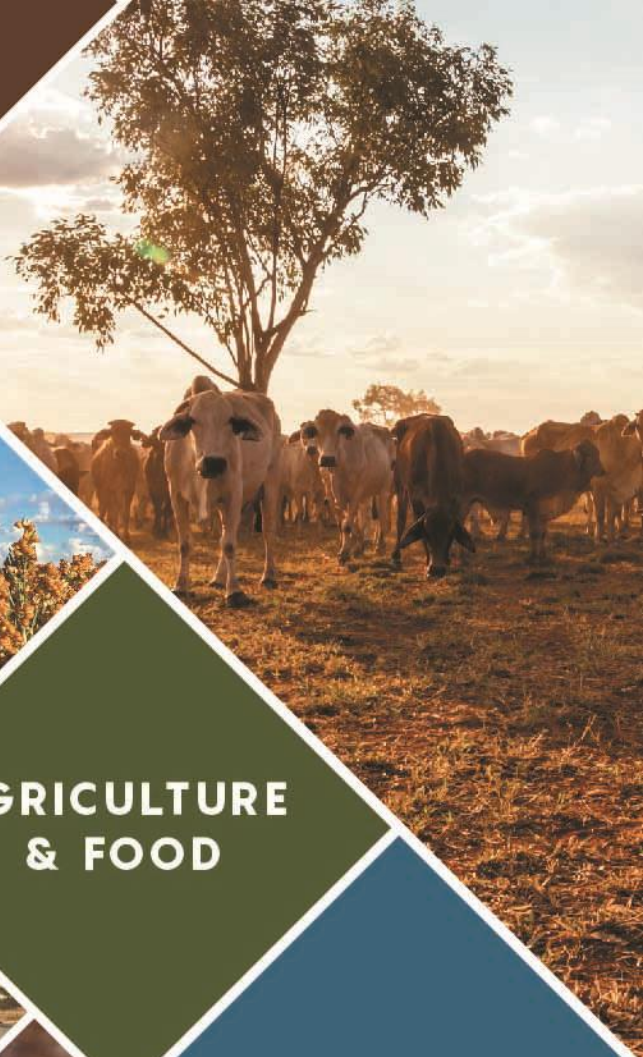
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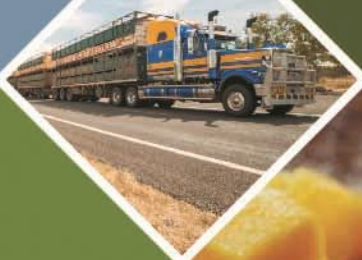






TRADITIONAL OWNER-LED DEVELOPMENT

AGRICULTURE & FOOD





PART B: FENNEL FINAL REPORT

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CRCNA
DEVELOPING NORTHERN AUSTRALIA

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The CRCNA recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2018),

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EXECUTIVE SUMMARY

The Spicing Up Northern Australia Project research contributed knowledge to the development of a high-value broadacre spice and condiments industry in northern Australia. The research focused on the production of five spices currently not commercially produced in Australia. The objectives were to identify suitable spice crop varieties and investigate agronomic practices underpinning production. The project, conducted over three years involved multilocation trials for initial evaluation of different varieties of spice including black sesame, fennel, kalonji, cumin, caraway and kalijiri in the first year, followed by variety and agronomic verification trials in the second year and scaling up for commercial production trials in the third year. Market anlaysis for these selected five crops and gross margin analysis for sesame, fennel and kalonji were performed in the third year of the project. The final report provides a summary of the whole project, whereas crop specific detailed technical reports are separately presented for black sesame (Part A), fennel (Part B), kalonji (Part C), and the results of the initial evaluation trials for cumin (Part D) and kalijiri (Part E).

This report presents performance evaluation of fennel varieties across six locations in Queensland and the Northern Territory Australia during 2019-2022. Fennel as summer crop in the first year (initial varietal evaluation) trials showed yield potential up to 1,574 kg/ha in small plot, hand harvested yield. The seed yield was highest in Ayr (1131 kg/ha), followed by Katherine (1,056 kg/ha) and Rockhampton (880 kg/ha), whereas the lowest in Biloela (366 kg/ha). AgriVentis fennel variety AVTFS#1 showed greatest adaptability, compared to AVTFS#2 and AVTFS#3 across all northern Australian sites. The summer planting presented challenges for fennel seed germination and emergence, and crop establishments resulting into poor plant population across all sites.

The opportunities for growing fennel as winter season crop was explored during the second-year for verification trial at Ayr, north QLD. The winter planted fennel recorded machine harvested seed yield of 337 kg/ha only, because of high harvest losses (30%). The harvest loos was associated with the wet weather during crop maturity causing poor desiccation and resulted in poor postharvest shelf life during storage prior to cleaning and grading.

A commercial crop trial, in third year, planted with Monosem precision planter as winter crop in Rockhampton produced machine-harvested seed yield of 629 kg/ha with estimated harvest loss of ~29%.

The seed quality specifications for market suggest for high purity (99-99.95%), and low moisture (8%). The machine harvested seeds from the verification trials showed clean seed recovery of only 29.3%, the option of primary cleaning after harvest on-farm and final cleaning at seed cleaning, grading, sorting and packing house in dedicated seed processing facilities is suggested.

Fennel also produces significant biomass (9.9 t/ha), with potential values for extraction of fennel essential oil and other value-added products.

The market analysis revealed growth of the domestic demand for fennel and similar seeds reaching Australian demand over 2000 tonnes by 2025.

Three years of cost and revenue data for fennel produced in Central Queensland, Australia with average seed yield of 0.629 t/ha resulted in an average gross margin of A$716/ha and A$932/ha in two different models. In both models, a seed yield over 0.35 tonnes/ha will be required to attract profits for the fennel producers at the price of A$2500/t.

Despite higher yield potentials demonstrated in the initial evaluation trials, the commercial scale yields reported were much lower, suggests for optimising the operation of planting and harvesting equipment for the precision and efficient applications on fennel.

The research over three years also documented other constraints associated with fennel production that includes slow seedling establishment, impacts of weed competition, crop susceptibility to insects particularly aphids, inadequate agronomic information (for crop water and nutrient management, optimum planting times and density for different regions), and postharvest technologies for achieving the seed quality standards for markets; which need to be addressed for successful integration of fennel in different farming systems in northern Australia.

The outcomes of the Spicing Up Northern Australia project have informed the scope of work for a follow up project, Great Northern Spices (GNS), 2022-2026 aimed to support commercial production of fennel seeds in Australia.

1. INTRODUCTION

As a part of the CRCNA-funded project Spicing Up of Northern Australia (2019-2022), the following progress and technical reports related to fennel research were delivered:

- "Spice Technical Report-Fennel" (2020) - https://www.crcna.com.au/resources/publications/fennel-summer-spice-technical-report
- "Fennel Verification Trials Report" (2021), and
- "Market Analysis of Fennel Seed" (2020) - https://crcna.com.au/resources/publications/market-analysis-fennel-seed
- "Broadacre Cropping in Northern Australia-Newsletter" 2021 - https://crcna.com.au/resources/publications/broadacre-cropping-northern-queensland

These reports have been published and are available via the CRCNA website.

The "Spice Technical Report - Fennel 2020" presents the results of a varietal evaluation for fennel as a summer crop in small plot, multilocation trials over six regions in northern Australia. The hand harvested yield and quality performance of three fennel varieties reported, and the challenges for summer season fennel production in northern Australia documented.

The "Fennel Verification Trials Report 2021" presents the results of fennel trial as winter planted crop in northern Australia. The machine harvested yield and the results of the post-harvest seed cleaning of the winter planted fennel crop is reported.

The "Market Analysis of Fennel Seeds 2020" analyses the current fennel global markets, identify major global producers and importers of fennel seeds. The report also analyse current demands, and forecast future demands of fennel seed for Australia.

The "Broadacre Cropping in Northern Australia - Newsletter 2021" presents the results of initial variety evaluation trials for five species crops, including fennel and sesame as summer season crop whereas kalonji, cumin and kailjiri as winter season spice crops. These trial results presented hand harvested yield to showcase the yield potentials of these selected spices crops in Northern Australia.

The project outlines eight key deliverables for achieving the project objectives and purpose. The five key deliverables are related to fennel crop production, quality assessment and economic analysis, and these are linked to this final report related to fennel crop. The common deliverables across the crops, i.e. deliverable 6- Extension; deliverable 7- Complementary Activities and; deliverable 8, Research Insights and Future Directions are common for all the spices commodities included in the project. Therefore, reporting on deliverables 6-8 are presented in Final Report (An overarching report) to minimise the duplication of information and contents across the commodity reports.

2. MARKET ASSESSMENT

The market assessment undertaken in 2019-2020 investigated the current and future trends of the Australian and international fennel market. The market data available for fennel is limited and is often presented in a larger "group of spices" including juniper berries, anise seeds, badian, caraway, coriander and fennel (as whole seed, not ground or crushed). The following extracts from the report summarise the key findings. The full report is available at https://crcna.com.au/resources/publications/market-analysis-fennel-seed. The report provides a baseline assessment of the global industry based on currently available information and identified areas for further research to address the gaps in market information. The fennel price in Australia is largely influenced by the global market price. AgriVentis Technologies Ltd accessed information on the global market price for fennel through Tridge (https://www.tridge.com/intelligences/fennel/price) and verification through the price on offer by the key importers/exporters in global fennel markets.

India is the world's largest fennel producing country with Syria, Egypt, Turkey, Germany, Spain and Pakistan also making significant contributions to global production. India and Egypt are significant exporters of fennel. Interestingly, for the group of spices including juniper berries and anise seeds, badian, caraway or fennel, India also imported the highest amount of these spices, followed by Germany. Other major importers include the United States of America (USA), Turkey, the United Kingdom (UK), the United Arab Emirates (UAE), Brazil and Malaysia.

India imported the highest amount of this spice group followed by Germany. Other major importers include USA, Turkey, UK, UAE, Brazil and Malaysia. Country-specific import quantity is available in the UN databank but not for all countries. India imported about 14,300 tonnes of these spices in 2018, while Germany and USA imported 12,950 tonnes and 8,760 tonnes respectively for the same period.

The annual growth in the import market is 8.9% (ITC, 2019, UN Com Trade, 2019). The reason for this growth is unknown but it has been suggested it may be due to population growth or increased purchasing power of middle-class consumers. Australia's domestic market for fennel and other similar spices is entirely supplied through imports. In 2018, Australia imported about 568 tonnes of the spice group in question, worth about US$1.37 million. Many imported spices in Australia are produced in India and China (UN Com Trade, 2019). There is evidence of continuous growth in the quantity of imported spices, which suggests there is an increasing demand for fennel and similar spices in Australia. The trend analysis suggests that in 2025 the demand for fennel and similar spices in Australia will exceed 2,000 tonnes per year.

Demand for fennel seeds is due to its pleasant flavour and multi-purpose application. For example, sugar-coated fennel is used as a breath freshener (Malhotra, 2012). They are a popular spice in Asian and European cuisine and they are often included in specific spice blends including Indian *panch-phoron* and Chinese five-spice powder. The seeds are commonly used in soups, German and Italian bread, Italian sausages, and in fish and seafood dishes (Shelef, 1983). Fennel oil, ground fennel and fennel seed tea are the common value-added products of fennel.

The unit trade price of fennel and other spices was volatile over the last few years. In 2018, the price was US$ 2,408/t. Given the unit value and the size of the market, it is likely that a local industry in Australia could initially target the domestic market before scaling up for international markets. The opportunity for an Australian fennel seed industry to expand production will be determined by a combination of several factors such as growing market demand, climatic conditions, geographical proximity to Asian markets, and availability of suitable variety, climate and land. Australia has now free trade agreement in place with the major market of India, China and Europe giving Australia a potential competitive advantage over traditional exporters.

However, high labour cost and lack of postharvest processing is a competitive disadvantage and a barrier to the growth of fennel cultivation in Australia. Technological innovation (mechanisation of planting, harvesting, processing), adoption of high yielding and high-quality fennel varieties, and economies of scale of Australian production systems will be key to overcoming labour cost competitiveness.

There are five factors - growing global demand, proximity to international markets, high crop prices, and access to suitable land and varieties– which position Australia with an opportunity to create a viable industry generating revenue through import replacement and export sales.

3. GROSS MARGIN ANALYSIS

3.1 Introduction

Global fennel production and market data are not available in the open source. The Food and Agriculture Organisation (FAO) groups fennel with anise (*Pimpinella anisum*), badian (*Illicium verum*) and coriander (*Coriandrum sativum*) to produce an annual production data set (FAO, 2019). Hence, it is difficult to identify the exact fennel production data from FAO statistics.

Fennel is cultivated mostly in India, Syria, Egypt, Turkey, Germany, Spain, and Pakistan (Rahman et al., 2020). According to Indian National Horticulture Board, in 2019-20, India cultivated fennel in about 83,000 ha areas and produced about 142,000t of fennel with an average yield of 1.71t/ha (NHB, 2023). In 2018, Turkey produced about 3,100t (TurkStat, 2019). The average yield of fennel is reported as 1.2-1.3t/ha (Lal et al., 2014).

The international trading price is variable over the last few years. The current price of fennel in international markets is US$1,910/t which is equivalent to about A$2,800/t (Tridge, 2023). Current data on fennel production in Australia was not available in the literature because of the non-commercial production of this spice.

There have been some studies regarding the profitability analysis of fennel farming conducted in south-Asian and Mediterranean countries. Singh et al. (2022) investigated the effect of different irrigation levels on the growth, and yield of fennel production in India. They reported that with an appropriate irrigation system, the fennel yield could be 2.3t/ha attracting a net return of A$2,311/ha (Indian rupee 129,000/ha) with a benefit-cost ratio of 4.16. A study in Turkey reported an average gross margin of TL 5,455.6/ha (in current Australian dollar value of A$1,464/ha) for fennel production (Gul et al., 2017). Literature on profitability analysis of fennel production in Australia has not been found in any of the databases or any published literature. Therefore, this case study undertaken to determine the gross margin analysis of fennel production will fill this gap.

3.2 Methods and Limitations

The study was conducted as a case study on fennel production from a field trial site in Central Queensland. Fennel production costs and revenues from three years (2020, 2021 and 2022) were collected to analyse the farm operation profit and sensitivity analysis. Data was collected using a quantitative questionnaire (attached in the appendix) and supplemented with a phone interview. The collected data was converted to cost and revenue per hectare. The process and protocol of data collection were approved by CQU's Human Ethics Committee (project number 0000022421).

3.2.1 Limitations of the study

The following limitations are applicable to the study:

- The report focuses on the gross margin with and sensitivity analysis of fennel production. While gross margin analysis helps compare similar enterprises; caution is advised when comparing with farming enterprises which require different resources input in the form of capital costs. The depreciation cost of the existing farm assets has been included instead of the entire new investment in the farm machinery and equipment.
- The farm size during the three years of production was 0.1ha. Given the availability of only three data points, it has been judged best not to extrapolate the findings for broadacre fennel farming. Also, the size of the cultivated land for the trial run was small and hence, restricts the results for generalization.
- Only the direct revenue of seed sales has been included in the benefits, which is considered as farm-gate base price. Value-added products including fennel oil with other indirect benefits from crop rotation on the farm are beyond the scope of the study.

- Fennel production has been assumed as an incorporation into the existing farming system as a rotation crop. So, fennel production as a completely new business venture including new farm and, capital costs of new farm establishment, are beyond the scope of the study.
- This fennel feasibility study is targeted for a rainfed production system in prime vertisol agricultural land. The semi-irrigated and fully irrigated production system is beyond the scope of the study.

3.2.2 Case study area

The case study was carried out in an area of prime agricultural land located in the Lower Fitzroy agricultural basin, Central Queensland. Central Queensland is a planning and administrative region in Queensland primarily including regions surrounding Biloela, Emerald, Gladstone, Rockhampton, Yeppoon and Woorabinda covering a total area of 117,588 square kilometres (QGSO, 2023). The region has a sub-tropical climate with hot humid summers and dry mild winters (Bureau of Meteorology, 2001 and 2021). The mean rainfall, average maximum temperature, and average annual minimum temperature for the chief locations in Central Queensland have been presented in table 1.

Table 1. Mean annual rainfall and minimum temperature for main locations in Central Queensland

Location	Mean rainfall (mm)	Mean maximum Temp (°C)	Mean minimum Temp (°C)
Rockhampton	815	28.5	16.8
Biloela	686	28.4	12.9
Emerald	544	29.9	16.3
Gladstone	853	27.4	18.2
Yeppoon	979	25.9	18.7

Data Source: (BoM, 2021)

3.2.3 Variables explanation

The cost of production involved was segregated into fixed and variable costs. Variable costs involved the costs that would change with the change in the scale of the production. Fixed costs involved costs that did not change with the change in the scale of production. Seed yield was obtained from the three years of fennel production. The appropriate yield range for sensitivity analysis was determined by considering factors like world average fennel production, fennel production from the field trials of the research, harvest loss percentage of fennel during mechanical harvest and average productivity of mechanised fennel production.

Labour costs are included in the fertilizer application and harvesting costs. The costs for vehicle rego, insurance and maintenance of the farm equipment are included in the fixed cost. To calculate the farm equipment repair and maintenance cost, the total repair and maintenance (R&M) cost of the farm vehicles and implements incurred was divided by the total expected life hours of the vehicles and implements respectively. It was then adjusted to cost per hectare, depending on the work efficiency of the vehicle/implement (hectare/hour) calculated by the farm owner. The cost of the R&M has been included in each farm activity, but the detailed individual R&M costs calculation has not been disclosed in this report as per the non-disclosure agreement with the farm owner. Herbicides and insecticides cost has been included in the variable cost calculation as weed management. All the capital costs incurred in the farm were halved, assuming two crops cultivated per year in rotation. Finally, all capital costs were adjusted to per hectare basis for all the years. Fennel farmgate price was collected from a trading company involved in spice and grains trading but have not disclosed for ethical reasons.

In this study, we have considered two models based on the fertilizer market scenario. The first model considered the highly volatile fertilizer price during the COVID-19 pandemic situation for the observed three years. The second model considered the normal market situation with fertilizer cost was about A$170/ha before COVID at CQ farms.

3.3 Results and Discussion

Fennel was farmed in 0.01, 0.01 and 0.021 hectares in 2020, 2021 and 2022 incurring total cost per hectare of A$930, A$929 and A$1189, respectively under model 1. Variable costs accounted for the majority of the costs, sharing on average 81% of the total cost (Table 2). Fertilizer cost is one of the main sources of variable cost in cropping industries and is also the case in fennel.

Fennel yield during the observed three years was 880 kg/ha, 337 kg/ha and 629 kg/ha respectively. The yield was considerably less compared to the world's average yield (1.2 tonnes/ha). The farmgate price of fennel was set at A$2,500 leading to a gross margin of A$1,462/ha, A$106/ha and A$581/ha in 2020, 2021 and 2022 respectively (Table 2). So, fennel production is marginally viable in CQ region but a better production and harvesting method would increase the gross margin.

Table 2. Fixed cost, variable cost and revenue for rainfed fennel farming during 2020, 2021 and 2022 in Central Queensland under model 1

Item	Cost ($/ha) 2020	Cost ($/ha) 2021	Cost ($/ha) 2022	Average cost / hectare
Fixed cost				
Land rent + rates	47	47	48	47
Office cost	15	15	16	15
Depreciation	85	85	85	85
Insurance + Rego +repair	45	45	48	46
Total fixed cost	192	192	197	194
Variable cost				
Land preparation	70	70	75	72
Planting	25	25	30	27
Fertilizer	385	385	560	443
Fertilizer application	55	55	55	55
Weed management	30	30	60	40
Harvesting	120	120	160	133
Post-harvest (freight and cleaning)	53	52	52	52
Other (in-kind labour)				
Total variable cost	738	737	992	822
Total expenses	930	929	1189	1016
Revenue Segment				
Global Fennel price/tonne	$2,500			
Production (Tonnes)	0.880	0.337	0.629	0.62
Total revenue	$2,200	$843	$1,573	$1,538
Gross margin	$1,462	$106	$581	$716
Gross margin ratio	66%	13%	37%	47%

Note:

- *Fixed cost considered of half a year to represent crop rotation.*
- *Red cells indicate the negative gross margin and not profitable option, while green cells indicate the profitable options.*
- *2021 production data was obtained from a small-scale trial from a different field under the same project because data was not available for the case study field.*

Under model 1, which considered the highly volatile fertilizer price, we ran a sensitivity analysis on fennel farming to observe the effect of price fluctuation and crop performance on gross margin (Table 3). The average variable cost per hectare incurred during the three years was used for the sensitivity

analysis. A minimum seed yield of 0.35t/ha would be required to secure some profit at the price of A$2500/tonne. Under the current base price, none of the price points below A$2,500 were profitable at the seed yield of 0.25 tonnes/ha (Table 3).

Table 3. Sensitivity analysis of the average gross-margin from three years of fennel production (Model 1)

Price (A$/tonne)	**Yield (tonne/ha)**				
	0.25	0.35	0.45	0.55	0.65
2300	-$163	$67	$297	$527	$757
2400	-$138	$102	$342	$582	$822
2500	-$113	$137	$387	$637	$887
3000	$12	$312	$612	$912	$1,212
4500	$387	$837	$1,287	$1,737	$2,187
5000	$512	$1,012	$1,512	$2,012	$2,512

The same gross margin analysis was undertaken in model 2, where we considered the base price of fertilizer before the COVID-19 pandemic. With the same trial run the total costs incurred per hectare were A$737.5, A$736.5 and A$909 in 2020, 2021 and 2022, respectively. On an average, variable cost is 76% of the total cost. With the given farmgate price of fennel at A$2,500, the gross margin of fennel production was A$1,655/ha. A$298/ha and A$861/ha in 2020, 2021 and 2022, respectively (Table 4). Table 18 summarises all variable and fixed costs with gross margin estimates. Similar to model 1 results, this analysis indicated that for the trial run output, the fennel production is economically profitable with better economic margin compared to model 1.

Table 4. Fixed cost, variable cost, and revenue for rainfed fennel farming during 2020, 2021 and 2022 in central Queensland under model 2

Item	**Cost (A$/ha) 2020**	**Cost (A$/ha) 2021**	**Cost (A$/ha) 2022**	**Average cost ($/ha)**
Fixed cost				
Land rent + rates	47	47	48	47
Office cost	15	15	16	15
Depreciation	85	85	85	85
Insurance + Rego +repair	45	45	48	46
Total fixed cost	192	192	197	194
Variable cost				
Land preparation	70	70	75	72
Planting	25	25	30	27
Fertilizer	192.5	192.5	280	222
Fertilizer application	55	55	55	55
Weed management	30	30	60	40
Harvesting	120	120	160	133
Post-harvest (freight and cleaning)	53	52	52	52
Other (in-kind labour)				
Total variable cost	545.5	544.5	712	601

Total expenses	737.5	736.5	909	794
Revenue Segment				
Global Fennel price/tonne	$2,500			
Production (Tonnes)	0.88	0.337	0.629	0.62
Total revenue	$2,200	$843	$1,573	$1,538
Gross margin	$1,655	$298	$861	$938
Gross margin ratio	75%	35%	55%	61%

Note:
- *Fixed cost considered of half a year to represent crop rotation*
- *2021 production data was obtained from a small-scale trial from a different field under the same project because data was not available for the case study field.*

With a lower fertilizer price in model 2, the gross margin analysis looks very promising. We ran the sensitivity analysis on fennel farming for model 2 and present the results in Table 5. The results indicated that at a seed yield of 0.25 tonnes/ha, the producers would gain some profits at all the given price points. The sensitivity results from both models indicated that unless we could achieve a yield over 0.35 tonnes per hectare, the return on investment for fennel production would be challenging.

Table 5. Sensitivity analysis of the average gross-margin from three years of fennel production (Model 2)

	Yield (tonne/ha)				
Price (A$/tonne)	0.25	0.35	0.45	0.65	0.3
2300	$30	$260	$490	$720	$950
2400	$55	$295	$535	$775	$1,015
2500	$80	$330	$580	$830	$1,080
3000	$205	$505	$805	$1,105	$1,405
4500	$580	$1,030	$1,480	$1,930	$2,380
5000	$705	$1,205	$1,705	$2,205	$2,705

Table 6 presents the average gross margin of the rainfed summer crops in central highland region of Queensland, Australia. The table 6 is to be used as an indication of the performance of the crops in the region, rather than exact figures. These data were collected from the Qld government and DAFF-hosted AgMargins websites.

Table 6. Gross margin of the dryland high value crops in Central Highland Region. Source: (AgMargins, 2023, QLD government)

Crop	**Calculation for year**	**Gross margin (A$/ha)**
Mung bean	2020	$164.35
Faba bean	2020	$565.92
Chickpea	2020	$251.47
Lentils	2020	$406.18
Soybean	2020	$180.86
Sunflower	2020	$396.76
Peanut	2020	$435.40

The Central Highland is one of the major agricultural regions of Central Queensland. Thus, the given figures are applicable for comparison with the gross margin from dryland cultivation of fennel in other parts of CQ. No other profitability analysis of dryland farming of mainstream crops was found in the literature sources. Our current study indicated fennel production would not be profitable with the current average yield of 0.12 tonnes/ha. The fennel field trial yield was higher in the third year at 0.629 tonnes per hectare. The current analysis indicated that at least 0.3 tonnes/ha yield would be needed to generate any profit at a market price of A$2,500/tonne. The long-term future of the fennel industry in Australia lies in the development and usage of high-yielding varieties and access to the export markets.

3.4 Summary

The seed yields recorded in the rainfed fennel in 2020, 2021 and 2022 were 0.88 t/ha, 0.337 t/ha and 0.629 tonnes/ha respectively. The yield is lower compared to the world average (1.2 t/ha). The lower yield impacted the gross margin and resulted in a negative value in model 1. However, fennel production is economically profitable under model 2. Sensitivity analysis under the two different models revealed that a seed yield of 0.35 t/ha would generate reasonable profit for the producers at a minimum farmgate price of A$2500/tonne. The results presented in this report are based on field trials on a small plot, so these results should be used with caution. However, further trial with different varieties of fennels with appropriate harvesting technologies would require developing a commercial business case.

4. AGRONOMIC CROP ASSESSMENT

4.1 Introduction

Fennel (*Foeniculum vulgare Mill.*) is a small herb belonging to the *Apiaceae* family and the order *Apiales* (Malhotra, 2012*). Foeniculum* is diploid having 2n=22 chromosomes. Fennel is a hardy, annual, biennial or perennial herb with yellow flowers and feathery leaves (Singh, 2012). Fennel produces aromatic dried fruits, which are commonly used as a spice in cooking. In addition to the seed, fennel leaves and essential oil are used as a spice for flavouring, while the bulb of fennel is consumed as a vegetable or herb.

It is a native of Southern Europe and the Mediterranean region. Later it spread to the Far East and Far North in Europe. Fennel has an ancient history of being used as a medicinal herb in the Mediterranean region and India. Historical records indicated that ancient Egyptians used fennel as a medicinal herb for Pharaohs (Guarrera and Savo, 2013). In the Hershey papyrus, fennel was mentioned as a gift for stomach ailments (Guarrera and Savo, 2013).

The fennel plant has hairy, feathery, and soft foliage and can grow up to 2m tall. The thread-like leaves grow up to 40 cm long and 0.5 mm wide. The flower and seeds are produced in terminal compound umbels and the dry fruits are 4-10 mm long. The dry fruit of fennel is generally known as fennel seeds, and it contains several vitamins and minerals. Based on appearance and composition, fennel is classified into several categories including wild fennel, bitter fennel, sweet fennel and culinary Florence fennel (Bagchi and Srivastava, 2003).

It is widely cultivated throughout the temperate and subtropical regions of the world and major growing countries are Romania, Russia, Germany, France, Italy, India, Argentina and USA. Fennel is considered an indigenous Mediterranean plant but is now cultivated in many parts of the world on different soil types and climatic conditions (Rather et al., 2016). Well-drained and calcareous soils in a warm temperate and subtropical environments are the most suitable conditions for fennel production (Bhattacharya, 2016).

As per a detailed market analysis (Rahman et al., 2020), it is estimated that India produced about 150,000 tonnes of fennel in 2018 (NHB, 2019) from 90,000 hectares. A Turkish government agriculture statistics website published production data and production area, with Turkey planting only 2,340 ha. A comparison of fennel yields from India and Turkey indicates an average yield of fennel per hectare is slightly higher in India (1.6 t/ha) compared to Turkey (1.3 t/ha) in 2018 (Rahman et al., 2020). For the Australian production to be competitive in the international markets, the variety development work for Australia need to target to achieve these yields and quality benchmarks achieved by major fennel producing countries of the world.

4.2 Fennel Initial Evaluation Trials (Year 1)

4.2.1 Materials and methods

Trial locations

Field trials were conducted to determine the suitability of three genotypes of AgriVentis fennel seeds to the climate, soils and environmental conditions in northern Australia. The trial locations included four sites in Queensland and two sites in the Northern Territory (Figure 1).

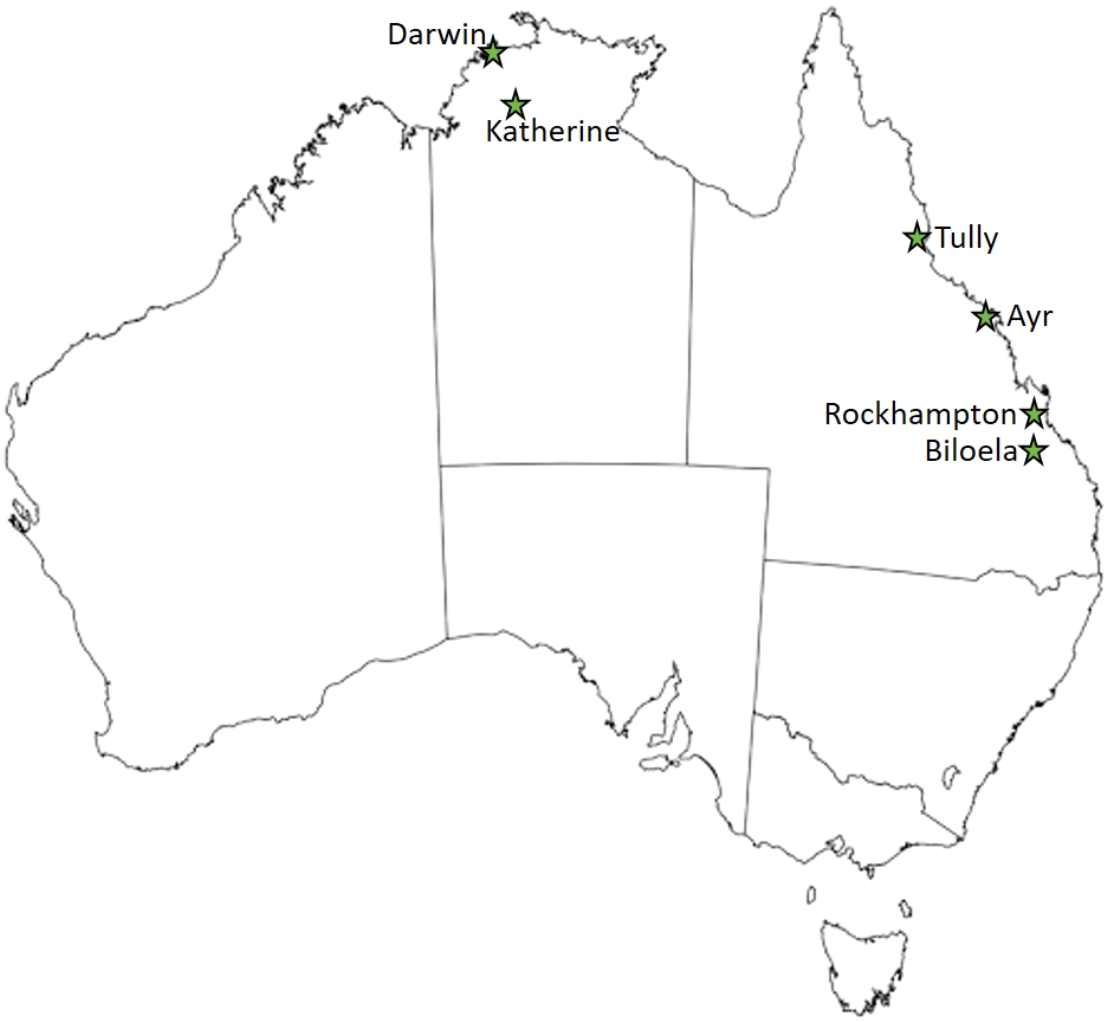


Figure 1. Trial locations in northern Australia, including Biloela, Rockhampton, Ayr and Tully in Queensland, and Katherine and Darwin in the Northern Territory

Site descriptions

The in-crop rainfall input varied between the sites significantly. Lowest rainfall of 405 mm during crop season was recorded at Biloela, whereas highest rainfall of 1,459 mm was recorded at Ayr. Likewise, soil types also varied from alluvial and sandy loams (Biloela, Ayr and Tully) to vertisol (Rockhampton) and ferrosols (Katherine and Darwin NT). The trials sites also represented wider range of farming systems (Table 7).

Table 7. Geographic location, in-crop rainfall, soil types and cropping systems of the fennel trial locations

Location	Latitude	Longitude	In-crop rainfall (mm)	Soils	Cropping system
Biloela, QLD	24º26'32S	150º31'53E	405	Alluvial loam	Hay crop-Fennel-hay crop
Rockhampton, QLD	23º18'24S	150º21'35E	454	Vertisol	Cotton-Fennel-Cotton
Ayr, QLD	19º37'8S	147º31'52E	990	Sandy loam	Melon-Fennel-Melon
Tully, QLD	18º7'23S	145º31'14E	1459	Sandy loam	Sugarcane-Fennel-Sugarcane
Katherine, NT	14º28'12S	132º18'28E	540	Ferrosol	Sorghum-Fennel-Sorghum
Darwin, NT	12º35'38S	131º18'16E	1097	Ferrosol	Sorghum-Fennel-Sorghum

Planting season

The crop was planted during summer season. The planting window, however, varied (Table 8) from early to mid-summer depending on the availability of soil moisture at planting and predictions for the onset of the wet season for the harvesting period, to avoid harvesting at wet period.

Table 8. Fennel trial planting and harvest dates

Location	Fennel planting date	Fennel harvest date
Biloela, QLD	17 Dec 2019	28 August 2020
Rockhampton, QLD	16 November 2019	28 May 2020
Ayr, QLD	28 November 2019	15 July 2020
Tully, QLD	29 November 2019	Not harvested
Darwin, NT	9 January 2020	Not harvested
Katherine, NT	10 January 2020	15 September 2020

Site preparation

At each site, the bed was prepared following grower's practice, and seeds were planted in well-tilled soils. At Biloela, Rockhampton and Tully, the fennel seed was planted in plots 3m wide and 2m long. Each plot had six rows of fennel planted 2m long. The two outside rows were guard rows and the four inside rows (data rows) were used for data collection.

Raised beds 1.5m wide were prepared in Darwin and Katherine and the fennel seeds were planted in four rows 2m in length. The outside two rows were guard rows, and the inside two rows were used for data rows.

In Ayr, 1.5m wide raised beds covered with plastic mulch were prepared and three rows of fennel seed 2m in length were planted in the plastic mulch and one guard row was planted on either side of a single data row. At this site, the blocks of replicates were randomly stacked along one long bed, rather than in a square block pattern.

Drip tape was installed in all sites for strategic irrigation. One drip line was installed along each of the guard and data rows. Irrigation was applied throughout the season to supplement soil moisture to refill point.

Varieties, trial design and planting densities and planting dates

Three varieties of fennel (AVTFS#1, AVTFS#2, and AVTFS#3) were grown for initial evaluation trials, following the randomised complete block design (RCBD), with multiple replications (seven) within the same farm in each location.

The between-row spacing was 50cm and the plant spacing within the row was approximately 6cm with an aim to achieve the target population of ~30 plants/m^2.

The planting date varied between sites (Table 2). At Biloela, the seeds were replanted on 17 December 2019, i.e. 40 days after the first planting on the 7 November 2019 as the emergence from the first planting date was very poor.

Nutrient management

RICHGRO all-purpose complete garden fertiliser (NPKS 9-2-7-12) and RICHGROW High Phosphate–Super Phosphate fertiliser (NPK 0-9-0) was applied to the soil, for the NPK rate of 81:40:63kg Ha^{-1} at planting as a basal dose of fertilizer application. No additional fertiliser was applied during the growing season. All sites received the same level of fertilizer. Soil samples pre-planting and post-harvest were collected and analysed.

Weed control at Katherine involved a pre-emergent herbicide Stomp (Pendimethalin A.I 440g/L) application at the rate of 1.5L/ha two days post-sowing for weed control (please see, http://www.herbiguide.com.au/labels/pen33_61322-1209.pdf). In all other sites, hand weeding was carried out throughout the first month of growth to keep the weed competition low during the seedling

establishment stage. Once the fennel canopy well developed, minimal weeding was required as the plant canopy supressed weeds growth.

Once the fennel seeds had emerged and established, each of the rows was thinned to a target population of 30 plants/m^2. Thinning occurred at approximately 2-3 weeks after sowing when the plant height reached about 15-20cm. Thinning provided uniform spacing of approximately 6cm between the plants within the row.

Data collection and analysis

Crop phenological, vegetative and reproductive data were collected throughout the growing season. The date of planting, emergence, emergence count, flowering, maturity and harvest, and plant stand at harvest were recorded. At maturity, the plant height, number of umbels per plant and height at the position of the first umbel were recorded on six randomly selected sample plants from each plot. The data rows were harvested, and the seeds were separated and cleaned, dried and weighted for determination of seed yield (kg/ha) and quality. The harvested biomass was oven-dried (65°C) until a constant weight was reached, and the dry biomass weight recorded for calculation of biomass yield (kg/ha). Harvest Index (HI) was calculated as the ratio of seed weight /total above ground dry biomass (seed +biomass) weight.

The quality assessments of the harvested seeds were undertaken in Central Queensland University's Crop Science Seed Laboratory. For the quality assessment, a 100g sample of seed was cleaned from plant trash and dust, dried in an oven at 40°C and weighed for determination of seed moisture content. The seed counter was used for the determination of 1000 seed weight from cleaned dried fennel seeds (Wavwer, Model IC-VA, Japan). The weight for 1000 seeds was taken for each sample using a precision laboratory weighing balance. A subsample of 50g of seed was dried to 70°C for 12 hours and the density of the seed was measured.

The seed density was calculated using the principle of a chondrometer modified to accommodate a smaller volume of seed (https://www.graintec.com.au/products/grain-testing/quality-measurement/test-weight-chondrometer/description/). Seed volume was measured in the graduated 50ml centrifuge tube, with seed samples compacted uniformly and seed weight measured in the Ohaus adventure pro-precision balance (Model AV2102N) and the results presented as kg/m^3. Data were analysed for individual sites following the procedure for analysis of variance (ANOVA) using GenStat 2020 (VSN International, 2020) for assessing the effects of treatments, and mean separated using Least Significant Difference (LSD).

4.2.2 Results

Climatic conditions

The weather data for each trial site was recorded using the closest BOM meteorological stations and data was sourced from the Climate Data Online (http://www.bom.gov.au/climate/data/) repository maintained by BOM. The web link for each of those sites for accessing weather data are listed below:

Biloela: Station number 039269.
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=039269

Rockhampton: Station number 039083.
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=039083

Ayr: Station number 033002.
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=033002

Tully: Station number 032167.
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=032167

Katherine: Station number 014902.
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=014902

Darwin: Station number 014183.
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=014183

The maximum temperature during the crop early establishment stage were routinely above 30 °C, and the crop vegetative growth coincided with wet and hot weather in all trial sites (Figure 2).

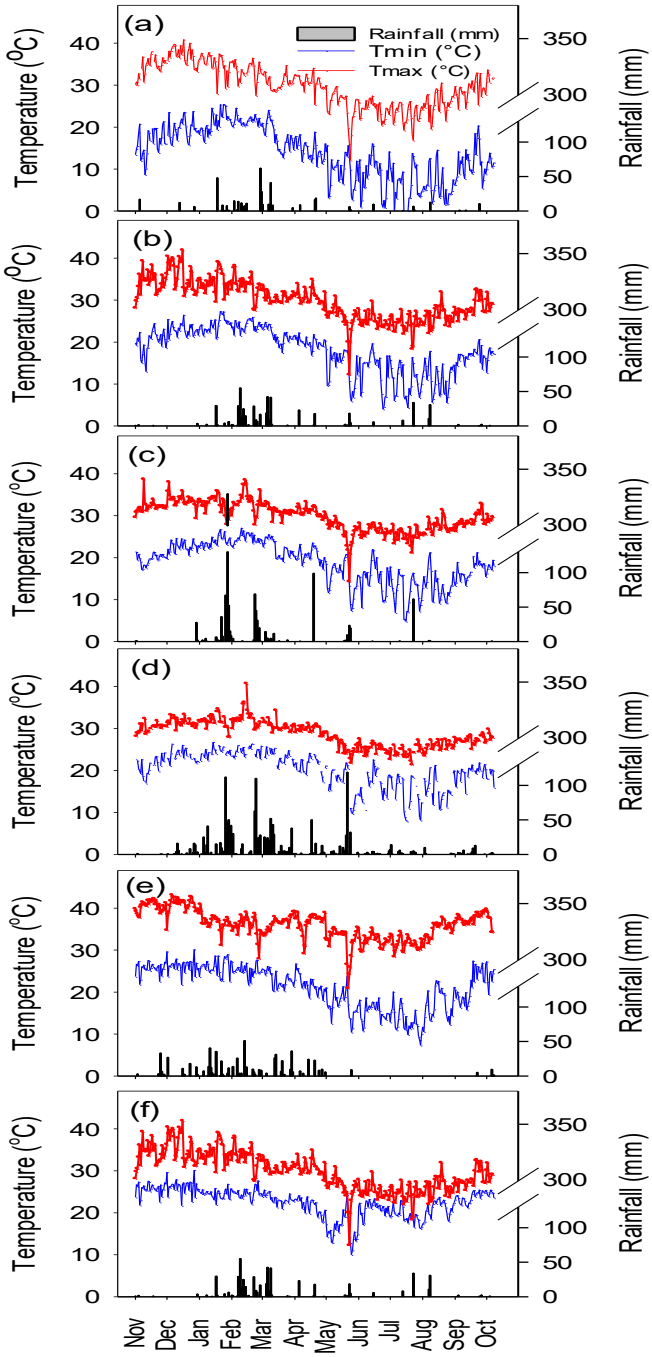


Figure 2. Daily minimum and maximum temperatures and rainfall were recorded over the fennel growing season at a) Biloela, b) Rockhampton, c) Ayr, d) Tully, e) Katherine and f) Darwin.

As the crop duration was longer, the crop reproductive stage extended to cooler weather (minimum temperature as low as 0-5 °C) in Biloela and Rockhampton (Figure 2). Low in-crop rainfall was recorded for Biloela (405 mm), Rockhampton (454 mm) and Katherine (540 mm) but higher for Ayr (990 mm). The crop was mostly rainfed, but supplementary strategic irrigation was applied to minimise the water stress during dry spells. All trial sites had drip irrigation set up for strategic irrigation.

The soil moisture was also recorded at 0-20cm depths from surface using the Campbell Scientific soil moisture sensors (Hydrosens) and irrigation commenced once the refill point for the soil was reached. The number of irrigation treatments applied varied from site to site. For example, Katherine had a total of 105 hours of supplemental irrigation over the crop growth period delivering 1,050 mm of irrigation water, whereas Rockhampton had only 64 hours of irrigation delivering 640 mm irrigation water over the growing period.

Crop phenology

The fennel seeds were planted at varying dates during the summer season of 2019-2020 (Figure 3). The emergence was as early as nine days in Katherine and 10-12 days for other sites. The duration from emergence to flowering ranged from 86 days (Ayr) to 98 days (Biloela). The flowering to maturity commenced from 81 days (Rockhampton) to 141 days (Biloela). The crop maturity and harvest commenced from 194-255 days after planting.

The sites were harvested manually after crop maturity. The crop at Rockhampton and Ayr were harvested over two occasions due to staggered maturity, whereas the crops at Biloela and Katherine were harvested completely on single harvest. In Biloela, the harvesting of two blocks was delayed by one week due to harvesting logistics. Fennel seeds remained intact in the umbels, therefore, seed loss due to over-ripening/shattering was not noticed as an issue for seed loss during hand harvest.

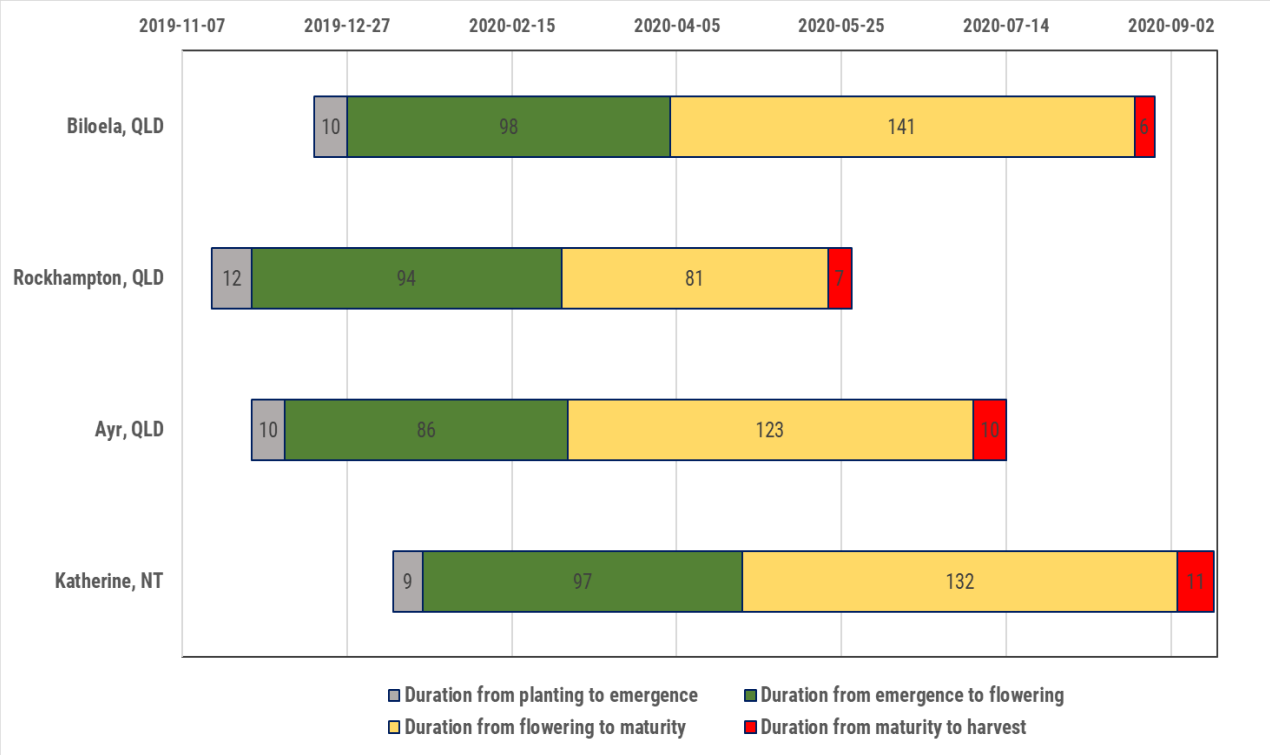


Figure 3. The growing season of fennel seeds from planting to harvest at the four trial locations.

Additional informal observation plots were planted during winter season at Rockhampton (2020/05/27 - 2020/11/15) and Tully (2020/06/15 – 2020/10/25) to assess the performance of fennel as a winter planted crop. Seedling emergence improved significantly for winter planted fennel and similarly the phenology of the winter-planted fennel was different in terms of the duration of each phenological

stage, with signs of early flowering and maturity compared to the summer planted fennel. Based on these observations, the verification trials for 2020 were planted as winter season crop at Ayr. Results of the fennel winter planting verification trial is presented in the following section.

The picture below showing the different growth stages of fennel crop (Figure 4) is indicative of fennel crop development in different sites. However, crop establishment at Tully and Coastal Plain Darwin was poor potentially caused by high soil temperature during germination and seedling establishment. Additionally, there was significant wind damage to the summer crops at flowering and seed setting stage in Darwin. Therefore, the results on crop performance are presented only for four sites: Biloela, Rockhampton, and Ayr, Qld, and Katherine, NT.

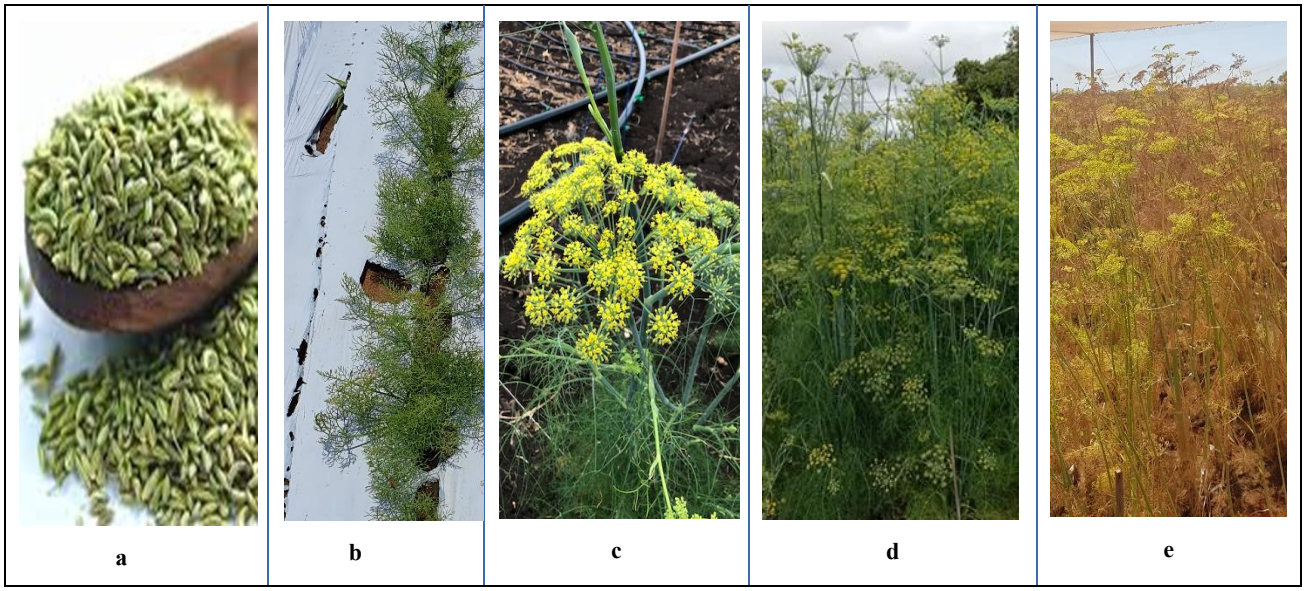


Figure 4. The growth stages of the fennel crop: a. seeds, b. seedling establishment and vegetative growth at one month, c. vegetative growth transiting to budding and flowering (2-3 months), d. flowering to seed set and seed growth and e. seed filling, seed maturation and umbel drying ready for harvest. (Pictures: S. Bhattarai)

Plant height and height to first umbel

The plant height at harvest ranged from 95-193 cm between the sites and 132-134 cm between the varieties, suggesting not significant different between the varieties in all sites except Rockhampton where AVTFS#2 showed shorter (124 cm), ATFS # 1 as medium (129 cm) and AVTFS #3 as taller (146 cm) plant height (Table 9). The greater plant height in Biloela could be associated with the impact of hailstorms on the crop promoting auxiliary shoot growth, and the low growth in Ayr could be due to sandy loam soil with limited water holding capacity, that could cause frequent mild water stress between irrigation events.

Table 9. Plant height at harvest (cm) of three fennel varieties planted at different locations in QLD and NT during 2019-20 cropping season

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	189	129	98	120	134
AVTFS #2	184	124	93	126	132
AVTFS #3	178	146	89	119	133
Mean	183	132	95	122	133
P value	0.516	<0.001	0.289	0.642	
LSD	20.44	3.614	15.11	16.46	

The height at the first umbel position in stem from the ground ranged from 38 - 106 cm between the sites and 68 - 74 cm between the varieties, with significant difference between varieties in Rockhampton and Ayr only (Table 10).

Table 10. Height at first umbel position (cm) of three fennel varieties planted at different locations in QLD and NT during 2019-20 cropping season

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	90	45	42	102	70
AVTFS #2	105	42	38	109	74
AVTFS #3	89	48	29	105	68
Mean	95	44	38	106	71
P value	0.307	0.002	0.005	0.346	
LSD	23.94	4.251	7.18	10.59	

Yield

Seed yield

Fennel seed yield ranged from 366 to 1,056 kg/ha across the four sites, and 647 to 1013 kg/ha between three varieties. The greatest mean seed yield was recorded in Ayr, followed by Katherine and Rockhampton, whereas the lowest yield (366 kg/ha) was recorded in Biloela. The seed yield between the varieties varied significantly only at Ayr, where highest seed yield was recorded for AVTFS#1, followed by AVTFS#2, and lowest for AVTFS#3 (Table 11). The crop at Biloela was also impacted by hailstorms which occurred at the flowering stage, causing the delayed maturity and development of additional shoots on the main stems.

Table 11. Seed yield (kg/ha) of three fennel varieties planted at different locations in QLD and NT during 2019-20 cropping season

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS#1	305	959	1574	1213	1013
AVTFS#2	373	521	996	1052	736
AVTFS#3	420	1212	50	904	647
Mean	366	880	1131	1056	858
P value	0.678	0.194	0.002	0.458	
LSD	282.6	1001.0	296.1	520.5	

Biomass yield

The fennel biomass yield across four test sites ranged from 4,092 to 9,366 kg/ha (Table 12).

Table 12. Dry biomass yield (kg/ha) of three fennel varieties planted at different locations in Qld and the NT during 2019-20 cropping season

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	5368	9497	5318	5142	6331
AVTFS #2	5135	8604	3885	4350	5494
AVTFS #3	5618	9997	525	3759	4975
Mean	5374	9366	4092	4417	5812
P value	0.949	0.432	0.001	0.136	
LSD	3249.6	3383.85	985.4	1388.5	

The higher biomass yield was recorded in Rockhampton (9,366 kg/ha), followed by Biloela (5,374 kg/ha) and the lower biomass yields were recorded at Katherine (4,417 kg/ha) and Ayr (4,092 kg/ha). The biomass yields between the varieties varied significantly only in Ayr, with highest yield recorded for AVTFS#1, followed by AVTFS#2 and lowest biomass yield for AVTFS#3 (Table 12).

Yield Attributing Characteristics

Harvest index

The mean harvest index (defined as the ratio of seed weight to the total above-ground biomass including seeds) ranged from 0.064 to 0.267 between four test sites, with a large difference noted between sites. The highest harvest index was recorded in Rockhampton followed by Katherine and Ayr, and the lowest in Biloela (Table 13). The harvest index did not vary significantly between the varieties at any sites (Table 13).

Table 13. The harvest index for three fennel varieties across four growing environments in Northern Australia

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	0.055	0.395	0.219	0.188	0.214
AVTFS #2	0.066	0.248	0.177	0.192	0.171
AVTFS #2	0.070	0.098	0.102	0.189	0.115
Mean	0.064	0.267	0.186	0.190	0.177
P value	0.694	0.141	0.032	0.992	
LSD	0.036	0.429	0.085	0.067	

Plant density at harvest

Mean plant density at harvest across four test sites ranged from 3.2 to 15.1 plants/m^2. The highest plant density was recorded in Rockhampton followed by Ayr, Katherine and lowest in Biloela (Table 14). Plant density in all sites was typically lower than the desired plant population of 30 plants/m^2. Plant density did not vary significantly between the genotypes in any tested sites except for Ayr where AVTFS#3 recorded significantly lower density than AVTFS#1 and AVTFS#2.

Table 14. The plant density (the number of plants per square meter of land) at harvest

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	3.2	17.4	20.7	15.3	14
AVTFS #2	3.2	15.8	15.3	11.5	11
AVTFS #3	3.3	21.3	1.4	13.3	10
Mean	3.2	17.9	15.1	13.4	12
P value	0.917	0.251	<0.001	0.259	
LSD	1.493	12.93	7.08	4.723	

Number of umbels per plant

The mean number of harvested umbels per plant across four test sites ranged from 7 to 66 umbels/plant. Umbel count per plant averaged over varieties was highest in Biloela (66/plant), followed lower counts for Rockhampton (9/plant), Ayr (8/plants) and Katherine (7/plants). Umbel count between varieties varied significantly only at Ayr but not at the other three sites (Table 15). At Ayr, the

higher number of umbels per plant was recorded for AVTFS#3 (11/plant), compared to AVTFS #1 (8/plant), and AVTFS#2 (6/plant).

Table 15. The number of harvested umbels per plant

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	52	10	8	8	20
AVTFS #2	79	7	6	7	25
AVTFS #3	66	9	11	6	23
Mean	66	9	8	7	23
P value	0.353	0.200	0.004	0.743	
LSD	39.03	4.203	1.88	4.756	

Seed Quality Parameters

Analysis of seeds for their physical qualities (1000 seed wt, seed density, seed shape and size) were assessed as a measure of seed quality parameters (Table 16).

1000 seed weight (g) - Test weight

The mean test weight (g) ranged from 2.81 to 4.34 g (Table 16) between the sites. The 1000 seed weight was higher for Katherine (4.34 g) and Ayr (4.0 g), compared to Rockhampton (2.83 g) and Biloela (2.81 g). The varietal differences for 1000 seed weight was statistically significant only at Ayr (p=0.003), with the highest weights of 1000 seeds recorded for AVTFS#3, followed by AVTFS#2 and lowest for AVTFS#1 (Table 16).

Table 16. The test weight (grams) of 1000 seeds

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	2.69	2.89	3.63	4.12	3.33
AVTFS #2	2.75	2.76	4.04	4.28	3.46
AVTFS #3	2.99	2.83	5.16	4.63	3.90
Mean	**2.81**	**2.83**	**4.00**	**4.34**	3.50
P value	0.671	0.812	**0.003**	0.082	
LSD	0.768	0.808	0.761	0.459	

Seed bulk density (kg/m^3)

The mean seed bulk density (kg/m^3) ranged from 337 to 402 kg/m^3 between the sites (Table 17). The highest seed bulk densities were recorded in Ayr (402 kg/m^3), followed by Rockhampton (388kg/m^3), Katherine (387kg/m^3) and the lowest was in Biloela (337kg/m^3). The seed bulk density between the varieties varied significantly only in Ayr (P=<0.001), where the highest seed bulk densities were recorded for AVTFS#2 (406 kg/m^3) and AVTFS#1 (402 kg/m^3) compared to AVTFS#3 (Table 17).

Table 17. The bulk density of fennel seeds from trial harvest (kg/m^3)

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	356	405	402	391	389
AVTFS #2	337	323	406	382	362
AVTFS #3	318	425	379	388	378
Mean	**337**	**388**	**402**	**387**	379
P value	0.093	0.131	**<0.001**	0.417	
LSD	34.07	150.5	13.17	13.53	

Seed shape and size (mm)

The seed shape and size for the three genotypes produced from the four trial locations are presented in Figure 5. The seed length ranged from 7-11 mm and the seed width ranged from 2-4 mm. The seed colour ranged from green to brown.

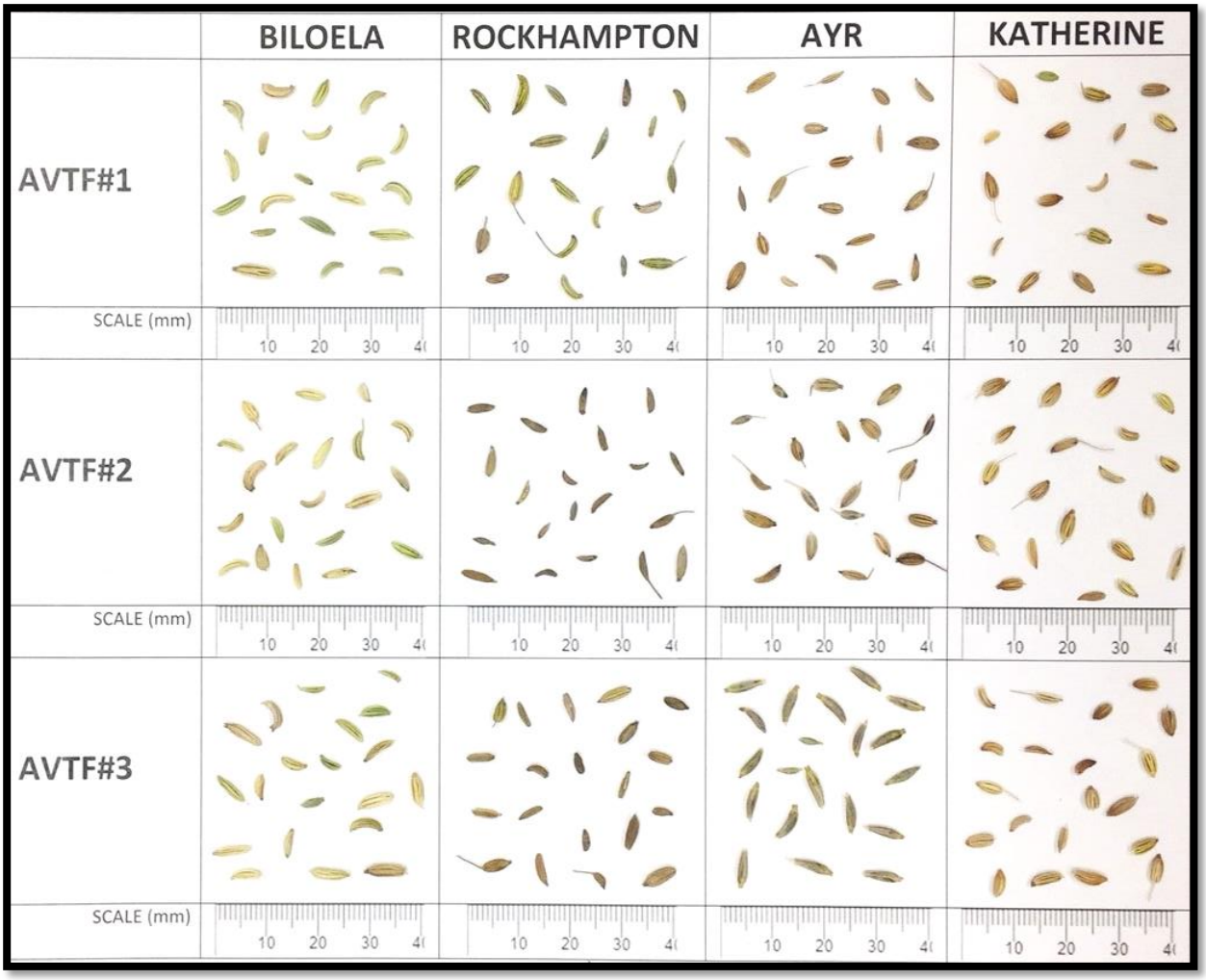


Figure 5. The seed size and colour of the fennel seed by site and variety (Image. T. Trotter).

4.2.3 Discussions

Yield associated with varieties across the northern Australia

The results from the first year of the multi-location field trials suggest that fennel varietal performance varied significantly across different locations. However, in general, the seed yield between the varieties was significantly different only at Ayr where variety AVFS#1 significantly out yielded variety AVTFS #2 and AVTFS#3. A higher seed yield for AVTFS#1 compared to AVFS#2 and AVFS#3 was also observed at Katherine (Figure 6). In other sites, the yield difference between varieties and not significantly different and AVTFS#1 was comparable to AVTFs#2 and AVTFS#3.

The average yield was high in Ayr (1,131 kg/ha), followed by Katherine (1,056 kg/ha) compared to a lower yield in Rockhampton (880 kg/ha), and lowest in Biloela (366 kg/ha). Significantly higher yields were found in North Queensland and the NT when compared with Central QLD, but these yields are still lower than the national average yield recorded (1,558 kg/ha) for India (Lal et al., 2020).

The combined analysis for the seed yield for genotype x environmental interaction suggests that the performances of the genotypes are not consistent across sites. The genotype AVTFS#3 was the lowest performer in Ayr whereas it was the best performer in Rockhampton. The performance of genotypes AVTFS#1 was reasonably consistent across Qld and the NT locations (Figure 6).

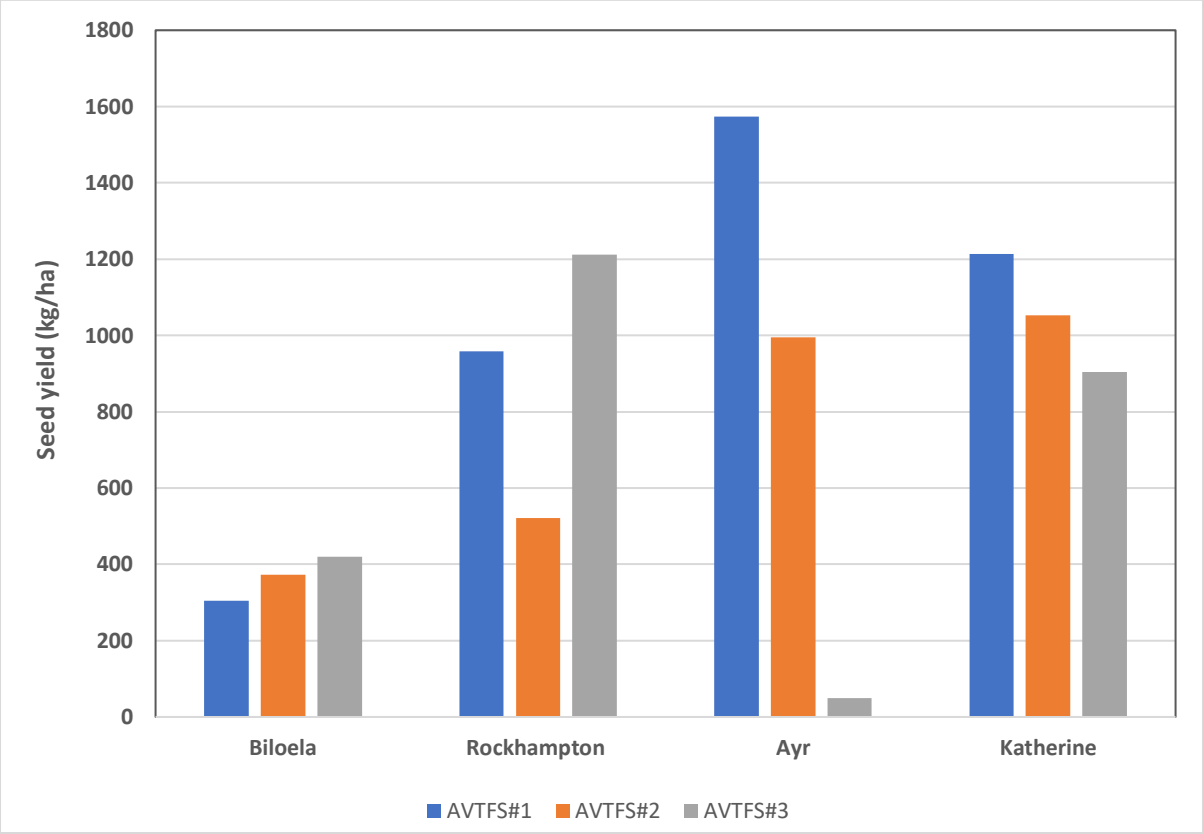


Figure 6. The genotypes x location (environment) interaction for seed yield (kg/ha) for three fennel genotypes tested over four different production environments across Qld and the NT

The analysis of seed yield and the seed quality traits - e.g., test weight referred to as 1000 seeds weight (gram) and seed weight density - did not show strong correlations. The correlation coefficient for the seed yield to 1000 seed weight was 0.077 and the yield to seed density was 0.298 only suggesting very weak correlations between these parameters (Figure 7).

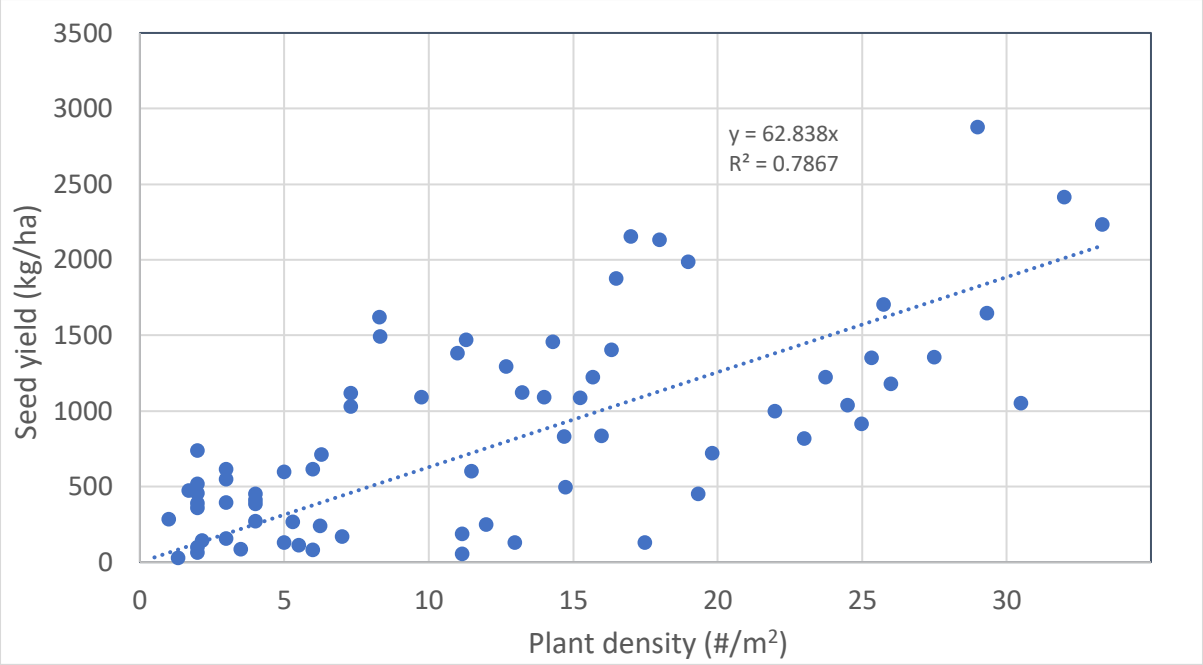


Figure 7. The relationship between the seed yield (kg/ha) to the plant density (number of plants per meter square) for three fennel genotypes tested over four different production environments across QLD and NT

The correlation between the plant population and seed yield, however, was significantly and positively correlated (0.690) and the relationship was linear (y= 62.838X) suggesting that seed yield increased with increasing plant population density at harvest (Figure 7). The lowest plant density at harvest (3.2 plants/m^2) were recorded in Biloela (Figure 7) largely due to poor emergence and the hailstorm damage to the crop.

Scope for yield improvements

The initial varietal evaluation demonstrated the potential of growing fennel seeds in Northern Australia as the hand-harvested yield for fennel variety AVTFS#1 at Ayr reached as high as 1.5 t/ha. The results from scoping study raised growers' interests for further evaluation of fennel as a new alternative crop for verification trials under farmer management in the 2021 season.

One of the major challenges for fennel production observed for summer planting was related to poor seedling establishment, as reflected by the very low plant population density at harvest for summer-planted crops across all the trial sites. This led to a consideration of planting fennel as a winter crop in the tropics through the verification trials. The slow establishment of the seedlings was also conducive for weed pressure at the early establishment stage of the crop.

The weed control for the trial crop was managed manually without herbicides in most of the sites except Katherine Research Station (KRS) where a pre-emergent herbicide option was adopted. The multi-location trial crops were planted in plots with various cropping histories - the crop at Biloela was planted in the plot following the crop of winter barely for hay ; the crop at Rockhampton was planted in a rainfed cotton farming system; and the crop at Ayr was planted in a plot following melon/pumpkin under plastic mulch and trickle irrigation; the crop at Tully was planted in the sugarcane-fennel farming system; and, the crop at Katherine was planted on a grain-based farming system with the previous crop of sorghum. The weed control was generally effective across all the trial sites, and crop was irrigated strategically using drip irrigation set up for trial plots, when soil moisture at the root zone reached refill. The fertiliser application rate across the sites was consistent, therefore, the response to the fennel seed yield is largely associated with the climatic conditions of the individual sites and the effects of the trial varieties.

The fennel seeds were less prone to shattering at maturity, hence it is expected to incur low harvest losses under mechanical harvesting. Therefore, the hand-harvested yields reported here can be considered somewhat reflective of a commercial header harvest under broadacre cropping.

Three important aspects that future trials need to consider are related to determining the optimum time of planting, weed control, and optimising the plant density. A parallel observation trial on winter planted fennel crops will bring information to growers for adapting fennel to winter cropping systems.

Further, the potential for fennel as a high-value crop in Northern Australian conditions can only be realised through optimisation of the time of seeding for different locations, and agronomy research for determining the optimum conditions for early establishment, planting density, effective weed control, management of insects/pests and diseases, and adoption of postharvest technologies for seed cleaning, grading and sorting. Additionally, the crop will need to be adapted for mechanical harvesting equipment with a focus on the of synchronization of maturity so that the crop harvest can be completed efficiently with less harvest losses.

The field trials were conducted in small plots, managed by manual operations for all activities, including planting, crop management and harvest. Hence, the results generated from manual operation under the small plot trials need to be taken into account for adapting the harvest data to mechanised management from seed sowing to harvesting.

4.3 Fennel Verification Trial - Winter Crop (Year 2)

The initial variety evaluation trials planted as a summer season crops during 2019-2020 showed poor establishment, longer crop duration, non-uniform maturity and low yield performance. An observation trial planted during the winter season of 2020 at Rockhampton and Tully, however, showed improved seed germination, crop establishment and homogenous crop maturity. The winter season in northern Australia remains generally warm (mean minimum above 12 °C), hence, it is unlikely that the winter-planted fennel crop would face chilling and frost injuries. A winter-planted crop also matures through the drier period (Figure 8) and finishes before the onset of the wet season in the summer, therefore, could fit within a dry window for seed maturation and harvesting, which is very important for high-quality fennel seed production.

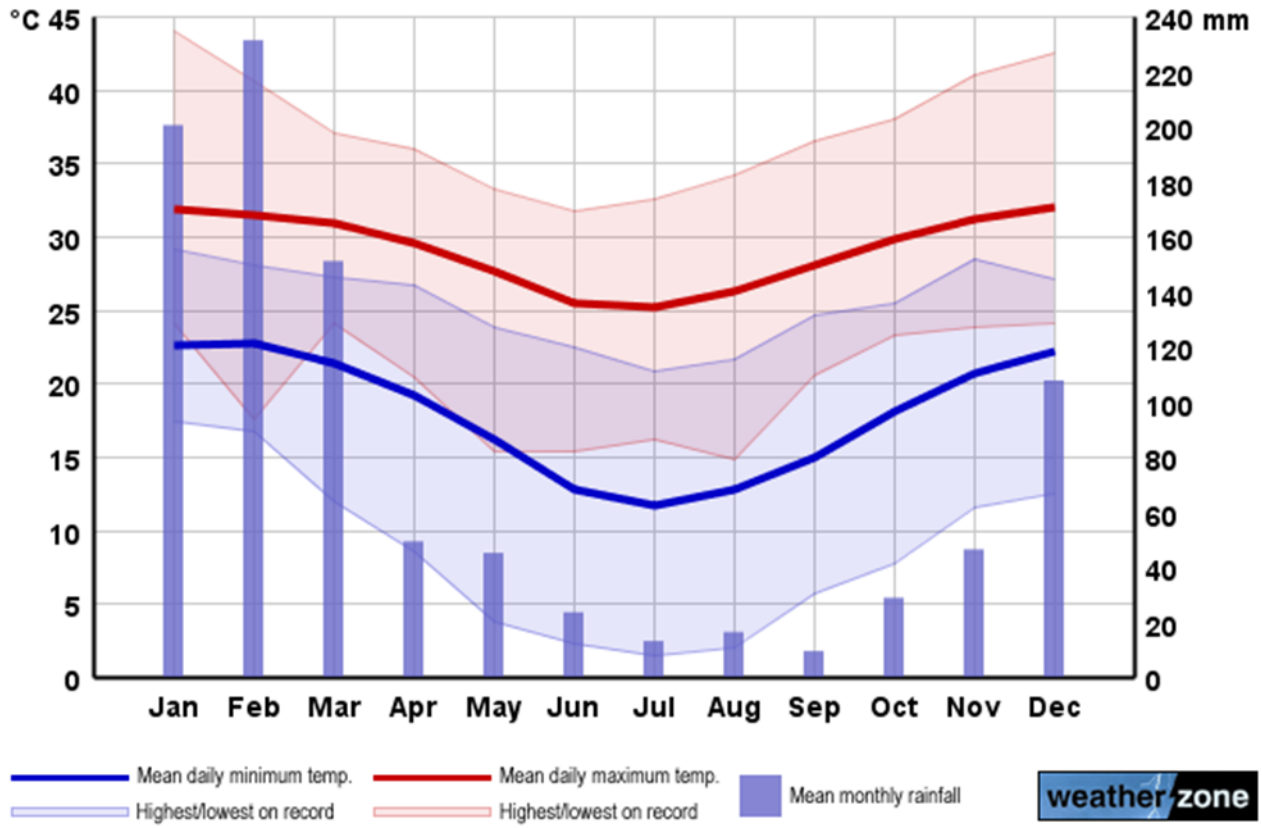


Figure 8. Longer term monthly maximum, minimum average temperature and the rainfall record for Ayr, north QLD, Australia (Source: Farm online Weather, 2022- https://www.farmonlineweather.com.au/climate/station.jsp?lt=site&lc=33002)

A large part of the Central and North Queensland regions remains frost-free and dry during winter, while wet tropic areas such as Tully provide the options for rainfed production. With the wider window for sowing during the winter season (May-July), provided greater flexibility to fit the crop for different farming systems and also produce the crop as an off-season commodity for major export markets in the Northern Hemisphere. This would also minimise the pressure on the processing, cleaning, grading facilities and supply chain during the summer months which are typically busy with grains and pulses crops processing in Northern Australia. Considering these benefits, a verification study of growing fennel as a winter season crop was evaluated at two North Queensland trial sites, Ayr and Tully presenting the dry and wet tropical environments respectively, during the second year of the project.

4.3.1 Materials and methods

The AgriVentis fennel variety AVTFS#1, selected from the initial evaluation trial in Year 2 was planted at Ayr and Tully) on 22 July 2021 and 28 July 2021 respectively. The fennel at Ayr was planted as an irrigated crop, whereas the fennel at Tully was planted as a rainfed crop, both in sugarcane-based farming system (Figure 9).

The crop at Tully did not establish well due to residual herbicide (the block was sprayed with 0.4L/ha of Implode on 23 February during the previous cane crop - Implode carries 240g/L of Imazapic). Therefore, the data for winter planted fennel crop is presented only for Ayr.

The fennel plot at Ayr was 0.261 ha with two beds (1.25 m x 700m) each accommodating two rows of fennel. The crop was planted in sugarcane fallow in well tilled and pulverised soil in raised beds using a Jang planter (Figure 9). The crop was furrow irrigated in between two beds with the irrigation water pumped directly from the Haughton River. The plot was fertilised with 350kg/ha of NITRA-KINS S of Nutrient Advantage (NKS 27.2:16.5:3.4) supplying about 95.5:59.5:10kg/ha NKS at pre-planting basal application. The ground preparation also involved weed control using herbicides for soybean volunteer plants sprayed with a mixture of 2-4D, Flagship (Fluroxypyr) and Gramoxone. The crop was directly sown into the bed with the seed rate of 4kg/ha. The crop received eight irrigations in furrows, at approximately fortnightly intervals from seeding until defoliation/desiccation. The crop was desiccated on 10 December 2021 with Glyphosate at 450g/L.



Figure 9. Winter fennel planted with Jang planter, double row configuration 50cm apart in a single sugarcane bed in Ayr, north Queensland (Picture: S. Bhattarai)

4.3.2 Results

Phenology

The crop planted on 22 July emerged after 13 days of sowing on 4 August 2021. The fennel crop established reasonably well for early canopy cover (Figure 10), particularly on the areas with precision seeding, but some missing plants in the rows are associated with inadequate control for singulation of seeds and control of planting depths by Jang planter (Figure 10), which suggest the need for optimisation of fennel planter for precision planting.



Figure 10. Early establishment of winter planted fennel showing the variable plant density, which was not due to temperature but rather the poor control of the Jang planter (Picture: A. Wessel)

The peak flowering took place on 27 September, 62 days after sowing (Figure 11) for the winter planted crop of fennel at Ayr.



Figure 11. Commencement of flowering of winter planted fennel (Picture: A. Wessel)

The crop maturity was enhanced for winter planted crop due to shorter vegetative phase compared to the crop planted in the summer season.



Figure 12. Winter planted fennel defoliated for harvesting, the crop prior to defoliation (left) and a week after the spray of defoliation treatment (right). (Picture: A. Wessel)

The sample crop was hand-harvested on 10 November and machine harvested on 23 December using a KEW research plot header, resulting into the total crop period of 154 days since sowing to the harvest.

The winter-planted crop showed positive effects of cooler weather during the vegetative growth period, resulting into shorter vegetative phase prior to flowering. The plant count at harvest was about 28 plants/m^2, equivalent to 280,000 plants per hectare. The number of shoots per plant was about 7; the distance of the lowest umbel from the ground was about 73cm, and the number of umbels per plant averaged 22 (Table 18).

Table 18. Fennel verification trial results from Ayr, north Queensland in 2021

Location	Plant count (#/m^2)	Plant height at harvest (cm)	Shoots (#/plant)	First umbel position (cm)	Umbels (#/plant)	Seed yield (kg/ha)	Biomass yield (t/ha)	HI*
Bottom of plot	34.3	131.8	7	76.2	23.9	1167	8.506	0.120
Middle of plot	25.5	134.5	7.2	73.1	23.3	1216	8.864	0.121
Top of plot	24.3	127.1	6.5	69.1	18.3	1434	10.604	0.119
Mean	28.0	131.1	6.9	72.8	21.8	1272	9.325	0.120
SE	4.16	5.23	0.56	4.22	2.81	47.07	0.32	0.002

*HI= Harvest index

Seed yield

The crop harvesting at Ayr coincided with wet weather, hence there was an effect on seed quality (Figure 13). Prolonged wet and humid conditions during harvesting did not allow for a drop in seed moisture content

to 6%. The crop was machine harvested with the KEW header. The machine harvested yield was 300 kg for the block, and clean seed recovery was 29.3%, resulting in a clean seed yield of 337 kg/ha. The header loss was informally assessed (hand harvested yield vs machine harvested yield), hence the estimate of harvest loss of 1,272 - 337= 73%. Such high loss was associated with the wet weather impact on desiccation, and postharvest deterioration of the seeds (due to high moisture) before seed cleaning and grading took place. According to the operator of the header, the crop was not challenging to harvest using the research plot harvester. The dry biomass weight of fennel was 9,325 kg/ha with the harvest index of the crop about 0.12. The biomass to seed ratio was about 8 times in those hand harvested samples (Table 12).



Figure 13. Winter planted fennel crop nearing the harvest as of 30 Nov 2021 at Ayr showing unsynchronised maturity of the umbels impacting seed quality at harvest (Picture: A. Wessel)

4.3.3 Discussion

Formal publication related to commercial fennel seed production research in Australia are scanty, therefore, this report presents results from the first trial of winter-planted fennel in northern Australia. The emergence and crop establishment improved for winter-planted fennel in 2020 compared to summer-planted fennel in 2019. However, the uniformity of the plant population across the paddock was still not achieved due to the

weak singulation, inconsistent precision spacing and inadequate control of depths by the Jang plot planter. Improvement in the planting technology for the control of depth, spacing and singulation of the fennel seeds will be important for improving the early and uniform establishment of the crop in the future commercial trials.

The crop was planted in a weed-free bed, however, weed competition visibly impacted crop growth. Manual weed chipping was carried out by the grower, particularly during the early establishment stage till the flowering period. A suite of pre- and post-emergent herbicides and weed control options will need to be developed for effective weed management for fennel production in the tropics. There is very limited chemical weed control options registered for fennel production, and this needs to be updated for weed control advice to growers for commercial fennel production in tropics.

Regarding the insects/pests and diseases challenges, the crop in general recorded low pests and diseases issues, however, the infestations of aphids in fennel were quite severe and the crop required targeted insecticide application (Lorsban 500 EC sprayed on 16 October 2021). Without control of aphids the crop would have been at great risk of significant damage. The insect/pests and disease pressures in general were lower for the winter-planted crop compared with the summer-planted crop in the same area. The low disease and pest incidence could also be due to a lack of inoculum from previous and surrounding crops, as there were no other fennel crops in the vicinity, and it was also the first season of fennel growing at scale in this locality (Ayr).

Winter planted fennel showed some promising results in terms of control of vegetive growth due to shorter vegetative period (early flowering), and shorter reproductive phase, that both positively contributed synchronous yield formation, as well as ease of harvest by the header. The perennial growth pattern (longer vegetative phase) of fennel under high temperatures and longer day conditions, similar to summer planted crop, has been reported earlier (Wisconsin Horticulture, 2023), as plant grown in short day conditions resulted into lower first flowering-node position and shorter plant height. In the verification trial, the crop maturity was also enhanced for the winter planted crop as the temperature sharply increased in October-November after the flowering and commencement of seed setting in September.

The crop was desiccated with glyphosate at physiological maturity (Figure 12) to ease the harvesting by machine (Figure 13). However, the harvesting time coincided with wet weather conditions, caused significantly higher seed moisture contents and delayed drying out of biomass. The harvest loss by machine, as estimated by the difference between the hand harvested yield and the header yield, was large. The clean seed recovery after harvest by header was only 30%, therefore, as much as 70% of the seeds was lost in the process of machine harvesting compared to the hand harvested yield. The trial results suggest that pre-harvest crop management, particularly the desiccation and optimisation of header operation could significantly reduce the large harvesting loss in fennel. Effective and efficient harvesting is highly essential for broadacre fennel farming and it is strong determinants for improving the gross margin of fennel production by the growers.

4.4 Fennel Commercial Crop Trials 2022 (Year 3)

The fennel variety verification trial, planted during Year 2 of the project at Ayr showed potential yield of up to 1.3 t/ha (hand harvest) and the option of growing fennel as a winter season crop for northern Australia. Winter planting in Year 2 also highlighted scope for integrating fennel crop into wider range of farming systems. The major challenges for potential scaling up for commercial production, however, are related to providing complete mechanisation of fennel cropping, ensuring crop establishment, control of insects/pests (primarily aphids), minimising harvest loss by a conventional grain harvester, and developing post-harvest management, particularly for the control of seed moisture after harvest and post-harvest cleaning, grading and seed sorting.

Growers interest for the commercial crop trial for Year 3 was raised from grower partners, hence the commercial crop trial was planned for Rockhampton to grow trial crop during the winter 2022. The 2022 winter season was representative of the long-term average for the temperature and rainfall (Figure 14). The crop was planted using a Monosem precision planter and a research plot harvester (Zurn 150) was used for harvesting after crop desiccation. The research results particularly the yield , seed quality and crop fit into the farming system, achieved in this trial in 2022 from commercial crop trial will inform the larger scale commercial contractual production of fennel seed for the seed companies (AgriVentis Tech Ltd.) for fennel variety AVTFS#1. As this trial used the foundation seeds for one of the high yielding varieties (AVTFS#1), the seed harvested from this trial site will be used as a seed supply for future trial works for the commercial fennel production in Northern Australia, hence the trial is also paving the way for commercialisation.

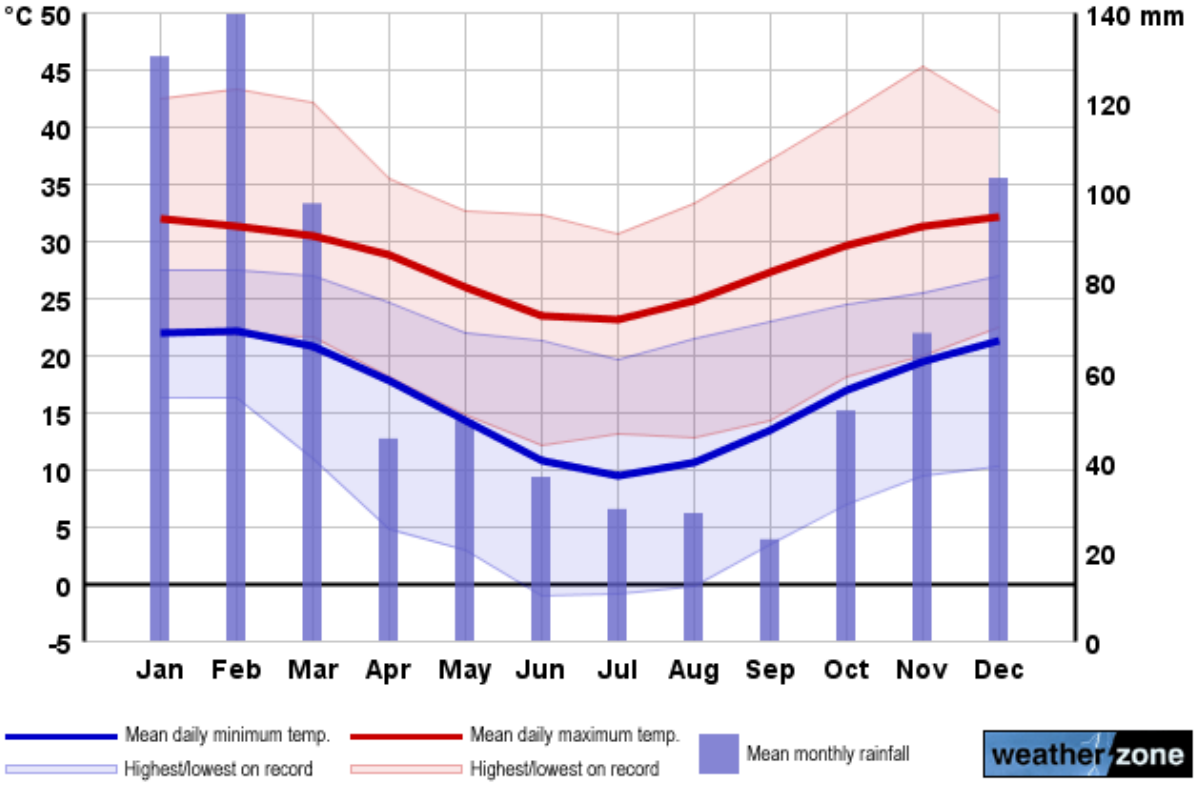


Figure 14. Longer term monthly maximum, minimum average temperature and the rainfall record for Ayr, north QLD, Australia. (Source: Farm online Weather, 2022- https://www.farmonlineweather.com.au/climate/station.jsp?lt=site&lc=39083)

4.4.1 Materials and methods

The AgriVentis fennel variety AVTFS#1 selected from the initial evaluation trial in the first year, and varietal verification trial in the second year of the project was planted in Rockhampton on 6 May 2022 following a summer cotton crop. The fennel crop was provided with supplementary irrigation using a temporary drip irrigation set up. Fennel was also sown in Tully in winter 2022, however due to an unusually wet winter the

crop establishment was extremely poor, and the crop failed. Therefore, the data for the winter planted fennel commercial trials is presented only for Rockhampton.

The fennel trial plot at Rockhampton consisted of a small block (0.021 ha) with three beds (1 m x 70 m) each accommodating four rows of fennel. The crop management followed full mechanisation (seed sowing to harvest), that allow translation of the results to larger scale commercial production in the following years. The crop was planted in the cotton fallow system in well tilled and pulverised soil in flat beds using monosem precision planter (Figure 15). The crop was irrigated by drip irrigation following seeding with moisture applied at the root zone to refill point for the heavy clay soil. The plot was fertilised with Incitec Pivot cotton blend fertiliser (NPKS 15:4:11:14) at 400kg/ha, supplying about 60:16:44:56 kg/ha NKS at pre-planting, all as basal application into the soil underneath the plant rows. The ground preparation involved clean cultivation with tillage without using herbicides. The crop was directly sown in the bed at a seed rate of 4kg/ha under a conventional tillage system. The crop received seven irrigations by drip lines, at approximately fortnightly intervals from seed sowing until defoliation/desiccation.



Figure 15. Monosem seed planter for planting fennel seeds under different soil conditions (Picture: P. Foxwell)

Weed control in the crop was performed manually by interrow cultivation and hand chipping over 2-3 occasions during the crop period. The crop was desiccated on 14 Nov 2021 with Glyphosate at 450g/L and harvested using the Zurn 150 research plot combine harvester, on 205 days after sowing, on 27 November 2022 (Figure 16).



Figure 16. New Zurn 150 research plot harvester used for harvesting of Fennel seed in the trial (Picture: P. Foxwell)

4.4.2 Results

Crop establishment, even after using the Monosem precision planter, was patchy (Figure 17). This was due to the irregular seed shape interfering with the singulation by the monosem seed plate. The crop emergence for fennel was slower (12-16 days of sowing) compared to other winter crops, such as Fenugreek (6-8 days) in the same farm.



Figure 17. Canopy cover by the fennel plant at peak flowering stage for a field trial crop in Rockhampton. Apparent patchiness was caused by poor emergence, resulting into patchy establishment (Picture: S. Bhattarai)

The crop was planted in early winter on 6 May 2022 and peak flowering of the crop commenced 91 days after sowing on 5 August 2022. The crop was ready for desiccation 190 days after sowing on 11 November 2022 and ready for harvest 205 days after sowing on 27 November 2022.

The plant population in the field was low (8-13 plants/m^2); the first umbel positions were quite high on the main stem above the ground (63-66 cm); the number of shoots per plant ranged from 6 to 8; umbels per plant averaged 10-11. The machine-harvested seed yield reached 629 kg/ha whereas hand-harvested seed yield ranged from 816 to 956 kg/ha. The calculated machine harvest loss is about 29% of the seeds. The biomass yield of 3.3-4.7 tonnes/ha was recorded in the samples with the harvest index ranging from 0.14-0.21 (Table 19).

Table 19. Fennel phenological and reproduction growth at Rockhampton during winter 2022

Harvest method	Days to flowering	Days to harvest	Plant count (#)/m2	First umbel position (cm)	Shoots (#)/plant	Umbels (#)/plant	Seed threshed wt (g)	Seed clean (g)	Biomass (g)	Seed yield (kg/ha)	Biomass yield (t/ha)	HI
Machine harvest	*91*	*205*	*11*	*65*	*7*	*11*	*16500*	*13200*		**629**		
Hand harvest 1	*91*	*205*	*8*	*66*	*8*	*11*	*122*	*95.6*	*328*	*956*	*3.280*	*0.212*
Hand harvest 2	*91*	*205*	*13*	*63*	*6*	*10*	*102*	*81.6*	*470*	*816*	*4.700*	*0.143*
Hand harvest Mean	*91*	*205*	*10.5*	*64.5*	*7*	*10.5*	*112*	*88.6*	*399*	**886**	*3.99*	*0.178*
Hand harvest SD	*0*	*0*	*3.54*	*2.12*	*1.41*	*0.71*	*14.14*	*9.90*	*100.41*	*98.99*	*1.00*	*0.049*

4.4.3 Discussion

Seed yield

The trial showed the scope of complete mechanisation of planting and harvesting of fennel seed production. However, the seed yield achieved with complete mechanisation of planting and harvesting was lower than potential yield recorded in the first year in small plot trial managed by manual operation for planting and harvesting. The yield gap between the manually managed crop and mechanically managed crop shows the opportunities for optimisation of mechanical operations. Large yield gaps (potential yield vs harvested yield) in other food crops are also frequently reported, and crop specific input management options (agronomic interventions) are recommended for closing such yield gaps in broadacre crops (Pradhan et al., 2015).

Improving crop establishment by the control of depth and singulation of seeds improved by the Monosem seed planter (Figure 15) compared to the small Jang planter used in the previous season for verification trials. However, clogging of the seed plate orifice was noticed due to irregular seed shape and small awing in the seed. Completely clean seeds and the use of a pressurised air nozzle to unblock the clogged orifice were practised to keep the planter in the correct working conditions. Seed plates more suited to fennel type of seeds, use of knocker assisted seed plates (as present in the John Deere MaxEmerge ™ planter), fine tilth seed bed preparation, and wheel press to ensure strong seed-soil contacts in moist soil are recommended (https://www.youtube.com/watch?v=dSQ3Uc0cJ14). Conventional plate planters can provide good seed distribution by correct planter plates, properly sized seed and proper seed knockers. Different options of grain drills and air seeders may be used for seeding, although uniform depth of planting and seed spacing may be a problem unless proper adjustments and modifications (NDSU, 2007) that are particularly suitable for sesame seeds are adapted for soil types and soil moisture situation at the time of sowing.

The machine harvesting with a combined plot harvester was not fully efficient due to incomplete separation of umbels and seeds from plant, as there was some harvest loss due to seed still intact with biomass at thresher end, needing further optimisation of harvester for fennel. Furthermore, the seed yield was also low due to the non-uniform maturity of the umbels in the plants (similar to Figure 13) and highly variable umbel size at harvest, needing better preparation of plants with effective desiccation options.

Biomass for oil extraction

Fennel produced large amounts of biomass, with maximum biomass recorded of 9.9 t/ha in the initial evaluation trial, provides opportunities for value added products, e.g., essential oils from the downgraded seed and biomass.



Essential oils can be extracted from fennel seeds, green and dry biomass (Saxena, et al., 2018), which could bring new economic opportunities for fennel producers for value-adding after seed harvest. The extraction of essential oil can be undertaken on an industrial scale, with the oil obtained via steam distillation of fresh herbage or from fennel seeds. The essential oil contents in the fennel herbage can be in the range of 0.05-0.7%. Therefore, the large quantity of herbage biomass that the crop can produce, can also potentially be utilised to produce essential oil. For example, 9.9 tonnes of herbage biomass at 0.5% essential oil content may produce about 50 litres of essential oil per hectare.

Biomass for value added products

Fennel produces prominent hollow stems and shoots with strong elongated fibrous cells that can be well utilised to produce drinking straws. The rampant use of plastic straws and their negative impact on the environment and wildlife, has led to the complete ban on the use of plastic straws in the EU by 2021. This could lead to a market for alternative natural products and bring a new opportunity for fennel biomass to be used to produce bio-based drinking straws. With a planting density of 250,000 plants per ha, and 4-5 prominent internodes per plant, there could be an opportunity to produce about a million straws ($10,000 with price of one straw at 1 cent) from one hectare of crop biomass after the harvest of seeds (Figure 18).



Figure 18. The fennel plants have a distinct hollow stem that provides materials suitable for drink straw (right). The photo of the field crop harvested from Biloela in 2020 shown (Picture: S. Bhattarai)

Fennel fibre from biomass for high value moulded products

There is increasing market interest in using natural fibres for high-value moulded products such as greeting cards, fragrant bags, cardboards etc. Preliminary discussions with biomass processing industries, such as Papyrus Australia (www.papyrusaustralia.com.au) have revealed a potential opportunity for the use of fennel biomass for fibre-moulded products.

Biomass for feed values

Seed type fennel has deep rap roots, enabling the extraction of soil moisture from the depth. In Biloela, a ratoon fennel crop attained height up to 1m and a sizable biomass within five weeks of the first harvest. Similar regrowth after harvest was also noticed in all other sites. The ability for fennel to regenerate quickly could provide the option for ratooning the crop for seed harvest, biomass for essential oil extraction or livestock forage. Further research would be required to assess the cost: benefit of this approach and how it may be incorporated into crop rotations (Figure 19).



Figure 19. Fennel regrowth after harvest at Biloela (Image. S. Bhattarai)

Fennel regrowth five weeks after harvest without any irrigation during the dry season at Biloela shows the potential for ratoon production.

5. WEEDS, PESTS, DISEASES & POST-HARVEST CHALLENGES

5.1 Post-Harvest Challenges

Fennel seed needs to be harvested at a low moisture content (8-10%). High moisture contents cause rapid deterioration of the fennel seed quality. Achieving the desired level of moisture content in the seed at harvest is a major challenge for growers. The crop harvest period needs to be dry to achieve such low seed moisture contents. The amount of biomass contents with seeds at harvest, and moisture contents of the biomass also influences the seed moisture content, hence, complete defoliation and effective desiccation is suggested prior to harvesting for achieving dry seeds at harvest.

The fennel market also demands very high seed purity - for example, USA fennel seed quality specifications requires purity of 99-99.95%, admixture 1-0.05%, machine, or colour sortex clean and moisture 8%, while Singapore quality specifications include purity 96-99.95%, admixture 4-0.04%, machine or colour sortex cleaned and moisture content of 8%. The quality specification varies with importing countries (https://virdhara.com/spices-oilseeds/spice/wholespices/fennel-seeds-exporter-india/fennel-seeds-usa-quality-exporter-manufacturer-prodcuer-supplier-unjha-gujarat-india-virdhara-international/).

Fennel harvested under unfavourable conditions (e.g. wet harvest, incomplete desiccation) results in significant amounts of debris in the seed lots (similar to that harvest from Ayr winter planting fennel 2021), which can create additional challenges for the seed cleaning/grading facilities. An on-farm primary seed cleaning machine (Figure 20) can reduce this burden as well as reduce the transport cost of the primary cleaned seeds from farm to the final cleaning/grading/sorting operations of seeds in pack house. Seed cleaning/grading operation, e.g., Allenden seeds (Biloela), suggested that, on-farm primary seed cleaning is essential for achieving the targets, for fine cleaning of spices seeds at the seed processing and packing operation, to meet the purity targets outlined in different quality specifications.



Figure 20. The on-farm seed cleaning machine, The VAL-1500-6 model, with the capacity of cleaning up to 25 tonnes of seed per hour (Photo: D. Frahn)

The application of mobile Grain cleaner VAL-1500-6 (Figure 20) was assessed at the grain cleaning lab facilities of Frahn Engineering, Drung, Victoria in 2021. The theory and operational procedure for the VAL-1500-6 grain cleaning equipment is summarised in box diagram (Figure 21).

Theory and procedure for operation of on-farm grain cleaning equipment, Farm VAL 1500 (Model. VAL-1500 x 6 – 2 x 3).

Theory: Precision weight and screen separation.

Design: Vertical aspiration leg 1500 mm wide, with six layers of screens, which consists of a double deck with 3 layers of screens in each deck.

Operation details:
The feed hopper is near the top of the machine at a convenient auger height.

The aspiration system has a large capacity fan with a 7.5 KW motor.

The fan will lift the dust, weed seeds, light and pinched grain. This material is collected in a cyclone.

In the bottom of the cyclone is a rotary valve which drops the material onto a tray.

This tray conveys the material to the bottom of the screening deck where it is combined with the small screening grain.

The screening deck has two electric vibrator motors with six layers of screens.

The vibrators give the deck a small orbital motion.

Under each layer of screens there is a tray which holds rubber balls.

The bouncing of these balls hits the underside of the screens removing the lodged grain in the screens.

Each layer of screens is made up of two pieces 1500 mm x 1200 mm, giving a total screen size per layer of 1500 mm wide x 2400 mm long.

By using screens with different apertures, which may be slots or round holes, it is possible to clean a large range of grains.

The screening deck can be setup with one layer of screens for scalping and two layers of screens for screening.

Another option is to have two layers of screens for scalping, and one layers of screens for screening.

The machine is transported on Tandem spring suspension.

Capacity: 6-25 tonnes/hour for larger seeds, e.g., chickpeas

It is very easy to operate, and the adjustments are simple and responsive.

Figure 21. Theory and procedure for the operation of on-farm grain cleaning equipment, VAL 1500-6-2x3 Model (Source: D. Frahn, 2022)

The lab grain cleaning equipment was setup with layers of screens for scalping and layers of screens for screening that can be applied to the mobile field grain cleaner. The setup of the screening deck with respect to the layer of screens for scalping and the layer of screens for screening in the lab cleaning machine was as follows:

Aspiration. Light materials separation.

Layer 1. Top scalper screen, 3.0 mm round hole. Coarse Scalped material.

Layer 2. Second Scalping Screen, 2.5 mm round hole. Scalp off weed seeds and large seeds.

Layer 3. Screening Screen, 1.9 mm/2.0 mm round hole. Good grain

Layer 4. Second Screen, 1.8 mm round hole. Smaller pinched seed.

Bottom Floor. Fine losses. Visual inspection for small, pinched seed and empty skins.

5.2 Results

The table below (Table 20) summarises the seed cleaning results for two small test batches (250-500 g) of uncleaned fennel seeds received directly from research plot harvester, with different scalper and screen arrangement in the laboratory seed cleaning machine (Figure 22). For the samples collected from verification trials at Ayr in 2021, the seeds needed 2 stages cleaning process in VAL. The first stage cleaning recovered 24.2% of the seeds from the grab samples of the bulk harvest (Table 20). In the second stage cleaning, the samples from first stage recovered clean seed as much as 87.2% (Table 20). On farm seed cleaning process with mobile seed cleaning system provided primary, and secondary cleaning of the fennel seeds in the field and demonstrated its utility for primary cleaning of fennel seeds.

Table 20. Test results for the fennel seeds after first and second stage cleaning in the laboratory grain cleaning equipment in Frahn Equipment seed cleaning lab, Horsham, VIC (seed received from winter planting verification trials at Ayr)

Cleaning stage	Screen types	Weight (g)	Weight (%)	Remarks
First stage cleaning				
Fennel seeds as harvested		500	100%	
Aspiration heavy materials		298	60.6%	
Aspiration light dust		30	6.1%	Machine aspiration
Scalper	Above 6.00 round hole	4	0.8%	Coarse material
Scalper	Above 3.00 round hole	25	5.1%	Large big seeds
Screen	Below 3.00 round hole above 1.38 square hole mesh	119	24.2%	Seed still contaminated
Fines	Below 1.38 square mesh	16	3.3%	Fines
Sub total		492	100.0%	
Error (moisture loss?)		8	1.60%	Inaccurate scale, moisture loss?
Repeated screening of the seed cleaned from first stage cleaning as above (table 14, row 8) for seed still contaminated)				
Second stage cleaning				
Cleaning stage	Screen types	Weight (g)	Weight (%)	Machines screen Layers
First stage clean seed		200	100%	
Aspiration			-	Aspiration. Not shown
Scalper Coarse	Above 4.00 mm Round hole screen	0	0%	Screen Layer 1. Not shown
Scalper Fine	Above 3.0 mm Round hole screen	21	10.5%	Screen Layer 2
Top screening screen	Above 2.0 mm Round Hole screen	141	70.2%	Screen Layer 3
Bottom Screening screen	Above 1.8 mm round hole screen	34	17.0%	Screen layer 4
Fines	Below 1.8 mm round hole screen	3.5	1.8%	Bottom floor
		199.5		
Notes: Machine capacity limited by the aspiration. • The Rotary valve at the bottom on the cyclone for the Aspiration will be the limiting capacity of the cleaning process. • Approximation capacity 1 – 2 TPH of harvested product				

*** Data sheet for use in optimisation of the screen and aspiration settings for the on-farm seed cleaning/grading unit*

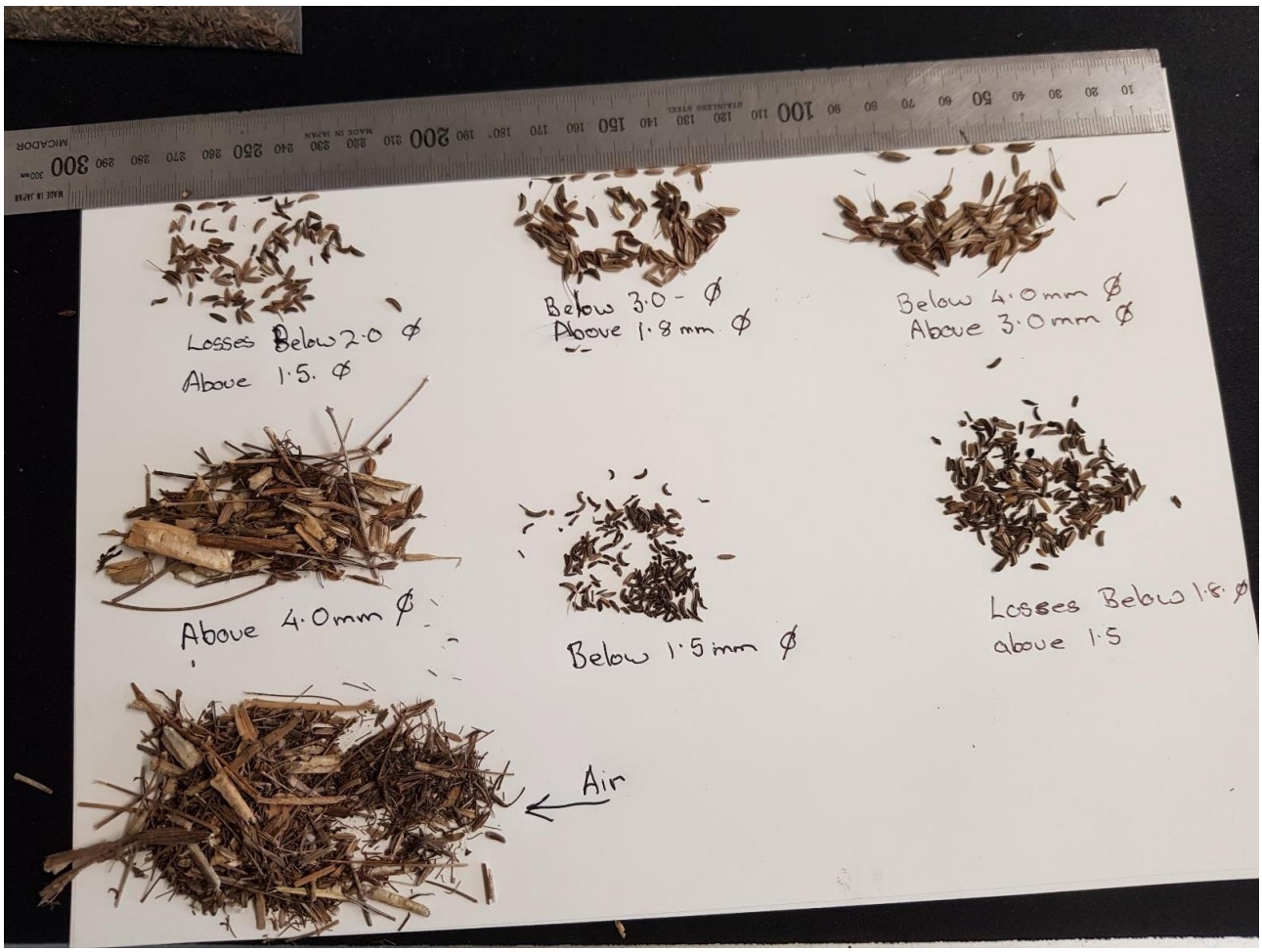


Figure 22. The fennel seed samples from the harvester header, separated into different size to remove debris (>2.4 mm), and fine debris and sub-size seed (<1.8 mm). This separation requires multiple screens combinations for the on-farm seed cleaning machine (Photo: D. Frahn)

5.3 Discussion

A pilot run of the seed cleaner using harvested seed from the KEW header showed that the recovery of clean seeds is about 29.3% (144 g from 500 g uncleaned product), (Figure 23). Very low recovery of the clean seed was due to excessive moisture and biomass debris associated with wet weather impacts on the crop at the late maturity stage and during harvesting. The trial showed that results varied according to the incoming sample quality. Optimising the screen settings improved significantly the efficiency of on-farm seed cleaning and the results.



Figure 23. Primary cleaning of fennel seeds following optimisation of screens for seed cleaning and grading in the VAL-1500-6. a. Grading seeds between 3-4 mm; b. Grading seed between 1.38-3.0 mm (Photo: D. Frahn)

The cleaned seed samples from the screens, in the primary cleaning process, will still need additional final cleaning with a Gravity Table followed by the final processing with a colour sorter. Achieving the purity targets of 99-99.95% will require these additional cleaning for meeting the market requirements linked with export standards associated with food standards for human consumption fennel seeds.

The on-farm seed cleaning machine VAL-1500 has been rated for its maximum capacity of 25 ton/hour seed cleaning. However, for the level of cleaning required for this sample of fennel seed, the machine capacity has been calculated to be 1-2 t/hr of harvested product. The greater proportion of biomass contamination reduced the efficiency of the cleaning equipment. This trial data presented here for the smaller sample run provides useful information for the users of on-farm seed cleaning machine (VAL-1500), for applying the setting of screen size and aspiration required for effective primary cleaning of fennel seeds.

The results from lab-based grain cleaning machine showed that multi-stage cleaning is required for fennel seeds that are highly biomass contaminated at harvest. The two test results presented above in Table 14 shows the clean seed recovery up to 29.3% in the first stage cleaning for the seed lot received from winter planting verification trial conducted in Ayr during the winter season of 2021. The second stage cleaning is more efficient and faster with the recovery of 96.5% clean seeds. The capacity rated on the cleaning machine are compromised when the seeds sizes are smaller and contamination levels are very high. However, the use of on-farm seed cleaning equipment run through the first and second stage seed cleaning will improve the seed presentation for on farm storage and also for the final cleaning, grading and colour sorting operations. On-farm seed cleaning are also increasingly favoured by grain industry. Using a two-stage cleaning process, Grain Cleaner designed by Farm King (https://www.burandohill.com.au/graincleaners) separate dockage, rocks and other unwanted contaminants from grain before it is shipped or stored. Cleaned grain when stored dries faster and sometimes screenings can be used as animal feed.

5.4 Insect Pests

The major insect pests noted during the fennel crop growing period includes:

- Aphid
- Thrips
- Cutworm
- Caterpillar

Meena et al. (2020), reported an infestation of thirteen insect pest species including Thrips (*Thrips tabaci*, *T. flavus* and *Scirtothrips dorsalis*), aphids (*Aphis gossypii* and *Hyadaphis coriandri*), jassids (*Empoasca kerri*), chalcid wasp (*Systole albipennis*), seed bug (*Nysius sp.*), tobacco caterpillar (*Spodoptera litura*) and grasshopper (*Acrida spp*.) as major; and whitefly (*Bemisia tabaci*), lygus bug (*Lygus sp*.), stinkbug (*Nezara viridula*), red cotton bug (*Dysdercus koenighii*), cutworm (*Agrotis spp.*) and leaf eating caterpillar (*Heliothis armigera*) as minor pests of fennel in semi-arid region of India under organic production system.

5.4.1 Crop damage by insects

Crop infestation by the aphid occurred in all trial sites. The infestation, however, was severe for the winter verifications trials at Ayr in 2021 and commercial production trial at Rockhampton in 2022. The crop was sprayed with Lorsban @ 70 ml/100 L water per hectare. The aphid infestation occurred from flowering to defoliation.

No detailed scoring for individual insect damage was carried out, therefore, the data is based on visual observations, collection of insects and crop samples and identification of the insects with the support of entomologists from NTDITT and QDAFF.

5.4.2 Beneficial insects

Several beneficial insects were identified at each of the locations, including a variety of spiders in all sites. Assassin bugs were present at Rockhampton and Ayr. Butterflies, European honeybees, and native bees were prevalent in all trial sites and were effective pollinators during flowering. Predatory shield bugs and pirate bugs were also observed at the Coastal plain research station, Darwin site. Satyagopal et al. (2014), have listed a large range of natural enemies including beneficial fennel parasitoids and predators recorded from fennel in semi-arid region of India.

Natural enemies of aphid:

- **Parasitoids:** *Lysiphlebus* sp, *Diaeretiella* sp, *Aphelinus* sp, *Aphidius colemani* etc.
- **Predators:** Ladybird beetle, lacewing, spiders, hover fly etc.

Natural enemies of thrips:

- **Parasitoid:** *Ceranisus menes*
- **Predators:** Predatory thrips, minute pirate bug, ladybird beetle, lacewing, mirid bug etc.

Natural enemies of cutworm:

- **Parasitoids:** *Trichogramma* spp., *Tetrastichus* spp., *Telenomus* spp., *Bracon* spp., *Campoletis* sp, *Chelonus* spp., *Ichneumon* spp., *Carcelia* spp. etc.
- **Predators:** Lacewing, ladybird beetle, spider, red ant, dragonfly, robber fly, reduviid bug, praying mantis, King Crow etc

Natural enemies of leaf eating caterpillar/gram pod borer:

- **Parasitoids:** *Trichogramma* spp., *Tetrastichus* spp., *Telenomus* spp, *Bracon* spp., *Campoletis* sp, *Chelonus* spp., *Ichneumon* spp., *Carcelia* spp. etc.
- **Predators:** Lacewing, ladybird beetle, spider, red ant, dragonfly, robber fly, reduviid bug, praying mantis, King crow etc.

5.4.3 Root knot nematodes

Root knot nematode (*Meloidogyne spp*) causes roots galls of up to 3.3 cm in diameter. No visible symptoms of root knot nematodes was observed in the trial plots. However, varietal difference for tolerance to nematode has been reported (Kumar et al., 2017). The three AgriVentis varieties planted in the trials were not evaluated and scored for their response to nematodes (susceptible or tolerance or resistance).

5.5 Diseases

The major diseases noted during the fennel crop growing period includes:

Cercospora leaf blight (*Cercosporidium punctum*)

Fusarium wilt (*Fusarium oxysporum*)

Powdery mildew (*Erisyphe heracleid*)

Collar rot (*Sclerotinia sclerotiorum*)

Root rot (*Rhizoctonia solani*)

Damping off (*Pythium spp*)

5.5.1 Crop damage by diseases

Disease infestation and damage was minimal in all trial sites. However, there were root rot challenges experienced at seedling establishment stage, which was a concern for all varieties. No detailed scoring for individual diseases was carried out, therefore, the data is based on visual observations of the symptoms, collection from diseased plant samples and identification of the disease by the pathology lab services of Queensland's Department of Agriculture and Fisheries and the University of Southern Queensland.

5.6 Other Challenges

5.6.1 Weather damage

Hailstorm incident during flowering stage impacted the crop in Biloela for the initial evaluation trial of fennel in 2019/2020, causing crop damage (Figure 24). The fennel at the site damaged the aerial growth of fennel plants, particularly the growing shoots tips, caused some temporary lodging, supporting the lateral g the vegetative growth and duration of the crop period. When the fennel crop did recover of hailstorm damage, the other crops (watermelon and pumpkin) in the same farm did not recover of the hailstorm damage, providing more confidence to the grower partners about crop tolerance to hailstorm damage.



Figure 24. Hailstorm damaged crop of fennel at Biloela recovered within one month (Image: S. Bhattarai)

5.6.2 Other pests (vertebrates)

The impact of birds, wallabies, and pigs were not noticed in the trial plots. However, the presence of mice was evident in Biloela. Introduction of new grain crops in northern Australian has often been challenged by these pests but fennel appeared to be largely unaffected at the early stage.

5.6.3 Weed control and herbicides residues

Weed management in fennel is one of the main production concerns for growers, as fennel especially at early establishment, has slow emergence and growth, hence a less competitive plant with weeds. Moreover, wider row spacing, and frequent use of water favours growth of weeds. Weed presence in fennel crops can reduce fennel yield and can also interfere with harvest efficiency and may cause staining of the seed coat colour reducing seed quality and market values.

To keep the field weed free for larger scale commercial production, cost effective weed control methods are required. Hand-weeding is only practical for small trials, because it is highly labour intensive, time-consuming, expensive and needs to be repeated often. However, there is only a limited number of registered herbicides for fennel production in Australia.

Further research to identify herbicides that provide broad-spectrum weed control for fennel is suggested. Fennel is a narrow leaf crop hence most of the herbicides applied to previous crops could cause residues effects. Fennel planted in a paddock with a preceding failed crop, the residual herbicides effects are more likely.

The chemicals approved by Australian Pesticides and Veterinary Medicine Authority (APVMA) with current permits for use in control of weeds in fennel farming is available at: (https://portal.apvma.gov.au/permits?p_auth=Clw0cYkv&p_p_id=permitsportlet_WAR_permitsportlet&p_p_lifecycle=1&p_p_state=normal&p_p_mode=view&p_p_col_id=column-1&p_p_col_pos=1&p_p_col_count=3&_permitsportlet_WAR_permitsportlet_javax.portlet.action=search).

These include permit 14158 which provides for the use of Metolachlor for the control of weeds in culinary herbs including fennel.

In other parts of the world commercial producers utilise pre-emergence application of Oxadiargyl @ 75g/ha or Pendimethalin @ 1.0kg/ha or Oxyflurofen @ 150g/ha along with one hand weeding and hoeing at 50DAS. At the time of application of herbicides, there must be sufficient moisture contents in the soil otherwise efficiency of herbicide is drastically reduced (Lal et. al., 2020).

6. CONCLUSIONS AND RECOMMENDATIONS

The Spicing Up Northern Australia project successfully carried out grower and industry participatory fennel varietal evaluation, verification, and commercial-scale production trials across various locations of Northern Australia over three years of the project. The major achievements of the project include a detailed assessment of the adaptability of fennel varieties across tropical Northern Australia that demonstrated the l feasibility of fennel production in North Australia. The project also established the opportunity for the fennel crop integration into existing farming systems.

Fennel as summer crop took longer maturity period (145- 255 days), and recorded max yield potential up to 1,574 kg/ha for hand harvest. The seed yield was higher in Ayr (1131 kg/ha) and Katherine (1,056 kg/ha), moderate in Rockhampton (880 kg/ha) and low in Biloela (366 kg/ha). AgriVentis fennel variety AVTFS#1 performed consistently higher compared to AVTFS#2 and AVTFS#3 across sites. However, the summer planting presented challenges for crop establishments. The winter planting evaluate in year2 at Ayr recorded hand harvest yield of 1272 kg/ha and machine harvested yield of 337kg/ha, accruing larger machine harvest loss associated with wet harvest. The commercial winter planted fennel in year3 at Rockhampton recorded machine harvest yield of 629 kg/ha and significantly reduced machine harvest loss (30%). Therefore, further investigations for effective desiccation and optimisation of header operation for machine harvesting is suggested for maximising the machine harvested yield of fennel. As the crop maturity period for current fennel variety is longer (154-205 days), the variety selection for early and synchronous maturity, high yield and seed quality is suggested for future breeding program.

The research also documented challenges for fennel crop establishments particularly at the early stage of the crop and documented key diseases, insects, pests and weed challenges that provide a basis for developing a compendium of fennel insect pests and diseases, and grower support guide.

Fennel being a small-seeded crop, faces post-harvest seed cleaning, grading and sorting challenges as the bulk harvest contained large amount of biomass resulting into only 29.3% of clean seeds outputs in the machine harvested product highlighting the post-harvest challenges for seed cleaning, and grading to meet the fennel seed specifications for the markets. The postharvest seed cleaning research optimised the operating conditions for fennel seeds in mobile field grain cleaning equipment, Frahn VAL-1500-6, that produced an acceptable level of primary seed cleaning, that can be applied for mobile seed cleaning unit on the farm.

An economic analysis of fennel production in Central Queensland evaluated the gross margin and sensitivity to price and yield fluctuations and revealed that a seed yield over 0.35t/ha would attract some profits for the producers at the price of $2500/t. The result presented in this study indicates that fennel production in the CQ region would only be profitable with a higher yield, that was reflected by machine harvested seed yield of 0.629t/ha in commercial trials as a winter crop in commercial trial at Rockhampton in 2022 season.

The current research assessed different fennel varieties and determined suitable season for production. However, the lack of adequate agronomic tools limit further scaling up of fennel production in northern Australia. Future research focuses on enabling agronomy is embedded in the CRNCA funded Great Northern Spices (GNS) project, along with an emphasis on mechanisation of planting and harvesting. Similarly, other impediments for the production associated with crop protection, nutrient and water management, farming system adaptation, crop establishments, harvesting, seed cleaning-grading and post-harvest storage are also embedded in the GNS project (2023-2026) for research translation towards commercial scale fennel production in northern Australia.

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