RESEARCH WITH IMPACT

SPICE TECHNICAL REPORT – FENNEL

Surya Bhattarai, Tieneke Trotter and Michael Thomson – CQUniversity Australia

October 2020

Contents

EXECUTIVE SUMMARY

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). It was not possible to separate the fennel from this group data so in these instances the overarching trends have been assessed. Throughout this report juniper berries, anise seeds, badian, caraway, coriander and fennel will be referred to as the 'group of spices.' Australia's domestic market for fennel and the similar others in the 'group of spices' is entirely supplied through imports. In 2018, Australia imported about 568 tonnes of this group of spices in question, worth about US$1.37 million. The majority of 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 (TrendEconomy, 2019) which suggests there is an increasing demand for fennel and similar spices in Australia. Calculations made by CQUniversity using the available data and trend analysis suggest that in 2025 the demand for fennel and similar spices in Australia will exceed 2000 tonnes per year.

CQUniversity is supporting on-farm trials to evaluate the suitability of new fennel germplasm for the sub-tropical and tropical environments of Northern Australia.The new fennel varieties for the trial are provided by AgriVentis Pty Ltd. The CRCNA investment has enabled this work to move from laboratory trials to field trials across Northern Australia as part of multi-year project. This report provides the results of the first year of multi-location trials of three fennel genotypes grown at four locations across Queensland and the Northern Territory. It covers the in-field crop agronomy and the results of the yield and quality analysis. The results from the first year of trials will inform the second phase of activities in the form of on-farm verification of fennel technologies. The verification phase will be followed by commercial cropping, resulting in contract production in the third year of the project.

Fennel was planted at varying dates over summer in 2019 and 2020, with a 194-255 day crop duration from planting until harvest. The establishment of the seedlings in the hot and humid conditions proved challenging and the seed was replanted later in summer at Biloela resulting in a crop that reached maturity and in Tully resulting in a second failure to establish. This is a long season crop (particularly for summer planted crop), taking more than six months to reach maturity, which shows promise as a perennial which might be able to harvested more than once.

The seed yield of the three varieties across each of the four trial locations, ranged from 50 to 1574 kg/ha, with the highest seed yield recorded in Ayr followed by Katherine and Rockhampton, and the lowest yield recorded in Biloela. The seed yield between varieties varied significantly at Ayr, but not at Biloela, Rockhampton and Katherine. Varieties AVTFS#1 and AVTFS#2 recorded higher yield compared to AVTFS#3. However, it is important to note that the yield data presented in this report are derived from one year's trial data only.

The fennel crop produced biomass in the range of 525 to 9997 kg/ha. There was a significant difference in biomass between varieties at Ayr only, reflecting a relationship between the low yield and biomass experienced in AVTFS#3 when compared with AVTFS#1 and AVTFS#2.

The quality attributes of the sesame seeds are reflected on the 1000 seed weight and seed density. The lower yielding genotypes AVTFS#3 recorded a greater 1000 seed weight compared to other varieties. The 1000 seed weight was low in Rockhampton and Biloela compared to Ayr and Katherine. The mean seed density (kg/m^3) across the four test sites ranged from 318 to 425 kg/m^3. The seed density was on average higher for AVTFS#1 and AVTFS#3 with AVTFS#2 recorded the lowest seed density.

The next stage of research involves on-farm verification of selected genotypes from the first year for evaluation of the adaptability of the varieties to local farming conditions under farmer's management. While the early results to date are encouraging, there are still challenges that need to be addressed before full-fledged production can commence, including weed control, optimisation of mechanical harvesting, and providing robust agronomic information including optimum planting times for the different regions and density of planting.

The authors acknowledge the financial support of the Cooperative Research Centre for Developing Northern Australia and the support of its investment partners: the Western Australian, Northern Territory and Queensland Governments.

We also gratefully acknowledge the financial and in-kind support of the project participants.

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 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 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 which 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 in 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 as an indigenous Mediterranean plant but is now cultivated in many parts of the world on dry soils near the coast or river banks (Rather et al., 2012). Well-drained and calcareous soils in a sunny situation are the most suitable conditions for fennel production (Bhattacharya, 2016).

As per detailed market analysis that was developed by CQUniversity for the CRC for Developing Northern Australia, the key fennel producing countries are India, Egypt, Turkey, Syria, Iran, Germany, Spain and Pakistan. While the actual production data for fennel are not available for many countries, it is documented 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 2340 ha. A comparison of fennel yields from India and Turkey indicate an average yield of fennel per hectare as slightly more in India (1.6t/ha) than Turkey (1.3t/ha) in 2018.

China, India and Egypt are the leading exporters by volume and value for the 'group of spices' (juniper, anise, badian, caraway and fennel). India's government statistics indicate that in 2017 India exported about 37,000t of fennel (NHB, 2019). Data from UN Com Trade and International Trade Centre (ITC) indicates that China exported about 14,200 tonnes of 'whole spice seeds' for the 'group of spices' which was worth approximately US$49 million in 2018 (ITC, 2019 & UN ComTrade, 2019). The same source indicated that of this trade value, badian accounted for US$ 43.7million or 89%, indicating that China's export value of fennel is relatively small component of their group of spices export.

There was a decline of about 24% in the international trade of this group of spices from India between 2017 to 2018 but global trade value increased by 1.6% during the same period.

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 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 total global import market is 8.9%.

The global market average import price of the selected group of spices was US$ 2,402 per tonne in 2017. However, import value of fennel differed from one country to another, as well as the variation of price based on the reporting organisations. The United Nations Economic Commission for Europe (UNECE) has published Standard FFV-16 detailing the marketing and commercial quality control for fennel, which sets out the details for grading of produce into different classes for market. The details of the UNECE standard can be found at https://www.unece.org/fileadmin/DAM/trade/agr/standard/standard/fresh/FFV-Std/English/16_Fennel.pdf

Australia's domestic market for fennel and other similar spices is entirely supplied through imports. In 2018, Australia imported about 568 tonnes of the group of spices in focus worth about US$ 1.37 million. The majority of imported spices in Australia are from India and China. The limited available data indicates a continuous growth in the quantity of imported spices, which suggests there is an increasing demand for fennel and similar spices in

Australia. The trend line indicates that by 2025 the demand for fennel and similar spices in Australia will exceed 2,000 tonne per year. 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.

Demand for fennel seeds is based on their pleasant flavour and multi-purpose applications. 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.

Research has shown fennel seeds to have benefits over and above nutrition and flavour enhancing. These include assisting in managing blood pressure to reducing symptoms of asthma. The literature also indicates fennel as having a positive impact in antibacterial, antifungal and antiflammatory treatments (Shabbara et al. 2018., Rather et al. 2012., Arora and Kaur, 1999).

Vegetative parts of the fennel plant other than seeds can also be utilised in various ways. The leaves of the fennel plant are also used for garnishes and salad dressing. Fennel bulb is a popular vegetable in Italy and with chefs and cooks the world over (Shelef, 2003) but it should be noted that different varieties are used for bulb and seed production. Fennel pollen can also be used – it is usually hand collected but doesn't taste like fennel seed or anise, and so it adds a different flavour to food. The vast array of applications of fennel in value-added products warrants further and more detailed investigation of value-adding opportunities for the Australian fennel industry. The opportunities for the value addition on fennel seed are very high.These include a wide range of end products for very diverse markets. Some of the expamples are presented here:

Food, health and cosmetics use

Fennel has a wide range of uses. Grains are primarily used as spices and condiments when cooking or flavouring food. It is widely used in various Indian dishes for flavouring soups, sauces, pastries, confectionery, bread products, liquors, meat-dishes and in the seasoning of pickles.

Fennel seed has a pleasing fragrance and aromatic taste. Hence, the essential oil is used as flavouring agent in various food items, pickles, perfumes, soaps, liquors, cough drops and liquor ice candy. The residue left after the distillation of essential oils from the fruit can be used as a cattle feed supplement.

The nutritional and medicinal benefits from the seeds include their ability to act as stimulants and carminatives. Owing to antimicrobial properties, it is used in cosmetic creams, body lotions and moisturisers. There are also wider perceptions about the health benefits of fennel associated with its use in treating diseases like cholera, bile, nervous disorder, cough and cold, constipation, dysentery and diarrhoea and also for diseases affecting chest, lung, spleen and kidneys.

Biomass for oil extraction

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 the fresh herbage or from fennel seeds. The essential oil contents in the fennel herbage can be in the range from 0.05-0.7%. Therefore, the large quantity of herbage biomass that the crop can produce, can also potentially be utilised for the production of essential oil. For example, 10t of herbage biomass at 0.5% essential oil content may produce about 50 litres of essential oil per hectare.

Biomass for drinking straws

Fennel produces prominent hollow stems and shoots with strong elongated fibrous cells that can be well utilised for the production of drinking straws. The rampant use of pastic 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 alterative natural products and bring a new opportunity for fennel biomass to be used for the production of 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 from one hectare of crop biomass after the harvest of seeds.

The fennel plants have a distinct hollow stem that provides materials suitable for use as a drinking straw (right). On the left is a photo of the field crop harvested from Biloela (Image. S.Bhattarai).

Fennel fibre from biomass for high value moulded products

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

Biomass for grain and graze

Seed type fennel has deep rap root, enabling the extraction of soil moisutre from the depths. At Biloela, a ratoon fennel crop attained a height of 1m and a sizable biomass within five weeks of 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.

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

SCOPE AND LIMITATIONS OF THE STUDY

Limited research has been carried out in Australia for evaluation of fennel production. This report presents research findings of preliminary field trials, which included an assessment of peformance evaluation of three new fennel lines in the field conditions across the six northern Australian locations representing various climatic conditions.

The report results are based on the data of the first year of field trials and discussion based on literature available through secondary sources. Hence, the conclusions offered in this report are based on only one year of replicated varietal trials in the field.

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 adpating the harvest data to mechamised management from planting to harvesting.

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).

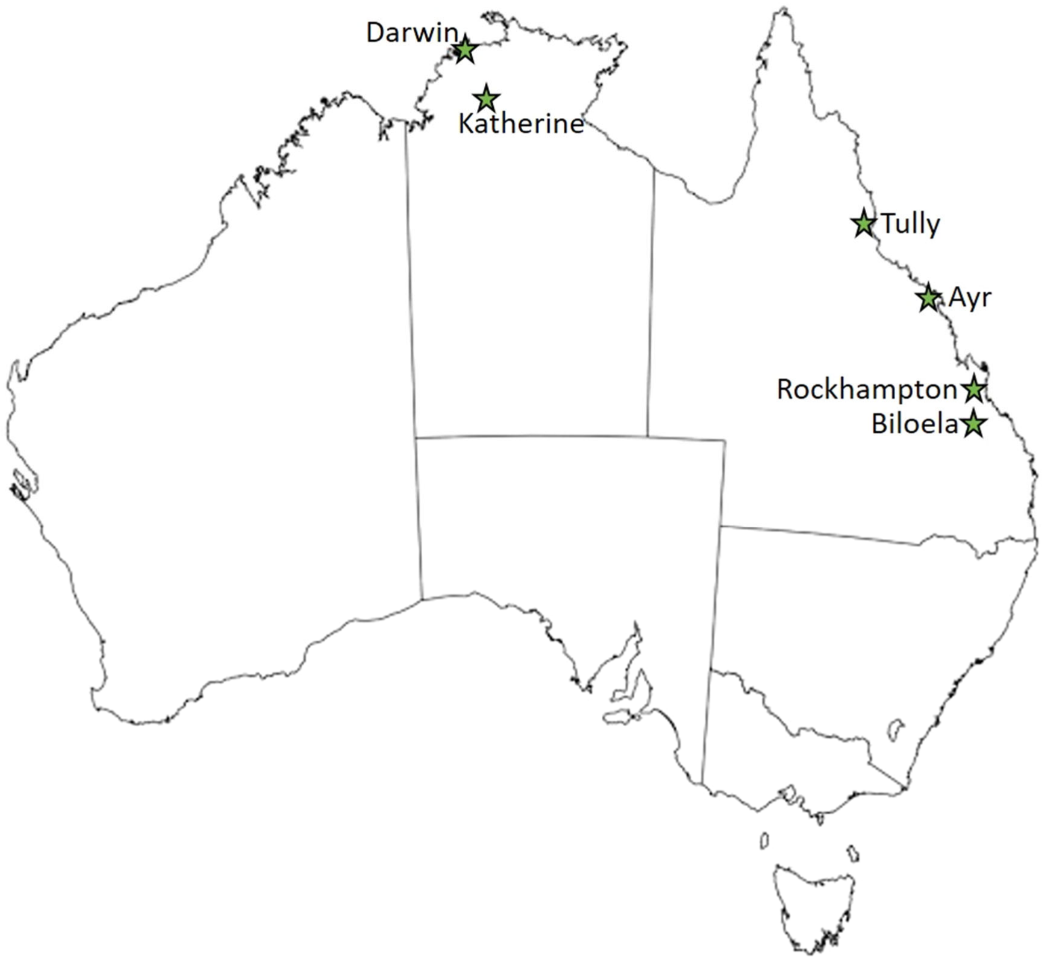

Figure 1. Trial locations in northern Australia, including Biloela, Rockhampton, Ayr and Tully in Queensland and Katherine and Darwin in the Northern Territory.

The range of in-crop rainfall was significant, from 405 mm at Biloela to 1459 mm at Ayr, and soil types unsurprisingly also varied from alluvial and sandy loams, to vertisols and ferrosols. Farming systems were just as diverse (Table 1).

Table 1. Geographic location, in-crop rainfall, soil types and cropping systems of the small plot trial locations.

Location	Latitude	Longitude	In-crop rainfall (mm)	Soils	Cropping system
Biloela, QLD	24º26’32S	150º31’53E	405	Alluvial loam	Hay crop-sesame-hay crop
Rockhampton, QLD	23º18’24S	150º21’35E	454	Vertisol	Cotton-sesame-cotton
Ayr, QLD	19º37’8S	147º31’52E	990	Sandy loam	Melon-sesame-melon
Tully, QLD	18º7’23S	145º31’14E	1459	Sandy loam	Sugarcane-sesame-sugarcane
Katherine, NT	14º28’12S	132º18’28E	467	Ferrosol	Sorghum-sesame-sorghum
Darwin, NT	12º35’38S	131º18’16E	1097	Ferrosol	Sorghum-sesame-sorghum

Planting Season

The planting window varied (Table 2) from early to mid-summer depending on the availability of moisture in the soil and predictions for the onset of the wet season. In two sites (Rockhampton and Tully, a winter planting (27 May 2020) is also being assessed in informal trial.

Table 2. Fennel trial planting and harvest dates

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

At each site, the host grower’s practice was followed with regards to soil preparation, which was followed by planting the crop in well-tilled soil. At Biloela, Rockhampton and Tully, the fennel seed was planted in plots 3m wide and 2m long. Each plot had six rows of black sesame planted 2m long. The two outside rows were guard rows and the four inside rows were used to collect data.

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

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

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

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, all as a basal application. No additional fertiliser was applied during the growing season. All sites received the same rate of fertilizer to add stability of comparison between fennel varieites and the locations. Soil sampling prior to and postharvest of the crop were collected and analysed.

For the weed control, at Katherine a pre-emergent herbicide Stomp (Pendimethalin A.I 440g/L) was applied at the rate 1.5L/ha two days post-sowing for weed control (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 competition with the seedlings low. Once the fennel had developed a canopy, minimal weeding was required as the plant was prolific enough to outcompete any weeds.

Once the fennel seeds had emerged and established, each of the rows was thinned to 30 plants per 2 m row (target population of 30 plants/m^2). This occurred at approximately week 2-3 when the plants were 15-20cm in height. This provided uniform spacing of approximately 6cm between the plants.

Varieties, Trial Design and Planting Densities and Dates

Three varieties of fennel were grown in small plots independently randomised at each site, following the randomised complete block design (RCBD), with multiple replications (seven) within the same farm in each selected location. The between-row spacing was 50cm and the plant spacing within 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 after 40 days of first planting on the 17 Dec 2019 as the emergence from first planting date (7 November 2019) was very poor.

Data Collection

Crop phenology and reproductive data were collected at each site at key times throughout the growing season. The date of planting, emergence, emergence count, flowering, maturity and harvest, and plant stand at harvest were recorded for each replicate. At maturity, the plant height, number of umbels per plant and height at the position of first umbel were recorded for six random plants selected as representative of the plot. The data rows were harvested and the seeds separated and cleaned for determination of seed yield (kg/ha). The remaining biomass was oven-dried until a constant weight was reached and the dry biomass yield (kg/ha) was recorded.

Calculations of various yield parameters and yield attributing characteristics (the plant physiological features which drive the yield the plant produces, such as amount of biomass available to produce yield) were made for explanation of the seed yield results. Harvest Index (HI) was calculated as ratio of seed weight (kg/ha)/total dry biomass weight (kg/ha).

The quality assessment of the harvested seeds were undertaken in CQUni's Crop Science Laboratory. For the quality assessment, a 0.1 kg sample of seed was cleaned from plant trash and dust, dried in an oven at 40ºC and weighed for determination of seed moisture content. The weight for 1000 seeds was taken for each sample using a seed counting machine (Wavwer, Model IC-VA Japan).**Error! Reference source not found.**. A subsample of 50g of seed was dried to 70ºC for 12 hours and the density of the seed measured. The seed counter was used for determination of 1000 seed weight from cleaned dried fennel seeds.

The seed density was calculated using the principal 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 measure in the Ohaus adventure pro-precision balance (Model AV2102N) and the results presented as kg/m^3.

RESULTS – FENNEL SEEDS

Climatic Conditions

The weather data for the trial sites were collected from on-site weather staton where available, and recorded from the nearby Bureau of Meteriology (BOM) meteorological stations where on-site weather recording facilties did not exist. The BOM data were 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: Weather station based on the Katherine Research Station. BOM 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

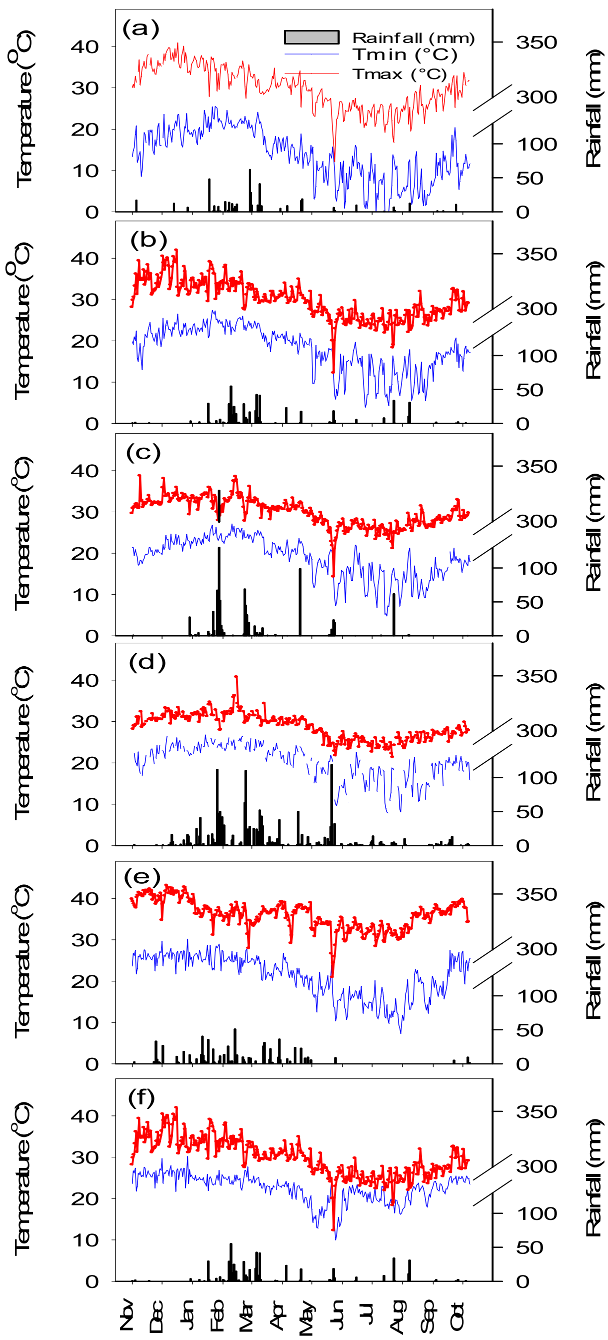

Figure 2. Daily minimum and maximum temperatures and rainfall records over the fennel growing season at a) Biloela, b) Rockhampton, c) Ayr, d) Tully, e). Katherine, f) Darwin

The crop during the vegetative stage grew through the wetter and hotter period in all sites. The crop during the reproductiove stage experienced cooler weather (minimum tempearutre as low as 0-5 °C) in Biloela and Rockhampton, but warmer weather in Ayr and Tully and hot weather in Katherine and Darwin (Figure 3).

The in-crop rainfall for Biloela was 405mm, Rockhampton 454mm, Ayr 990mm and Katherine 540mm. The crop was largely supported by rainfall but supplementary strategic irrigation was applied to minimise the water stress on the crop. All trial sites had a drip irrigation set up that was utilised for strategic irrigation. The decision for irrigation was based on visual observation of temporary wilting symptoms of the plant. The soil moisture was recorded at 0-20cm using the Campbell Scientific soil moisture sensors (Hydrosens) and irrigation commenced once the refill point for the soil is 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 1050mm from the irrigation, whereas Rockhampton had only 64 hours of irrigation delivering 640mm over the crop period.

Crop Phenology

The fennel seeds were planted at varying dates throughout the summer of 2019 and 2020 (Figure 4). The crop maturity and harvest ranged between 194-255 days after planting. The average emergence for each replicate was as early as nine days in Kathrine and 10-12 days at the other sites. The duration from emergence to flowering ranged from 86 days (Ayr) to 98 days (Biloela). The flowering to maturity duration ranged from 81 days (Rockhampton) to 141 days (Biloela).

The sites were harvested manually as soon as practically feasible after crop maturity. The crop at Rockhampton and Ayr were harvested over two occasions due to staggered maturity, whereas the crops at Biloela and Kathrine were harvested over one occasion. In Biloela, the harvesting of two blocks was delayed by one week due to harvesting logistics. Fennel seeds generally stay intact in the umbels, therefore, seed loss due to over-ripening was not noticed as a major issue.

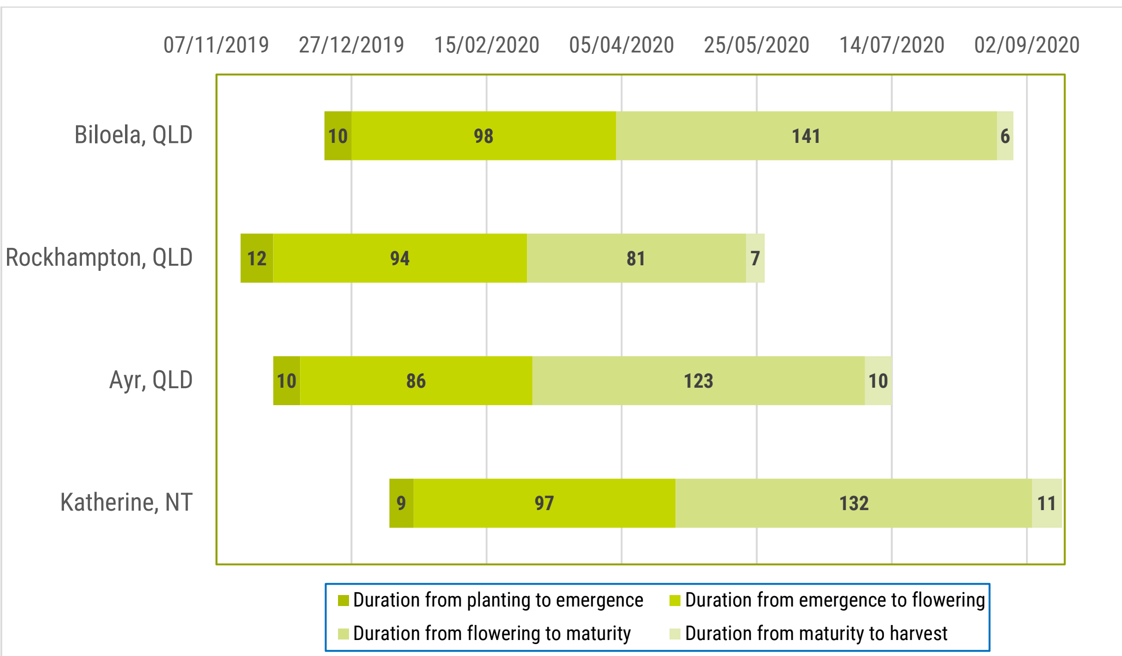

Figure 3. The growing season of fennel seeds from planting to harvest at the four trial locations.

Additional observation trials were planted Rockhampton and Tully to assess the performance of fennel as a winter planted crop. The phenology of the winter-planted fennel appeared to be different in terms of the duration of each phenological stage, with signs of early flowering and maturity compared to the summer-planted fennel measured in the trial. The data collected from the winter planting will be included as supplementary material in this Fennel Technical Report once the winter crop harvesting is completed.

The picture below showing the fennel crop stages at the Rockhampton site (Figure 5) is also indicative of the other sites, with a summer planted crop emerging and progressing through the vegetative stages to flowering and maturity.

Crop establishment at Tully and Darwin was poor. This may have been caused by high soil temperature during germination and seedling establishment. Additionally, there was significant wind damage in the summer spice crops in Darwin. Therefore, the results on crop performance are presented only for four sites (Biloela, Rockhampton, and Ayr in QLD and Katherine in NT).

Figure 4. The growth stages of the fennel seed crop at the Rockhampton trial: 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 (Images. Spices folder).

Plant Height and Height to First Umbel

Table 3. 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 plant height of the tested lines varied between 89 cm and 189 cm (Table 3) and the height of the first umbel in the stem varied from 29-109 cm from the ground (Table 4). The higher plant height in Biloela could be associated with the impact of hailstorms on the crop promoting axillary bud outgrowth coupled with a longer growth period (255 days). The low height in Ayr could be due to soil type (sandy loam) with limited water holding capacity.

Table 4. 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

Table 5. 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	

Fennel seed yield across the four test sites ranged from 50 to 1574 kg/ha. 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 at Ayr, but did not differ between the varieties at Biloela, Rockhampton and Katherine. AVTFS #1 and AVTFS#2 recorded higher yield compared to AVTFS #3 (Table 5). The crop at Biloela was also impacted by hail storms which occurred at the flowering stage, causing the delayed maturity and development of the shoots in the main stems.

Biomass Yield

Table 6. Dry biomass 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	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 fennel biomass yield across four test sites ranged from 525 to 9997 kg/ha. The greatest mean biomass yield was recorded in Rockhampton (9366k kg/ha), followed by Biloela (5374 kg/ha) and lowest mean biomass yields were at Katherine (4417 kg/ha) and Ayr (4092 kg/ha). The biomass yields between the varieties varied significantly only in Ayr.

Yield Attributing Characteristics

Harvest Index

Table 7. The harvest index (seed yield (t/ha)/above ground biomass (t/ha) + seed yield (t/ha))

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	

The mean harvest index (defined as ratio of seed yield to the total above-ground biomass including seeds) across four test sites ranged from 0.055 to 0.394, showing large difference between sites. The greatest harvest index was recorded in Rockhampton followed by Biloela, Katherine, Ayr, and the lowest in Biloela (Table 7). The harvest index between the varieties did not vary significantly between the varieties in any sites (Table 7).

Plant Density Per M²

Table 8. The plant density (the number of plants per m^2) 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	

Mean plant density at harvest across four test sites ranged from 1.4 to 21.3 plants/m^2. Plant density in general remained lower, but did not vary significantly between the genotypes in any tested sites. The higher plant density was recorded in Rockhampton followed by Ayr, and Kathrine. Lower plant densities (3.2 plants/m^2) were particulary noted in Biloela (Table 8) which was largely due to the hail storm damage to the plants at early establishment phase of the crop. Removal of apical dominance by the hailstorm damage could be the cause of axillary bud outgrowth leading to more shoots and umbles per plant in Biloela compared to the other sites (Table 9).

Number of Umbels Per Plant

Table 9. 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	

The mean number of harvested umbels per plant across four test sites ranged from 6 to 79 umbles/plant. Umbel count did vary significantly between the genotypes only at Ayr and not in the other sites. In Ayr, the highest number of umbels per plant (11) were recorded for AVTFS#3, compared to the other varieities. The umbel count for the varieties ranged form 20-25 umbels/ plant (Table 9).

Seed Quality Parameters

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

1000 Seed Weight (g)

Table 10. The test weight (gms) 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	

The mean test weight (g) of 1000 seed across four test sites ranged from 2.69 to 5.16 g (Table 10). There was a significant difference in the 1000 seed weight between the genotypes and locations without any significant interaction effects between varieties and locations. In general, mean test weight for fennel varieites across the sites showed the trend of AVTFS#1 < AVTFS#2 < AVTFS#3 except in Rockhampton where this trend did not follow. It is only in Ayr where the varietal differences were statistically significant with the highest weights of 1000 seeds recorded for AVTFS #3, followed by AVTFS #2 and AVTFS #1 (Table 10).

Seed Bulk Density (kg/m^3)

Table 11. The mean bulk density of seeds (kg/m^3) for three varieties of fennel at four locations.

Varieties	Biloela, QLD	Rockhampton, QLD	Ayr, QLD	Katherine, NT	Mean
AVTFS #1	356±11.2	405±14.9	402±7.0	391±2.7	389
AVTFS #2	337±6.7	323±81.0	406±3.9	382±7.3	362
AVTFS #3	318±10.3	425±19.8	379±0.1	388±2.6	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	

NB: The bulk density value are mean ± Standard Error of Mean (SEM).

The mean seed bulk density (kg/m^3) across the four test sites ranged from 318 to 425 kg/m^3 (Table 11), however, the trends between the varieties was not consistent across the four sites. The highest mean seed bulk densities were recoded in Ayr (402 kg/m^3), followed by Rockhampton (388 kg/m^3), Katherine (387 kg/m^3) and the lowest was in Biloela (337 kg/m^3). The seed bulk density varied significantly between the genotypes only in Ayr as there was a smaller standard error of means between varieties at this site (Table 11) but not in the other test sites. In Ayr the highest seed bulk densities were recorded for AVTFS #2 (406 kg/m^3), followed by AVTFS #1 (402 kg/m^3) and AVTFS #3 (379 kg/m^3). Likewise, in Biloela the seed density for genotype AVTFSS #1 was highest followed by AVTFS#2, and the lowest for AVTFS#3 (218 kg/m^3) (Table 11).

An analysis of the seed yield and the seed quality traits – e.g. 1000 seeds weight 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 a very weak correlation between these parameters.

Seed shape, size (mm), and colour

The visual impression of the seed shape for the three genotypes produced from the four trial locations are presented in Figure 6. The seed length ranged from 7-11 mm and seed width range from 2-4 mm. The seed colour is geneally light greenish to light yellow. Consumer preferences suggest that green and plump seeds are preferred when consuming as fresh whole seed, however the colour and size becomes less relevant when fennel seeds are utilised as a ground product (Verma Sarkar, 2020). The association between the seed shape, colour and size were not obviously related to the yield.

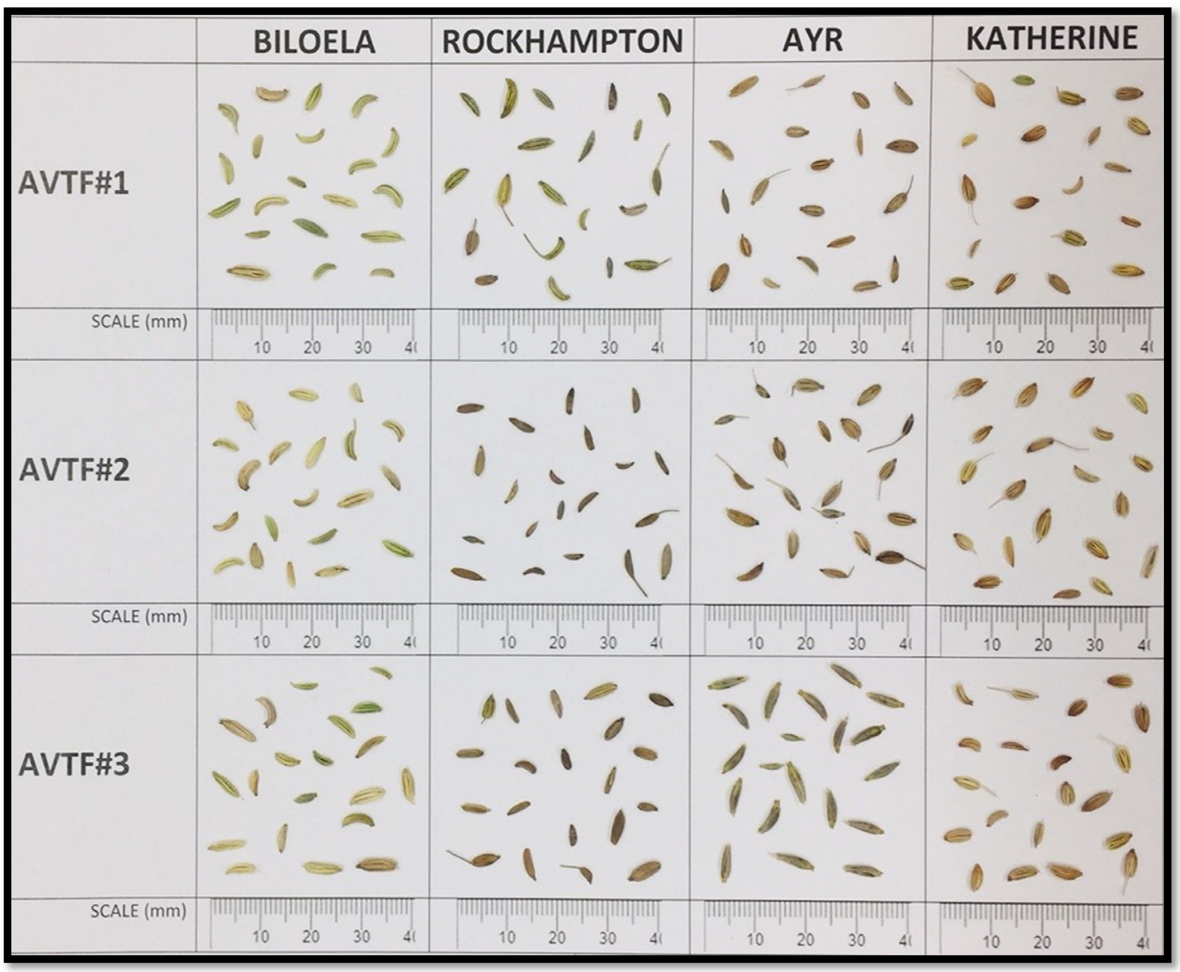

Figure 6. The seed shape and colour of the fennel seed by site and variety (Image. T.Trotter).

Yield Associated with Varieties Across Northern Australia

The results from the first year of the multi-location field trials suggest that fennel varietal performance varied significantly across locations. However, in general the seed yield was higher for AVFS#1, followed by AVFS#2 and AVFS#3 (Table 5).

The average yield was the greatest in Ayr (1131 kg/ha), followed by Katherine (1056 kg/ha) compared to lower yield in Rockhampton (880 kg/ha), and lowest in Biloela (366 kg/ha). Significantly higher yields in North Queensland and the NT were noted than the Central QLD, but these yield are still lower than the current yield recorded (1558 kg/ha) for fennel in India (Lal et al., 2020). The lowest yield was recorded in Biloela, which was explained by low plant density (3.2 plants/m^2), smaller seeds (low 1000 seed weight = 2.81g), and lower seed bulk density (337kg/m^3), which concurrently contributed to lowest harvest index (0.064). Hailstroms that sigificantly impacted the crop during reproductive phase was likely the cause of these effects on the yield and yield attributing characteristics.

The combined analysis for the seed yield for genotype x environmental interaction suggest that the performance of the genotypes is not consistent across sites. The genotype AVTFS #3 was the lowest performer in Ayr whereas it was the highest performance in Rockhampton. The performance of genotypes AVTFS # 1 was reasonably consistent across Queensland and NT locations (

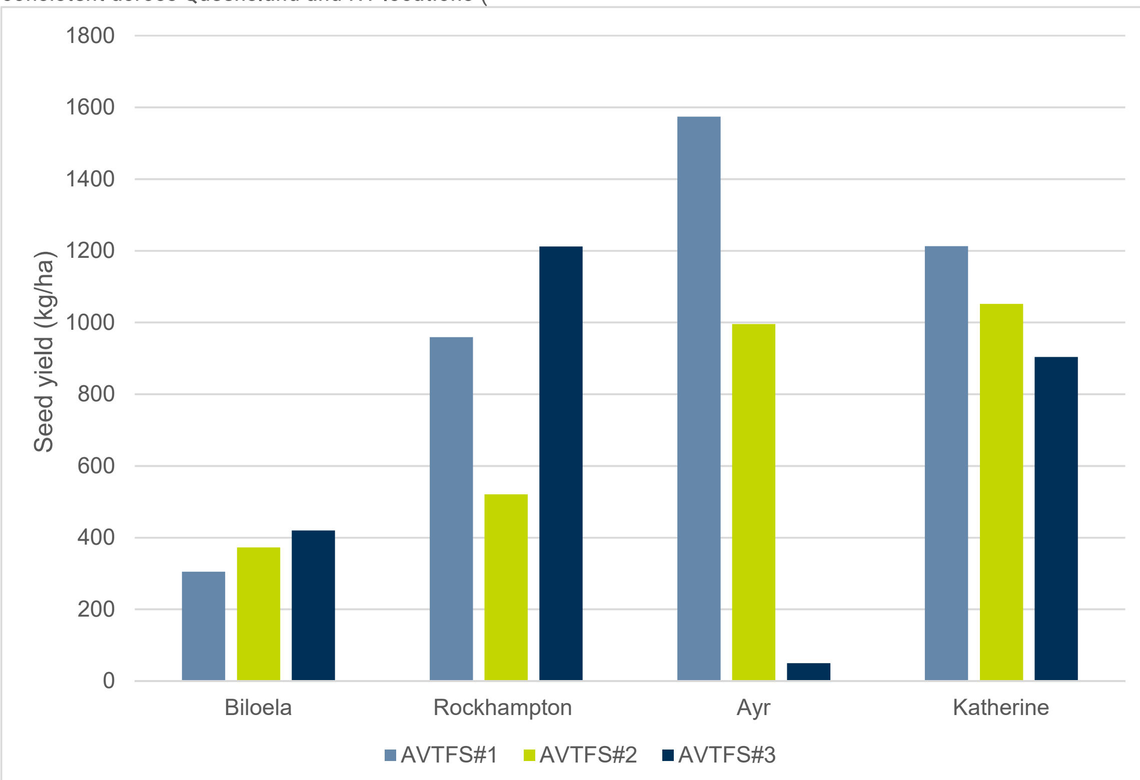

Figure 5).

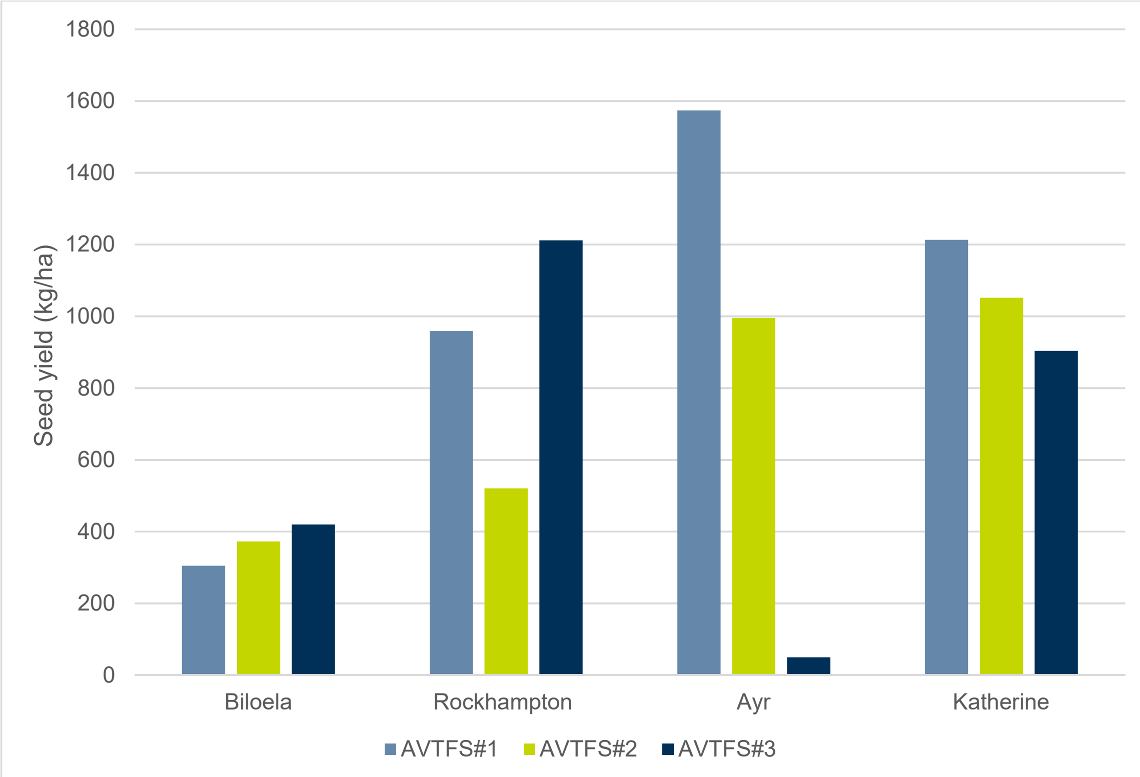

Figure 5 The genotypes x location (environment) interaction for seed yield (kg/ha) for three fennel genotypes tested over four different production environments across QLD and NT.

The correlation between the plant population and seed yield, however, was significant and positive (0.690**) and the relationship was linear (y= 62.838 * X) suggesting that seed yield increased with increasing plant population density at harvest (Figure 8).

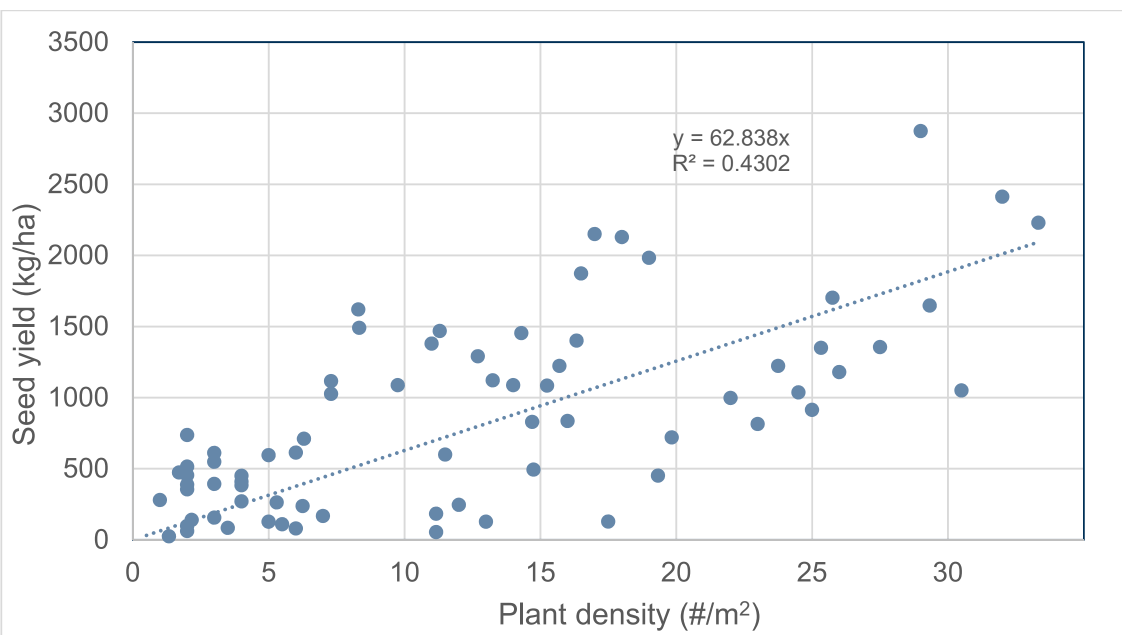

Figure 8. The relationship between the seed yield (kg/ha) to the plant density (number of plants per square metre) for three fennel genotypes tested over four different production environments across QLD and NT.

Scope for Yield Optimisation

In all sites other than Katherine, weeds were managed manually or by mulching, therefore, the penaltiy of weed on yield was not obvious. Weed control in Kathrine was undertaken with herbicide and was effective, with no visible impacts of herbicide noticed in the crop.

Fennel yields of 1700kg/ha, and potential yields of 2400-3000kg/ha, have been reported in India by Meena and Panwar (2016). The yields in this trial in Northern Australia are comparable to the yields reported in India, but were lower than the potential yields reported by these authors. In order for fennel to realise its potential as a high-value crop in Northern Australian conditions, additional research is required to optimise the time of seeding for different locations, agronomy for developing the planting density, and crop adaptation under different farming systems. These need to be assessed alongside assessment of the impact of variables such as tillage, previous crops and fertiliser regimes, and the impact of previous season herbicide applications.

Further, crop harvesting methods, in particular the use of mechanical equipment, will have implications for agronomy and breeding. The synchronization of maturity will need to be investigated so that the crop harvest can be completed in single pass, along with selection for seed lines that are less prone to shattering at maturity thus reducing harvest losses.

Three important aspects that future trials need to consider are determining optimum time of planting, herbicide options for weed control, and optimising the plant density for fennel cropping. A parallel trial of winter-planted fennel is worthy of consideration to bring forward comparative information to growers for adapting the fennel to different northern Australian environments.

The grower participants shared their experiences of growing fennel during a summer crop workshop held in Rockhampton in February 2020 and the online workshops in September 2020. The following feedback from the participants of the workshop are recored which will guide the agronomy techniques required for the optimisaton of yield:

- Winter planting of fennel to overcome high soil temperatures and heat stress.
- Different agronomic practices such as planting date, density and weed management
- Mechanization of harvesting
- Cropping system trials (for vegetable and crop based production systems).

Major Biotic and Abiotic Challenges

Weeds

Trials were managed by hand weeding at all sites except Katherine where herbicide treatments were used. Some sites experienced more weed intensity than others, but the effective weed control measures used meant that weed pressure did not impact trial yields.

Under larger scale production systems, it will be important to evaluate herbicide treatments more thoroughly. There are currently seven chemicals currently registered for use on fennel with the Australian Pesticides and Veterinary Medicine Authority (APVMA). These permits allows for the use of chemicals for control of insects, diseases and weeds (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).

They are:

- » Permit (PER), 82895 provides for the use of Chlorothalonil for the control of fungal diseases;
- » PER89289 provides permit for the use of Lannate Insecticide for the control of Fall Armyworm;
- » PER89185 provides perimit for the use of Mainman 500 WG Insecticide for the control of Thrips;
- » PER10918 provides perimit for the use of Imidacloprid Insecticide for the control of whitefly and Aphids;

» PER12221 provides perimit for the use of petroleum oil as nsecticide for the control of wide range of inspects;
» PER13698 provides perimit for the use of phosphorus for the control of Downey mildews; and,
» PER14158 provides perimit for the use of Metolachlor for the control of weeds in culinary herbs.

In other parts of the world commercial production regions utilize 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/ha. At the time of application of weedicide, there must be sufficient moisture otherwise efficiency of weedicide is drastically reduced (Lal et al., 2020).

Physiological disorders
Symptoms of nutritional deficiency, nutritional toxicityand abiotic stress (such as salinity stress) may occur, depending on the level of stressors.

Fennel crops are vulnerable to frost damage particularly those planted during winter, and there may be issues in a severe winter season for the winter planted crops.

The seed fennel was vulnerable to intense heat in the germination stage, seedling stage, impacting the emergence and seedling establishment in the current trials particularly in Tully and Darwin.

Pests and Diseases

Fennel crops also attract large numbers of pollinator predators and parasites which contribute better quality and yield of crop. The major insect pests noted during the growing seasons were aphids, thrips, caterpillars, seed wasps, cut worms and termites. Some of the common insect pests of fennel crop noted in the field are presented below.

Aphid (*Hyadaphis foeniculi*)

Aphid was the major pest at all sites causing serious damage to the crop and resulting in poor quality of seed and reduced yield. Three types of aphids – Hyadaphis, Cavariella and Aphis – are known to damage fennel crops (Lal et al., 2020). Heavy infestation of aphids may cause severe yield losses in comparison to normal crop. The presence of aphids started at the vegetative stage of the crop and continued to develop until seed matured. Maximum colonization of aphids developed on umbels. Nymph and adults suck sap from the tender leaves, which make the plant weak and shrivelled. Aphid attack at flowering stage resulted in serious damage. They exuded copious honeydew, which also favoured the growth of sooty mould. As a result, the growth of plants retarded and quality and quantity of fruits were also affected. When infestation occured at flowering and fruiting stage, the fruits were not formed and if formed they shrivelled and were of poor quality.

Figure 10. Aphid infestations in the crop are more likely after flowering.

Thrips

Thrips damage the undersides of leaves by sucking their juices. They damage young and soft parts of plants such as new leaves and shoots. As a result, leaves curl downwards and change to a blackish-silver color. Severe infestation causes young leaves to wilt and dry out.

Figure 11. Typical thrips damage symptoms on the leaf of fennel crop both at vegetative and reproductive stage

Cutworm

Cutworm infestations could be serious in some areas. The larvae remain inside the soil near the base of the plant. They hide under the soil during the day and travel above the soil surface at night. At night the larvae feed voraciously on the leaves and tender stems and branches. The cutworm attacks fennel by cutting the stem at, or just below the soil surface. A single cutworm is capable of damaging several plants in one evening and a large population can destroy an entire fennel stand. When cutworms have been active, several wilted or cut off plants in a row might be observed.

Figure 12. Fennel cut worms typical damage is seen as cutting of the stem at, or just below the soil surface

Caterpillar (*Helicoverpa armigera* Hubner and *Spodoptera litura Fabricius*)

The caterpillar can appear in large numbers and consumes the leaves. The eggs are laid singularly or in clusters and when hatched, the young larvae feed on leaves. Early instar larvae scrape out the green matter from the leaves and give the appearance of papery white structure. The last instar of larvae feed voraciously causing defoliation of plants and thereby causing considerable losses in yield and quality of fennel (Figure 13).

Figure 13. Fennel caterpillars are commonly called parsley worms because they're most often found on parsley, carrot, dill and other members of the carrot family devouring the leaf and soft stems tissues.

Root knot nematodes

Root knot nematode (*Meloidogyne spp*) causes galls on roots which can be up to 3.3 cm in diameter but are usually smaller (Figure 14), causing a reduction in plant vigor and yellowing of plants which wilt in hot weather.

Figure 14. Typical rootknot nematode symptoms on the root of fennel crop

Major diseases

The fennel crop can harbour a number of diseases at various stages of crop growth *viz*., damping off, Ramularia blight, *Alternaria blight*, Angular leaf spot and powdery mildew causing damage to the crop at different stages.

Cercospora leaf blight *Cercosporidium punctum*

Small, necrotic flecks on leaves which develop a chlorotic halo and expand into tan brown necrotic spots, the lesions coalesce and cause the leaves to wither, curl and die (Figure 15).

Figure 15. Typical leaf blight symptoms in fennel crop

Fusarim wilt

Figure 15. Typical Fusarim wilt symptoms in fennel crop

Downy mildew *Peronospora umbellifarum*

Yellow spots appear on the upper surface of leaves, white fluffy growth appears on the underside of leaves and lesions become darker as they mature.

Powdery mildew *Erisyphe heraclei*

Powdery growth on leaves, petioles flowers stalks and bracts; leaves becoming chlorotic and in severe infections flowers can become distorted.

Figure 16. Typical powdery mildew symptoms in fennel crop.

The CRCNA acknowledges the support of its government partners.

Queensland Government

NORTHERN TERRITORY GOVERNMENT

GOVERNMENT OF WESTERN AUSTRALIA Department of Primary Industries and Regional Development

Australian Government Department of Industry, Innovation and Science

Business Cooperative Research Centres Program

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