassica* crops, including vegetables. NSW DPI surveillance operations throughout canola producing regions of NSW over the last 4 years have not found the pathogen in canola crops, despite extensive soil and plant testing.

Black rot (*Xanthomonas campestris*)

This bacterial disease has appeared recently in dual-purpose canola crops grown in southern NSW. Heavy grazing and damage to the crowns combined with mild, wet conditions favours disease development across a wide production area. Symptoms include the rapid death of established canola plants in dual-purpose crops, even with adequate moisture, with a distinct rotting smell and breakdown of the epidermis of the tap root and crown.

Viruses

Several virus diseases affect canola in Australia. These include *Turnip mosaic virus* (TuMV) and *Turnip yellows virus* (TuYV) – formerly known as *Beet western yellows virus* (BWYV). Viral diseases periodically affect canola growers in Australia depending on seasonal conditions. In 2014 mild winter temperatures in combination with a build-up in green peach aphid (*Myzus persicae*) populations resulted in serious outbreaks of TuYV in establishing canola crops in South Australia and southern NSW (Coutts et al. 2015). This resulted in large areas of crop becoming stunted and displaying typical virus like symptoms of cupping of new growth and mosaic colouring on leaves. Despite the early severity of infection, crops developed through the season to maturity and were harvested, although yield loss was significant. Since that time, periodic localised outbreaks of virus disease in canola crops have been identified. Conditions that maintain high aphid vector populations leading up to and during sowing favour early infections, as aphids migrate and feed on establishing canola crops. This includes introducing dual-purpose crops which tend to be sown earlier (sometimes in spring and are in the ground for approximately 15 months), which can act as a green bridge and maintain aphid populations. Growers are advised to treat seed for sowing with either imidacloprid or imidacloprid + clothianidin to protect against infection. The foliar insecticides sulfoxaflor and flonicamid are also registered for green peach aphid.

Future directions

Effective disease management practices are crucial to maintain or increase canola production in Australia, particularly for blackleg and sclerotinia stem rot.

Breeding outcomes will be improved by:

- improved understanding of the basis of blackleg disease resistance, particularly quantitative resistance
- identifying novel major genes and deployment strategies that optimise their effectiveness in limiting disease severity and slowing the evolution of *L. maculans* populations
- adopting digitised phenotyping platforms for improved blackleg resistance
- increased knowledge of genetic resistance and management for UCI.

Blackleg management could be improved by:

- adapting fungicide use to changes in canola production systems and identifying new active ingredients as well as alternative control methods such as biocontrols or RNAi to target different parts of the *L. maculans* lifecycle
- developing integrated crop-disease models which improve disease predictions and the impacts of changing climate and production systems
- continuing to monitor *L. maculans* populations to identify resistance to fungicides and host genetics.

Sclerotinia stem rot management can be improved by:

- understanding disease development drivers across the cropping system and putting management strategies in place that effect all host crops in the rotation

- identifying host resistance to SSR and incorporating it into commercial varieties.

This would give producers a level of confidence in managing the disease in regions where it frequently occurs and reduce the need for fungicide.

It is imperative that surveillance activities continue on an annual basis in commercial canola crops to identify new or emerging disease threats to the industry.

More information

References and resources relating to this chapter are listed in Appendix 1 (p. 104).

Pests

Dr. Michael Nash[1], Dr. Jo Holloway[2] and Dr. Melina Miles[3]
[1] AgNova Technologies Pty Ltd, Hamilton QLD 4007
[2] NSW Department of Primary Industries, Wagga Wagga NSW 2650
[3] Department of Agriculture and Fisheries Queensland, Toowoomba QLD 4350

Summary

- Susceptibility of canola to insect pests.
- Focus of current management strategies.
- Research developments in canola pest management.

Introduction

Canola crops grown in southern Australia can be threatened by over 40 invertebrate species (Bailey 2007) that cause economic loss (Murray et al. 2013) (Table 13: p. 81). Pests often occur as a complex of species, with one species typically dominant each season, but prevailing environmental conditions determine which of the complex will be dominant (Nash and Hoffmann 2012).

Traditionally, seedling canola is most susceptible to damage (Gu et al. 2008) and this has been attributed to decreased glucosinolate concentrations in the plant that deter insect feeding (Giamoustaris and Mithen 1995). A comparison of pest outbreak reports from the early 1980s to 2006–07 from south-eastern Australia indicated an increase in the importance of some pest groups such as clover springtail, Balaustium mite, blue oat mites, clover mites, slugs and snails (Hoffmann et al. 2008). The transmission of viruses has made green peach aphid a species of concern (Valenzuela and Hoffmann 2015). Snails have emerged as a major contaminant pest, restricting access to some markets if not cleaned from canola grain before delivery.

Many invertebrates have the potential to damage canola yet are not pests. This could be because of unfavourable conditions limiting populations (Nash et al. 2014), natural enemies (predators, parasitoids and/or pathogens) maintaining levels below a damage threshold, or crop tolerance to the damage they might inflict. Species can become more damaging when farm ecosystem management changes. For example, the recent resurgence of clover springtail. This pest is more tolerant of neonicotinoids and synthetic pyrethroids than the cohabiting red legged earth mite (RLEM) populations and continues to cause crop loss even after treatments are applied for earth mites (Roberts et al. 2009). Consequently, spraying for RLEM removes many natural enemies while allowing clover springtail to thrive.

It is difficult to predict what pest might dominate in a given season (Weeks and Hoffmann 2000) because little is known about the basic biology of many of the native Australian species that can damage crops (Macfadyen et al. 2019). This presents Australian canola growers with a significant challenge in managing unknown, and often intangible, pest threats each season (Nash and Hoffmann 2012).

The Australian canola industry relies on prophylactic insecticide applications, including synthetic pyrethroids (Group 3A), organophosphates (Group 1B), and more recently neonicotinoids (Group 4A). These insecticides are either applied to seed, applied post-sowing and pre-emergence, and/or post-emergence, and are the key method of controlling canola establishment pests (Maino et al. 2023). The unintended cost of targeting earth mites and clover springtails with prophylactic treatments is the mortality of non-target populations that prey on pests (Hill et al. 2017). Adopting integrated pest management (IPM) strategies is an industry-wide goal. In recent years there has been a slight shift away from blanket applications of insecticides at establishment to seed treatments. This creates the opportunity for natural enemy communities to be retained in crops (Horne and Page 2008). However, widely applying one class of insecticide (neonicotinoids) to all commercially available seed before sowing creates significant challenges for IPM because of off-target impacts: for example, increased slug threats due to reduced beetle predators (Douglas et al. 2014). Further, protection using seed treatments is relatively short-lived due to dilution in growing plants, hence migratory pests at flowering and grain-fill are not controlled. Therefore, monitoring is still required for responsive chemical controls based on thresholds. The steady decline in the rate of insecticide expressed over time when applied to seed also exposes pest populations (both target and non-target species) to sublethal doses of those actives, increasing the risk of insecticide resistance developing.

Stubble retention and reduced tillage (conservation agriculture) are often perceived to lead to higher pest numbers, particularly at establishment (Micic et al. 2008). However, no-till farming systems can foster predatory species such as carabid beetles (Coleoptera: Carabidae) that predate on slugs (Nash et al. 2008), and earwigs that predate on caterpillars (Lepidoptera) (Horne and Edward 1995). Lepidopteran and aphid pests that migrate into canola and cause loss can be supressed or controlled where natural enemies are active.

Once conservation agriculture is uncoupled from intensification, growers would benefit from enhanced ecosystem services (Nash et al. 2019). Invertebrate communities need to be managed holistically in modern farming systems, however, in many regions management is still focused on individual pest threats, such as RLEM.

Management – species where chemical control is limited

The Australian canola industry is concerned about emerging resistance and tolerance to insecticides by key pest populations as this can threaten production (Thia et al. 2023).

Resistance research has focused on:

- sharing information on using pesticides that are less disruptive to natural enemies
- automated monitoring tools that feed into decision support tools.

Emerging research focusing on bottom-up IPM (Han et al. 2022) provides an example of novel pest control strategies that could provide the canola industry with cost-effective and environmentally stable tools that limit production threats. In the future, it is likely that reliance on chemical options will be reduced by several factors. Examples of each factor are given below.

Resistance

Three pest species (discussed below) continue to develop resistance to commonly used chemical controls. The key drivers of this are:

- all commercial canola seed being treated with similar insecticides
- industry reliance on relatively few modes of action, despite the registration of new modes of action (Umina et al. 2019).

Adopting new modes of action could be further hindered by the ability of green peach aphid and diamondback moth to rapidly evolve resistance. Pests' resistance to insecticides is seen as a motivator for industry to adopt non-chemical strategies to manage threats.

Red legged earth mite (RLEM)

Historically RLEM was considered a major threat to canola seedlings. These small black mites with red legs survive over summer as a diapause egg. They are a minor pest where seed treatments are applied and disruption caused by insecticide applications is limited. However, resistance to organophosphate and synthetic pyrethroids has been detected in populations across southern Australia (Umina 2007; Maino et al. 2018), especially where pastures are still part of cropping rotations.

Green peach aphid (GPA)

This aphid is the most important aphid vector of yellows viruses in Australia, which can reduce yields by up to 34% (Valenzuela and Hoffmann 2015). This was observed in autumn 2014 when widespread GPA infestations carrying *Turnip yellows virus* (TuYV) were associated with severe crop loss in South Australia. The same level of loss has not been observed in subsequent seasons despite increasingly frequent and widespread reports of aphids. This suggests that virus-related threats are sporadic, despite virus transmission by GPA. Industry relies heavily on seed treatments to manage this threat, yet virus severity, hence yield loss, is not predictable. There has been a trend towards earlier planting, which means that crops are emerging when aphids are still active. This increases the risk and the reliance on neonicotinoid seed treatments to limit virus transmission. However, GPA has developed resistance to over 80 insecticides worldwide. In Australia, it has evolved high-level field resistance to synthetic pyrethroids and carbamates (Group 1 A), and low-level resistance to organophosphates (Edwards et al. 2008), neonicotinoids (de Little et al. 2017), spirotetramat (Group 23) (Umina et al. 2022) and sulfoxaflor (Group 4C). Laboratory studies also indicate GPA can develop field resistance to the newly registered insecticides flonicamid and afidopyropen (Arthur et al. 2022).

Diamondback moth (DBM)

This ubiquitous species is highly adapted to feeding on *Brassicacae* and is a sporadic threat to canola (Hopkins et al. 2009). Genetic studies indicate that, despite localised populations, this species interbreeds across all of Australia and New Zealand (Perry et al. 2020). This has major implications for population and resistance management as internationally DBM has evolved field resistance to nearly all classes of synthetic and biological insecticides (Mubashir and Seram 2022). In Australian canola, DBM resistance has been detected for a number of commonly used insecticides: diamides (Ward et al. 2021) (Group 28), pyrethroids, organophosphates, indoxacarb (Group 22A), spinosad (Group 5) (Eziah et al. 2008), *Bacillus thuringiensis* (Group 11) and emamectin (Group 6). Control failures occur most often where growers persist with low-cost options, especially Group 1 or 3A insecticides.

Natural tolerance to insecticides

Balaustium mites

These are an emerging pest across southern Australia. They are the largest of the pest mites commonly found in broadacre crops. This species has a high natural tolerance to many insecticides and will generally survive applications targeting other mite pests (Arthur et al. 2008). Only high field rates of bifenthrin [20 g/ha] (Group 3A) control this pest in canola, a practice that is highly disruptive to natural enemies (Nash et al. 2008; Overton et al. 2023).

Limited options – market access threats

Relying on a limited number of older chemistries that might be withdrawn from market or are banned in overseas canola markets will limit future market access for Australian growers.

Clover springtail (syn. Lucerne flea)

The common named often used, Lucerne flea, misrepresents what invertebrate group this arthropod belongs to. It is often found in the winter rainfall areas of southern Australia, or in irrigation areas where moisture is plentiful. They are patchily distributed within paddocks and across a region and are generally more problematic on loam/clay soils. Due to their natural tolerance to synthetic pyrethroids (Roberts et al. 2009; Arthur et al. 2020), omethoate (Group 1C) is the chemical control of choice after sowing. However, the use of this active has been restricted recently with changes to its registration (APVMA 2016). Although it is still registered for use in canola, this might be restricted in the future. Western Australian grain company Cooperative Bulk Handling (CBH) Group has adopted the International Sustainability and Carbon Certification (ISCC) scheme whereby growers must be certified each year to ensure the crop is sustainably produced and greenhouse gas emission reduction standards are met. In 2020, CBH wrote to growers telling them to stop using omethoate if they had signed up to a European accreditation scheme (i.e. ISCC) which gave canola producers a premium (A$40–$60/t) into the EU biodiesel market. Organophosphate use will soon have to cease in Australia to meet overseas customers quality assurance programs. This will make it difficult to control this pest using existing chemical options.

European earwig

European earwig is known to attack seedlings when conditions favour population build-up and alternative food sources such as aphids are not available (Binns et al. 2022). There are no foliar insecticides registered for European earwigs in broadacre crops, although registered insecticide seed dressings will give limited protection of seedlings (Umina 2019). Recently, fipronil [1.5 g/kg] (Group 2B) has been added to metaldehyde [50 g/kg] into a bait registered for the control of earwigs. However, fipronil is currently under review by the Australian Pesticides and Veterinary Medicines Authority (APVMA) (https://apvma.gov.au/node/105641) (APVMA 2022). Being polyphagous, earwigs can also provide pest control services (Horne and Edward 1995), and recent research revealed a number of native species co-existing with European earwigs in Australian farming systems where canola is grown.

Poor control

Slugs and snails

Snails in particular pose economic threats beyond the more traditional definition of a pest causing crop loss by feeding directly on plants. Snails are a harvest contaminant that limit access to markets, particularly in South Australia and western Victoria. Currently registered molluscicides have limited efficacy in limiting populations below receival standards: 1 per hL. Natural enemies in Australia are limited and not well researched.

Changes to farming systems in Australia have reduced cultural control use, such as tillage and burning (Nash et al. 2019). In the case of slugs, molluscicides are used as a crop protectant, with cultural controls integrated to achieve successful establishment (Figure 25). One key factor in successful crop establishment has been the shift to earlier sowing, when soil temperatures are still warm and the crop emerges and grows more quickly, if moisture is available.

Figure 25 *Slug damage in canola.* Photo: Michael Nash.

Cryptic species

Blue oat mites

Three species of blue oat mite have been identified in Australian cropping systems. *Penthaleus falcatus* is mainly found on canola, whereas the other 2 species have other crop preferences (Weeks and Hoffmann 1999). *P. falcatus* has a higher tolerance than RLEM and other blue oat mite species to a range of pesticides, and might be responsible for chemical control failure (Umina and Hoffmann 1999).

Clover mites

The complex of *Bryobia* spp. is an establishment threat to canola, and their management is complicated as it is difficult to identify which of the cryptic species are present (Umina et al. 2022). Clover mites are mostly managed by using foliar sprays containing organophosphates, omethoate, and bifenthrin, or insecticide seed treatments based on neonicotinoids. However, there have been increasing concerns around chemical control difficulties in the field (Arthur et al. 2008). To date, only the chemical sensitivity of *Bryobia* sp. one has been investigated in Australia (Arthur et al. 2008) and it has a similar response to that of *Balaustium medicagoense* (see above). Further compounding the increased clover mite threat in some regions is the earlier sowing of canola when this species is more active than RLEM (Arthur et al. 2010; 2011).

Rubble beetle – Mandalotus spp.

These weevils are an establishment pest, consisting of a species complex. Their management is complicated by their cryptic nature and endemic populations that might or might not overlap. There is limited research on this pest, with almost nothing known about the ecology of the various species. Control currently relies on fipronil. Where species complexes exist, separate strategies might be needed for the different species.

Integrated pest management (IPM)

Integrated pest management (IPM) adoption is limited across southern Australia because:

- current chemical controls generally work and are cost effective
- monitoring (Figure 26) across southern regions is resource limited and there are not enough trained scouts and growers to monitor and manage invertebrate pests well

- action thresholds are largely best-guesses, and do not incorporate the contribution of natural enemies
- selective options for managing key pests are currently limited, and resistance development in some species is exacerbating this issue
- prophylactic insecticide use is perceived to be an effective way of minimising risk, however the widespread use of neonicotinoids in canola and wheat since the incursion of Russian wheat aphid in 2016 (Yazdani et al. 2018) is fuelling the development of resistance to neonicotinoids (Nash et al. 2019)
- the logistics of farming large areas results in mixes of insecticides with herbicides and/or fungicides being applied to reduce the number of applications per season
- an increasingly variable climate is resulting in changes to traditional sowing windows and practices that change the risk of pest threats
- non-chemical control options (i.e. cultural controls) are poorly established as viable management tools
- growers lack confidence in the whole IPM system.

Figure 26 *Basic setup for monitoring in south west Victoria.* Photo: Michael Nash.

Table 13 *Common pests of canola.*

Pest	Common name	Species [1]	Canola stage damaged	Distribution in Australia
Gastropoda:				
Agriolimacidae	Slugs	*Deroceras reticulatum* Müller	Establishment	Southern >450 mm
Milacidae		*Milax gagates* Draparnaud		
Helicidae	Snails	*Theba pisana* (Müller)	Establishment and harvest	Southern
Hygromiidae		*Cernuella virgata* (Da Costa)		Southern
		Cochlicella acuta (Müller)		SA & WA
		C. barbara (L.)		Southern
Diplopoda:				
Julidae	Portuguese millipedes	*Ommatoiulus moreleti* (Lucas)	Establishment	Southern
Isopoda:				
Armadillidae	Slaters	*Australiodillo bifrons* (Budde-Lund)	Establishment	NSW, Qld
		Armadillidium vulgare Latreille		Widespread
Porcellionidae		*Porcellio scaber* Latreille		
Acarina (mites):				
Erythraeidae	Balaustium mite	*Balaustium medicagoense* Meyer and Ryke	Establishment	Widespread
Tetranychidae	Clover mite	*Bryobia* spp.		
Penthaleidae	Red legged earth mite	*Halotydeus destructor* Tucker*		Widespread (not north NSW & Qld)
	Blue oat mite	*Penthaleus* spp.		Widespread
Collembola:				

[1] resistance to insecticides indicated by *
Adapted from Murray 2013, Nash 2012, and Bailey 2007.

Pest	Common name	Species [1]	Canola stage damaged	Distribution in Australia
Sminthuridae	Clover springtail (Lucerne flea)	*Sminthurus viridis* (L.)	Establishment	Widespread (not N NSW & Qld)
Dermaptera:				
Forficulidae	European earwig	*Forficula auricularia* L.	Establishment	Widespread (not north NSW & Qld)
Labiduridae	Black field earwig	*Nala lividipes* (Dufour)		Widespread
Hemiptera:				
Lygaeidae	Rutherglen bug	*Nysius vinitor* Begroth	Establishment, podding and harvest	Widespread
	Grey cluster bug	*Nysius clevelandensis* Evans		
Aphididae (aphids)	Turnip	*Lipaphis erysimi* (Kaltenbach)	Flowering to podding	Widespread
	Green peach	*Myzus persicae* (Sulzer)*		
	Cabbage	*Brevicoryne brassicae* (L.)		
Coleoptera:				
Tenebrionidae (false wireworms)	Bronzed field	*Adelium brevicorne* Blessig	Establishment	Southern
	Eastern	*Pterohelaeus darlingensis* Carter		Eastern
	Striate	*Pterohelaeus alternatus* Carter		Qld & NSW
	Grey	*Isopteron punctatissimus* (Pascoe)		NSW, VIC
	Southern	*Gonocephalum* spp.		Widespread
Curculionidae (weevils)	Vegetable	*Listroderes difficilis* (Germar)	Establishment	Widespread
	Mandalotus	*Mandalotus* spp.		SA, VIC, NSW
Lepidoptera:				
Crambidae	Weed web moth	*Achyra affinitalis* (Lederer)		Southern & Western
Noctuidae	Cutworms	*Agrotis* spp.	Establishment and vegetative	Eastern
		Diarsia intermixta (Guenée)		
		Neumichtis spp.		
	Loopers	*Ciampa arietaria* (Guenée)	Vegetative	Widespread
		Chrysodeixis argentifera (Guenée)		
Plutellidae	Native budworm, cotton bollworm	*Helicoverpa punctigera* (Wallengren)	Flowering to podding	Widespread
		Helicoverpa armigera Hubner		
	Diamond back moth	*Plutella xylostella* L.	Vegetative to podding	Widespread
Crambidae	Cabbage centre grub	*Hellula hydralis* Guenée	Establishment, vegetative (autumn)	Widespread

[1] resistance to insecticides indicated by *
Adapted from Murray 2013, Nash 2012, and Bailey 2007.

Significant research developments

Increased knowledge around pest ecology is slowly accumulating and has been referenced where applicable (see above individual pest examples). Some key developments in the past 20 years are outlined below.

Real time monitoring – smart traps

Advances in insect trapping technologies provide early warning of pest migration into crops. Knowing when low densities of colonising aphids arrive is important to prevent the spread of crop diseases vectored by aphids, and for targeting surveillance activities to fields that have been colonised. Technologies aiding crop monitoring and decision support for pest management have been termed 'smart' trapping (Nash et al. 2019). Examples include:

- The Limacapt system: counts and monitors slug activity throughout the night. This tool enables highly detailed analysis of the risks caused by this pest and hence provides data to inform decisions on action.
- DTN Smart Trap®: uses established pheromone lures for specific pest moth species and traditional sticky material housed within a delta-type trap.
- Trapview®: uses a similar infrastructure to the DTN Smart Trap® with imaging and automated pest identification using algorithms.
- Automated suction traps linked to eDNA determination are being developed (iMap pests 2023, https://imappests.com.au/).

Together with remote pest detection and automated counting, predictive models are being developed which quantify the risk of caterpillar damage using temporal moth counts and climate data. These digitally based technologies are considered a breakthrough in the monitoring of highly variable pest populations when resources for scouting are limited. The latter 2 moth technologies detailed above are no longer commercially available in Australia, possibly due to the limited connectivity in rural areas.

Biorational products

Pesticides that are relatively non-toxic with few ecological side-effects are called biorational, although there is no official definition of this term. The major categories of biorational products include botanicals (e.g. Sero-X®), microbials (e.g. DiPel® DF), minerals (e.g. IRONMAX Pro®), and synthetic materials (e.g. Steward® EC).

A knowledge of pest ecology underpins effective biorational approaches where application timing is critical for success. For example, the recent registration of an organic product, IRONMAX Pro® (9 g/kg of iron present as iron phosphate) to control slugs and snails in canola requires a greater understanding of the population's active density to ensure the correct rate is applied or re-applied if needed. Feeding on the product by non-crop slug pests also present, for example *Ambigolimax* spp. (Nash et al. 2007), adds to the application cost. By contrast, the application rate of traditional metaldehyde products was not as critical as over feeding did not occur.

Further research is needed to understand what species are present and their ecology across the different canola growing regions. Research by Stuart et al. (2019) and Binns et al. (2021) on earwigs is an example of this.

Sero-X®

Cyclic peptides (Sero-X®) are an extract of *Clitoria ternatea* (Butterfly pea). It is claimed that they:

- play various defensive roles, including pest suppression
- have 3 distinct modes of action: anti-feedant, direct mortality and as an ovipositing/oviposition deterrent.

Sero-X® is registered for use in Australia to control *Helicoverpa* spp. in cotton (APVMA Approval No: 81070). Large scale (10 ha) paired field experiments were conducted in canola in southern Australia during 2021. Application times were informed by monitoring with pheromone and smart traps and phenological development models. In canola, some pod damage will occur before it is economic to apply a treatment, so action thresholds were based on yield loss caused by native budworm. The yield was significantly greater (P<0.001) in the Sero-X® area (3.4 t/ha) than in the untreated area where native budworm was causing pod damage (2.8 t/ha). Protection from DBM was poor, especially when applied earlier in the season; Sero-X® 2.175 t/ha vs grower practice 2.225 t/ha (Nash 2022). These experiments, run in collaboration with growers, also provided insights into adoption. Several factors often limit the adoption of biorational products including that they:

- are expensive
- must be applied before the pest becomes a problem

- are harder to apply as you must know about the pest's ecology.

Whilst Australian canola growers currently consider biorational products as less attractive options than conventional insecticides, biorational products could have an important role in mitigating the rate of insecticide resistance development and reducing off-target impacts on natural enemies.

Endosymbionts

Endosymbionts are unique bacteria that live inside the cells of many organisms: the most common is *Wolbachia* that is believed to be present in about half of all insect species. An alternative to new technologies such as RNA-guided nucleases (e.g. CRISPR/Cas9) to control pests, is to engineer the symbionts that already live within their bodies. When transferred to mosquitoes, engineered *Wolbachia* effectively blocked RNA virus transmission, such as dengue fever (Utarini et al. 2021). Current research in Australia is looking to block plant *Turnip yellows virus* (TuYV) transmission that occurs through GPA. In addition, other avenues to manipulate these endosymbionts are being investigated to suppress the impact of insecticide resistance, and host plant preferences.

Endosymbionts can impact the susceptibility of attack by predators and parasitoids. For example, *Rickettsiella* in natural populations of GPA could reduce crop damage by modifying age structure and reducing intrinsic growth rates (Gu et al. 2023). However, endosymbionts have also been shown to confer various fitness advantages on their hosts such as nutritional upgrading, thermal tolerance, or enhanced pathogen/parasitoid resistance (Ratzka et al. 2012).

Future directions

In 1999, there was optimism about the potential for host plant resistance through the selection of canola lines with tolerance to key pests, specifically earth mites, and the prospects of cultural controls to manipulate pest populations in the farming system. Neither of these approaches have eventuated in the face of low-cost and effective insecticides and the industry is facing a potential insecticide resistance crisis because of the heavy reliance on a small number of insecticide modes of action.

Research on pest ecology has made some advances (e.g. earth mites, DBM, earwigs) but pest outbreaks are not routinely forecast in a way that would give growers the confidence to opt out of prophylactic seed treatments or post-sowing treatments.

In the future, external factors may exert greater pressure on the Australian canola industry to move away from an insecticide-focused approach, and perhaps result in a renewed enthusiasm for IPM.

In this context, the following approaches might warrant investigation and adoption.

Bottom-up IPM

Top-down forces have been conceptualised for practices in agriculture (e.g. biocontrol services), yet bottom-up forces have received little attention in the framework of IPM. Bottom-up effects are major ecological forces in crop-invertebrate pest-natural enemy multitrophic interactions and need to be considered to optimise IPM. Irrigation, fertiliser use, crop resistance, habitat manipulation, organic management practices and landscape characteristics have all been shown to trigger marked bottom-up effects and thus effect pest management (Han et al. 2022). Current research in Australia is investigating the role plant nutrition plays in crop susceptibility to herbivores, in particular the role excess plant nitrates play in increasing population intrinsic growth rates. For example, slug populations fed a diet high in nitrogen increased at a greater rate (Albrectsen et al. 2004).

Polycultures

Can diversification of Australian enterprises lead to more stable production systems with reduced threats? Couëdel et al. (2019) identified a need to refocus cover crop biocontrol research from a largely "pesticide" paradigm targeting maximum production of bioactive compounds by sole crucifer cover crops, to a multi-service paradigm in which selected crucifer-legume mixtures may offer promise in the quest for the sustainable intensification of agriculture.

Canola and field peas have been grown together in Australia since the 1980s. Despite this history, limited information is available other than a reduced incidence of pea aphid (*Acyrthosiphon pisum*) infestation compared with mono-cropped peas (Dowling et al. 2021). No difference was found in DBM numbers between a polyculture of beans and canola compared with a monoculture of canola (Nash 2022). The hypothesis is polycultures planted prior to canola establishment would provide an alternative food source for resident pests such as slugs (Frank and Friedli 1999) and earwigs. Future research is required in this area to determine reasons for observations such as there being less canola damage due to earwigs where aphids are present (Binns et al. 2022).

Conclusions

Despite much optimism about the potential role of host plant resistance and farming system manipulation to reduce invertebrate pest risk in canola, the industry remains highly reliant on the use of low-cost, broad-spectrum insecticides. The move towards earlier sowing might also increase canola's exposure to threats from invertebrates. This could be directly due to patchy establishment resulting from dry conditions or indirectly from viruses vectored by more active aphid populations (Congdon et al. 2020).

Management based solely on prophylactic and reactive insecticide use has resulted in insecticide resistance emerging in a few key pests. Changes in the expectations of overseas markets have also brought the sustainability of invertebrate pest management practices in Australian canola into sharp focus. Despite this gloomy outlook, there are opportunities for the industry to explore a holistic, systems-based approach to incorporating biological control and suppressing pest populations across rotations, not just in canola. There is a critical social aspect to making these changes, which is achievable when growers are willing to change.

More information

References relating to this chapter are listed in Appendix 1 (p. 105).

Quality

Jamie Ayton[1], Kerrie Graham[1] and Dr. Rod Mailer[2]
[1] NSW Department of Primary Industries, Wagga Wagga NSW 2650
[2] Australian Oils Research, Lambton NSW 2305

Summary

- Changes in quality since canola was introduced to Australia.
- Quality attributes and antinutritional aspects of Australian canola.
- Influences on Australian canola quality.

Introduction

Canola breeding programs in Australia over the last 30 years have significantly enhanced canola as an oilseed crop, particularly the improvements in oil and meal quality characteristics. Current breeding programs continue to concentrate on yield, oil content, disease and insect resistance and drought tolerance.

Australian canola quality

Australian canola is recognised and highly sought after around the world for its consistent high quality. Australian exporters promote the quality benefits of Australian canola seed, oil and meal which enables them to differentiate their product in a commoditised marketplace (AEGIC 2021).

Each year the Australian Oilseeds Federation (AOF), together with NSW DPI, publishes *Quality of Australian Canola*. This publication provides a detailed breakdown of key canola quality attributes from the most recent harvest.

Measures of oil, protein, glucosinolates, test weight, fatty acid composition and iodine value are reported by the primary receival site and/or port zone and weighted to give a state and national average. These annual benchmarks provide the industry with a valuable resource database for ongoing comparison and review of Australian canola quality.

Grades and standards

Strict receival and grade standards are applied to Australian canola to maintain the highest quality. The AOF and Grain Trade Australia (GTA) set grower delivery standards for Australian canola.

Quality attributes and parameters

With so many parameters important to achieve good returns from canola, oil and meal quality can sometimes vary. Table 14 shows the mean quality characteristics of Australian canola from 2012–21.

Oil content

Canola is grown primarily for oil, which accounts for 65–85% of the seed value, with the meal accounting for the balance (Salisbury and Barbetti 2011).

In Australia, oil content is expressed at 6% moisture in whole seed which represents the average moisture content, whereas in other canola producing countries, including Canada, the average is closer to 8.5% (Barthet and Daun 2011). Oil content varies significantly depending on variety, agronomic conditions and the environment in which canola is grown. Over the last decade in Australia, the national oil content in canola averaged 45%. This is an increase from an average of 42.3% the previous decade (AOF 2023).

Protein content

The oil-free meal, produced as a by-product when oil is extracted from canola, is commonly used as a protein supplement in the animal feed and aquaculture industries. There is also a growing trend towards the isolation of proteins in canola meal for use in producing food for human consumption (Tan et al. 2011). Protein levels in canola are affected by seasonal growing conditions, with drier seasons likely to result in higher protein levels. The increase in the Australian canola crush capacity has seen the amount of canola meal produced increase from about 100,000 tonnes in 1995 to 500,000 tonnes in 2021 (Slee 2012; Biki 2022).

The average protein content in Australia over the last decade was 38.6% (Table 14), which is generally consistent with the previous decade (AOF 2023).

Glucosinolate content

Before the development of canola from rapeseed, glucosinolates, an antinutritional component of the crop, were a limiting factor in the use of rapeseed meal for livestock feed. Breeding activities have significantly reduced glucosinolates in canola to a level where the meal is considered a highly nutritious stockfeed, particularly for the pork and poultry industries.

The current Australian standard for glucosinolates is less than 30 µmoles/g in oil-free meal @ 10% moisture. The average glucosinolate content in Australia over the last decade was 12 µmoles/g (Table 14), a slight decrease from 14 µmoles/g the previous decade (AOF 2023). Glucosinolate levels can be affected by variety, agronomy and climate. Moisture availability during the growing season is especially important as water stress can significantly increase glucosinolates (Ayton et al. 2011).

Fatty acid composition

The fatty acid composition of canola oil is traditionally about 60% oleic acid (C18:1), 20% linoleic acid (C18:2) and 10% linolenic acid (C18:3). This produces an iodine value of over 114. Between 2002–11, the Australian average fatty acid composition was 60.8% oleic acid; 19.9% linoleic acid and 10.4% linolenic acid. This changed only slightly in the subsequent decade (2012–21) to an average of 62.0% for oleic acid, 19.2% for linoleic acid and 10.0% for linolenic acid (Table 14). During the same periods, iodine values averaged 115.0 (2002–11) and 113.8 (2012–21) (AOF 2023).

Variations in fatty acid composition occur due to variety and the climatic conditions where canola is grown. Cooler finishes to the season decrease oleic acid content (Pritchard et al. 2000), while warmer conditions increase oleic acid content and decrease the level of saturation (Werteker et al. 2010).

Table 14 *Mean and range of quality characteristics of Australian canola over 10 years (2012-21)*.*

Quality parameter	Mean	Range
Oil content (% in whole seed @ 6% moisture)	45.0	42.0–47.2
Protein content (% in oil-free meal @ 10% moisture)	38.6	37.3–39.9
Glucosinolates (µmoles/g in oil-free meal @ 10% moisture)	12.0	10–15
Oleic acid (C18:1), %[1]	62.0	59.9–64.3
Linoleic acid (C18:2), %[1]	19.2	17.9–20.4
Linolenic acid (C18:3), %[1]	10.0	8.6–10.9
Erucic acid (C22:1), %[1]	<0.1	<0.1
Iodine value	113.8	109.8–116.2
Chlorophyll content (mg/kg in whole seed as received)[2]	4.8	4.0–5.0

[1] Fatty acids are reported as a % of total fatty acids.
[2] Chlorophyll mean and range from 2017–2021.
*Data sourced from *Quality of Australian Canola*, 2012–21 (AOF 2023).

Chlorophyll content

High chlorophyll levels in canola oil are undesirable. Canola oil is marketed as a clear, golden coloured product and the costs of bleaching the oil to remove the green colour are high (Mailer et al. 2003). Unlike canola grown in the Northern Hemisphere, Australian canola matures, and is harvested during rising temperatures in early summer. As a result, chlorophyll contents in Australian canola oil are generally low, and only occur in the event of high plant stress or very early harvest.

The chlorophyll content in Australian canola has generally remained stable for the past 5 years, between 4–5 mg/kg (Table 14).

End uses

Australian canola is a sought-after product because it:

- has a reputation as a food-grade healthy oil, biofuel and stock feed
- meets sustainability criteria as it is produced using sustainable farming methods
- produces reliable crop yields.

Domestic and export markets

The domestic canola crush is currently about 1–1.1 Mt per annum. Most canola oil produced in Australia is for domestic use, industrial frying and margarine production (Biki 2022).

The European Union (EU) is Australia's major export market, accounting for around 60% of total canola exports in 2019–20. Other export markets include South Korea, Japan, and Malaysia. Canola exported to the EU is mainly used for biodiesel production. Australian canola growers sell into the European biofuel market by certifying their canola as sustainable. Since 2018, the EU has accepted Australia's justification that its canola production process meets its new greenhouse gas emissions savings requirement of 50–60%, up from 35% (Roth 2018). In Asian markets, canola is used to produce oil for human consumption as well as meal for livestock feed.

Future directions

Further research investigating the effect of varying agronomic inputs such as fertiliser type and rate, sowing time and harvest time on oil quality is needed. The effect of weeds on grain quality (e.g. high glucosinolates present in wild mustard and charlock that can contaminate canola grain) also requires further investigation.

Research opportunities also exist to:

- investigate the effect of fertiliser application on quality factors
- improve protein quality, which would extend the use of canola meal for human consumption.

Challenges include Australia's diverse growing areas particularly with respect to the impact of climate change on grain quality.

More information

References and resources relating to this chapter are listed in Appendix 1 (p. 107).

The Australian Oilseeds Federation

Rosemary Richards and Nick Goddard
Australian Oilseeds Federation, P.O. Box H236, ROYAL EXCHANGE NSW 1225

Summary

- Providing leadership for the Australian oilseeds industry.
- Facilitating a collaborative approach to industry opportunities and challenges.
- Driven by a member-supported Strategic Plan – focused on the consumer, market access, sustainability and innovation.

Introduction

The Australian Oilseeds Federation (AOF) is the peak body for the oilseeds industry, with representation from across the value chain. AOF provides leadership and coordination for the industry. The values that underpin AOF's activities are equal participation for all members, industry collaboration and partnerships with the commercial sector.

While AOF was established in 1970, it really began to drive industry growth in the early 1990s with the development of its first 5-year industry development plan. AOF has continued to guide and facilitate industry development and growth through its strategic plans, with the current plan being for the 2020–25 period.

The current plan acknowledges the dynamic nature of the industry, highlighting the growth in use of vegetable oils as replacement for fossil-based oils (especially as fuel and lubricants) as well as non-oil based opportunities such as feed and the emerging plant-based protein sector. The Strategic Priorities detailed in the Plan are centred on:

- consumer focus
- market access
- sustainability
- innovation.

AOF achievements for the oilseed industry

The successful outcomes from the implementation of AOF's successive strategic plans has benefited all sectors of the industry.

While initially focused on core aspects such as building grower confidence in oilseeds, building consumer demand and supporting export growth, AOF has and continues to shepherd the strong growth of the industry through core initiatives revolving around innovation, market access, sustainability and facilitating industry communication and collaboration.

Innovation

The AOF played a pivotal role in enabling the introduction of genetically modified (GM) canola in 2008 working across the value chain and through State and Federal Government advocacy to ensure the successful introduction of this technology. Genetically modified canola today is a core tool in the grower's toolbox for effective and low-environmental impact weed management. Working with industry, the AOF developed the Market Choice Framework to provide choice for customers and enable supply of both GM and non-GM canola. The Market Choice Framework has since been adopted by the broader Australian grains industry for the management of the future introduction of crop types developed through both GM technology as well as emerging new breeding technologies such as gene editing.

The Market Choice Framework and stewardship protocols developed for canola supported the successful introduction of super high oleic safflower into the Australian market in 2019. This variety of safflower has enabled the Australian oilseed industry to access new markets, in particular, the high value biobased applications.

Market access

The Australian oilseeds industry is export focused with two thirds of production typically destined for export markets. As such, a core focus of AOF has and will continue to be protecting and developing access to export markets.

Japan has been core to this strategy, particularly enabling the establishment and subsequent growth of canola in Western Australia (WA) through Japan's commitment to source from WA in the early days of the crop. Japan remains a very important market for Australian canola with the AOF and Japanese counterparts (Japanese Oil Producers Association (JOPA) and Japanese Oils and Fats Importers and Exporters Association (JOFIEA)) holding regular bilateral meetings to identify opportunities and address issues to strengthen the trading relationship.

China has been a long-term buyer of Australian canola over the past 2 decades. Australia's market choice approach has seen Australia become a major supplier of canola oil and seed to China. Today, China is the number one destination for exports of Australian canola oil, while seed exports have been disrupted by SPS concerns by China. AOF led the initiative with the Australian Government to address China's phytosanitary concerns related to the presence of blackleg (*Leptosphaeria maculans*) which resulted the resumption of trade in canola seed in 2013. AOF represented the Australian canola industry with Chinese officials on numerous occasions, both in China as well as with visiting Chinese delegations of Government representatives and researchers. AOF continues to advocate for the industry with the Australian Government for market access to China.

The European Union (EU) has also been a long-term buyer and in recent years the dominant market for Australian canola. European Union demand for Australian canola rapidly accelerated following the introduction of the Renewable Energy Directive (RED) in 2009 which resulted in the EU becoming the number one market for Australian canola. AOF led the process to establish the greenhouse gas (GHG) emissions for production of Australian canola which is a critical requirement for ongoing access to this market. The 2 country reports produced for the EU, in 2016 and 2022, demonstrated the low GHG emissions footprint of Australian canola. This provides a strong competitive advantage for Australian canola in the production of biodiesel in Europe compared to most alternate canola supplying nations.

Other important markets such as Pakistan, Bangladesh, Taiwan and United Arab Emirates (UAE) remain reliable buyers of Australian canola with Taiwan and South Korea also proving to be valuable markets for Australian soybeans. The AOF maintains a close oversight of market access issues related to all markets and works closely with the Australian government and allied parties such as Grains Australia (GA) and Grain Trade Australia (GTA) to identify and understand market access issues raised by importing markets, working collaboratively to address market access issues.

Sustainability

The rapid growth of the EU as a core destination for Australian canola provided the catalyst for AOF to embrace sustainability as an emerging opportunity for Australian oilseeds. This resulted in AOF establishing the Central Office for farm certification under the International Sustainability and Carbon Certification (ISCC) scheme. The Central Office, operating as Sustainable Grain Australia (SGA), facilitates the ISCC farm certification for over 5000 farms per annum enabling these farms, through their trading and export buyers, access to the lucrative EU market. As the market demand for sustainable certified grains and oilseeds has grown in recent years, so too has SGA expanded to facilitate certification of farms supplying other grains such wheat, barley and oats.

AOF, through SGA, has arguably been at the forefront of the acceptance, understanding and increasing adoption of the sustainability agenda throughout the Australian grains industry.

AOF and a Canola Vision for the future

In 2023, the AOF undertook a broad industry consultation to identify the issues and opportunities that were likely to impact the ongoing growth of the canola segment of the Australian oilseeds industry. The result was an industry-endorsed Canola Vision which provided a roadmap for the industry for the next decade.

The Vision acknowledged the role of a continued focus on doing the basics better and adding value to current activities across the value chain while being strongly oriented towards the steps the industry needs to take to generate future growth. The Vision also acknowledged that realising the opportunities will take significant effort and collaborative action across the industry, supported by public and private sector partners and stakeholders.

The Vision is anchored by 6 pillars which are designed to deliver industry value through focussing on enabling activities (Figure 27).

The intent is that the pathway that the Canola Vision presents will deliver a vibrant industry that continues to contribute significantly to Australia's economy and community and generate growth through building on the foundations while accessing new growth opportunities.

The shared Vision for canola is intended to deliver outcomes by 2035 that include a larger, more diversified and resilient industry that will deliver value across a more profitable, connected and adaptable value chain.

Doing the Basics Better **Driving Future Growth**

Pillars for key areas of focus

Market diversification	Sustainability	Productivity/ performance	Supply chain	Innovation	Influence
Ensure the canola industry can meet current customer requirements and changing market demands for oil, protein and fuel	Australian oilseed industry globally recognised as environmentally, socially and economcally sustainable	Increase productivity and meet current and future customer needs for oil and protein while remaining a preferred crop for growers with enhanced sustainability credentials	Create the environment for investment in value adding and technologies to support industry growth	Freedom to operate (regulatory, industry and social licence) and access to all new tools that can deliver value for the industry	Effective leadership and communication to facilitate industry collaboration within the canola sector and broader grains industry organisations to drive and support Vision 2035

Industry value delivered through focus on enabling activities: capacity, people, data, partnerships

Figure 27 *The 6 pillars of the industry-endorsed 'Canola Vision'.*

About the authors

Dr. Anthony Clark is an experienced agricultural climatologist with a 30-year career in climate and agricultural sciences having worked in the Australian Government, the private sector as well as in New Zealand and the United States. Anthony leads the NSW DPI Climate Applications team. He applies his skills in climate variability and change to lead the DPI seasonal conditions and drought monitoring program. Anthony plays a crucial role in the department's research and development program in climate variability.

Dr. Barbara Howlett is an Honorary Professor at The University of Melbourne. Between 1990 and 2014 she initiated and supervised both field and laboratory research projects on blackleg. She played a leading role in developing and analysing the genome of the blackleg fungus and discovered features of this genome that enables fungal populations to evolve quickly under selection pressure from blackleg resistance genes in canola.

Dr. Carl Ramage is the Managing Director of Rautaki Solutions, an Australian based consultancy business that supports national and international biotech organisations take products to market. He focuses on providing strategic and regulatory direction for the commercialisation of biotech products including the development of regulatory strategy and the drafting of regulatory dossiers for submission and assessment by regulatory authorities. His career has focused on building sustainable capability and capacity in biosafety and bio-risk management. He is actively involved in developing and implementing compliance management frameworks and compliance plans for biosafety containment facilities as well as programs for the intentional release of genetically modified organisms and gene edited products into the environment. Carl sits on several agriculture industry committees, is a former board member of the Association of Biosafety Australia and New Zealand, is a Graduate of the Australian Institute of Company Directors and the only south pacific Excellence Through Stewardship auditor, a program that promotes the universal adoption of product stewardship programs and quality management systems for the full life cycle of agricultural technology products.

Don McCaffery spent his entire career in agriculture, starting in irrigated crop research in southern NSW. He progressed to District Agronomist (irrigated summer and winter crops), then Technical Specialist (Pulse and Oilseeds); a role that included leading the NSW component of collaborative research into canola profitability. Don has been an executive member (Canola representative) of the AOF, and co-author of the annual NSW DPI *Winter crop variety sowing guide*, since 2003.

Dr. Harsh Raman is a Senior Principal Research Scientist with NSW DPI, based at Wagga Wagga Agricultural Institute. He led the National Brassica Germplasm Improvement Programs (2013–22) supported by the GRDC and research partners. He conducts pre-breeding research on acid soil tolerance, blackleg resistance, pod shatter resistance, drought tolerance and yield in canola. Currently, he is closely involved with the Australian Research Council Training Centre on Future Crops Development led by the Australian National University, Canberra.

Jamie Ayton has been with NSW DPI since 1995. He has worked for most of that time with the edible oil industries in Australia, mainly olive oil and canola. He has coordinated research projects determining quality and authenticity of these and other products. Jamie is a member of several technical committees, including Standards Australia, U.S. Pharmacopeia, the American Oil Chemists Society, the International Olive Council, and the AOF.

Dr. Jo Holloway has been employed as an entomologist with NSW DPI for over 20 years. Her research has been focused on integrated pest management in broadacre crops and management of insecticide resistance.

Dr. John Kirkegaard (FAA) is a Chief Research Scientist at CSIRO in Canberra and has been involved in canola research since 1990. His teams have worked on the rotational benefits of canola and biofumigation, development of dual-purpose canola, overcoming subsoil constraints, and improved water use efficiency and productivity with early sowing systems. He has been on the organising committees of the 1999 and 2023 IRC in Australia and is a member of the GCIRC.

Dr. Julianne Lilley has expertise in crop physiology, phenology and simulation modelling and is interested in crop response to environmental stress. She uses simulation modelling in innovative ways to quantify the benefits of novel genetics and crop and soil management practices on crop productivity in variable and changing climates.

Justin Kudnig is the National Canola Technical and Commercial Extension Specialist for Pacific Seeds located in Melbourne, Victoria. Pacific Seeds is a subsidiary of the Advanta Seeds Global Business. He has been in the Australian canola industry for 30 years focusing on national canola breeding and technical evaluations, seed production, GM and non-GM technology trait introgression, agronomy and extension trials and varietal commercialisation.

Kate Light is the Senior Canola Breeder for Nutrien Ag Solutions based in Horsham, Victoria. She has been in the Australian canola industry for 28 years beginning her career as a field and glasshouse research officer. She has been involved in specialty canola, the quality assurance, compliance and introduction of GM technology and the development of hybrids in Australia working with all herbicide tolerance systems and strongly focused on the development of disease resistance in *B. napus*.

Katherine Hollaway is an independent technical communicator with a research background. Based in Horsham, she has more than 10 years' experience with NVT data and reporting. She is co-editor of the NVT *Harvest Reports* and a former editor of the *Victorian Winter Crop Summary*.

Kerrie Graham has been with NSW DPI since 1995. She has worked with many different industries in that time, mainly canola, olive oil and meat. She is the lead author of the *Quality of Australian Canola* book published annually by NSW DPI and the AOF. She has contributed to many different research projects, with expertise in many different analytical techniques and the use of analytical instruments.

Kim Broadfoot has extensive experience working in agriculture, climate and hydrology. She has worked in many research and development teams in NSW DPI for over 15 years, applying her skills in farm systems research, agricultural modelling and climate change impact and adaptation assessments. Kim is currently the State Seasonal Conditions Coordinator for southern NSW and plays an important leadership role with monitoring seasonal conditions and drought across the state.

Dr. Kurt Lindbeck is a Senior Plant Pathologist with NSW DPI, based at Wagga Wagga. He leads research in southern NSW into diseases of pulses and oilseeds, with a focus on epidemiology and management.

Mathew Dunn is a Research and Development Agronomist at NSW DPI in Wagga Wagga. He has worked across a range of crop agronomy and farming systems research all with the aim of enhancing the productivity and sustainability of Australian plant production systems.

Dr. Md Asaduzzaman (Asad) is a Research Scientist in the NSW DPI Weed Research Unit and co-author of the *Integrated Weed Management Manual* for Australian growers. He has more than a decade of experience in various weed research disciplines and has also worked as a research fellow and lectured (as a sessional academic) at the Graham Centre, CSU. Asad uncovered Australia's first paraquat resistance and the world's first double-knock resistance (glyphosate followed by paraquat) in tall fleabane in Australian cotton cropping systems. His research into weed ecology, sustainable weed management strategies and herbicide resistance and hormesis development in weeds has been recognised internationally.

Dr. Melina Miles is an entomologist with a passion for improving the management of insect pests in broadacre cropping systems of the Northern Grains Region. Over the past 30 years, Melina has worked on developing economic thresholds, monitoring strategies and integrated pest management tactics for key insect pests of broadacre grains and cotton.

Dr. Michael Nash grew up on the family farm located in western Victoria. An applied invertebrate ecologist, he is a regular contributor at industry events. Michael is widely accepted as a leader in the study of the ecology, and control of molluscs in Australia.

Michelle Miller has recently left her role as the Seasonal Conditions Officer for NSW DPI. Michelle was responsible for informing the Government about current seasonal conditions and how this information could be used to provide support to farming communities.

Neale Sutton is the Systems Manager at NVT. Working with NVT since 2007 he manages the collection and distribution of the largest coordinated field trial network in the world and has overseen substantial system improvements and technology advances. He also manages the disease rating program for NVT.

Nick Goddard is the Chief Executive Officer of the AOF, which is a 'whole of value chain' industry body representing the Australian oilseed industry both locally and internationally. Nick has had a long and successful career in the food industry, working for the end-user portion of the agricultural value chain, with global multinational organisations. Nick draws on his end-user and consumer knowledge in bringing a 'market driven' approach to the oilseed value chain. Nick's links with canola date back to 1985 when he introduced the canola name to the Australian consumer market with the launch of the first canola-based cooking oil. Nick continues to be a strong advocate for the role canola oil can play in a healthy diet. Nick holds an MBA, a B.Comm (Marketing), and a Grad. Dip in Rural Science, and is based in Sydney, Australia.

Dr. Rajneet Uppal has expertise in crop physiology and agronomy research to understand crop responses to abiotic stress tolerance. Her current research program seeks to develop novel phenotyping techniques and facilitate the development of germplasm that can mitigate and/or adapt to abiotic stress (heat, drought and frost).

Dr. Raymond (Ray) Cowley is employed by Corteva AgriScience as the Senior Canola Breeder responsible for developing new Pioneer hybrid canola varieties for the Australian market. The Pioneer program covers all canola growing areas in Australia and some international geographies. Ray is committed to providing evolving genetic solutions that match the needs of producers and consumers. Ray led the Optimum *GLY*® breeding program in Australia and was involved in stewarding the trait from development to commercial launch.

Dr. Rob Norton has expertise in crop nutrition, farming systems and agronomy. He worked in education, graduate training and research with The University of Melbourne where he holds an adjunct position. Following a role as Regional Director for the International Plant Nutrition Institute, he is now engaged in soil fertility projects in Africa as well as local consultancies to a range of public and private organisations. He holds a PhD in crop agronomy (canola N, water use and seed quality) and has authored 150 refereed scientific publications, as well as many more articles and reports for industry. On his retirement from full-time employment in 2018, his contribution was recognised with awards from the GRDC and Fertilizer Australia.

Robert (Rob) Wilson has a long and distinguished career in agriculture, plant breeding and seed production having spent 42 years with Pioneer Hi-Bred Australia/GenTech Seeds. Rob commenced his career as a seed production agronomist before transitioning into research as a Lucerne (alfalfa) breeder for Pioneer. In this role he released 5 new varieties before being appointed to establish and manage Pioneer's Australian canola research program, releasing 33 canola varieties, including the first Clearfield® and Roundup Ready® hybrids into the Australian market. In 2015 he was appointed Canola Business Development Manager until retiring in May 2023. Rob has long been an active grains industry representative and is a past President of the AOF, the peak oilseeds body within the Australian grains industry, and a former President of the Canola Association of Australia. Rob is currently President of the GCIRC 2021–2025 and Chairman of the IRC (IRC-16) being held in Sydney, 24–27 September 2023.

Dr. Rodney Mailer joined the NSW Agricultural Research Institute in Wagga Wagga in May 1979. As Principal Research Scientist, he worked with the breeder, Neil Wratten, on the canola breeding program until he resigned in 2012. The Wagga Wagga breeding program released around 22 highly successful canola cultivars.
www.Australian-oils-research.com

Rosemary Richards is the principal of Bowman Richards & Associates (BR+A), a consulting firm specialising in providing strategic support to agribusiness firms. Rosemary is a passionate senior executive, communicator and industry advocate. Her experience in project management, trade policy and strategic development extends across all facets of agri and food businesses and she works with public and private companies; industry organisations and government departments. Rosemary undertakes a range of strategic planning, market analysis and trade policy activities for the grains and food industry and has led work on non-tariff trade measures for both sectors. She also has extensive experience in the biotechnology sector including regulatory frameworks, impact evaluation and advocacy. Rosemary is President of the AOF, Deputy Chair of the Cotton Research and Development Corporation, and a director of Sugar Research Australia.

Sean Coffey is the NVT Senior Manager with a background in project management, stakeholder engagement, business development and strategy. With former roles in both the domestic and international seed industries he has a strong appreciation of the value of reliable data in variety decision making.

Dr. Shihab Uddin is a Research Scientist with NSW DPI based at Wagga Wagga Agricultural Institute. Dr. Uddin's research focuses on improving farming productivity through better nutrient management (particularly N and P) of broadacre crops. Minimising the yield gap by ameliorating alkaline dispersive subsoil with various organic and inorganic amendments is another area of Dr Uddin's research interests.

Dr. Susie Sprague is a Senior Research Scientist at CSIRO Agriculture and Food. She leads a research team investigating different aspects of sustainable management of plant diseases in agricultural systems with a special research interest in blackleg of canola.

Trent Potter has undertaken research into *Brassica* crops since 1975, including agronomy, pathology and breeding studies. Originally Trent worked for SARDI until October 2012 when he established his own company – Yeruga Crop Research, to undertake projects. Trent has held industry roles including but not limited to Chairman of the Canola Association of Australia and Vice President and President of the AOF.

Appendix 1: References, further reading and resources

Crop limiting factors: climate

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Crop limiting factors: soils

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Resources

BlacklegCM App for iPad and android tablets

UCI BlacklegCM App for iPad and android tablets

Sclerotinia CM app for iPad and android tablets

Blackleg management guide (https://grdc.com.au/resources-and-publications/all-publications/factsheets/2023/blackleg-management-guide)

Australian Fungicide Resistance Extension Network (https://afren.com.au)

GRDC National Variety Trials™ (https://nvt.grdc.com.au)

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Quality

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