Final Report

On Farm Evaluation of Vegetable Seed Viability Using Non-Destructive Techniques

Project leader:

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Delivery partner:

The University of Queensland

Project code:

VG16028

Project:

On Farm Evaluation of Vegetable Seed Viability Using Non-Destructive Techniques – VG16028

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Content

Summary

Vegetable crops that are field established from seed require high seed quality, otherwise a substandard crop will result and essential farm inputs and investments are lost or wasted. The **project objective** of VG16028 is to provide the Australian vegetable industry with a range of options and recommendations to overcome poor seed quality and viability on farm. This program builds upon VG15021, which is developing transformational technologies for the vegetable industry to optimise seed quality, enhance healthy and uniform germination and improve seedling establishment. The **target audience** are Levy payers and commercial partners within the Australian vegetable industry, while supply chain participants and allied industries are the secondary audience. **Project activities** encompassed (1) Grower interviews to identify needs and opportunities. On farm visits and surveys of 10 leading growers and 2 industry affiliates within the Lockyer and Fassifern Valleys (Qld), Sydney Basin and Bathurst (NSW) vegetable growing areas have determined that seed viability, purity and/or quality issues are a major concern for industry; (2) A comprehensive literature review of: (2a) The range of available technologies to assist growers in maximising seed vitality on farm with a particular focus on new technologies for real time non destructive grading for seed viability, (2b) Information pertaining to the seed longevity of economically important vegetable crops and (2c) Conditions needed to maximize seed quality and storability on farm; (3) New relationships have been formed with researchers at The University of Sydney *Australian Centre for Field Robotics* with a view to a potential collaboration to progress technologies via future R&D Levy investment. **Outputs** are (a) a review of Industry needs and recommendations from the grower survey, highlighting areas that need improvement and providing recommendations for future R&D investment to improve on farm seed quality outcomes, (b) new knowledge to assist growers in maximizing seed vitality on-farm with a focus on emerging technologies that show potential to non destructively grade seed viability pre planting, (c) knowledge of research providers who can deliver the development of technologies via future R&D levy funding, (d) communication to Levy Payers via one field day and three industry bulletins detailing grower survey outcomes and recommendations for technology and future project development. **Outcomes** are recommendations for new R&D investment/s towards (a) development of novel technologies with the potential for real time grading to maximize vegetable seed quality and (b) a long-term program to optimise seed quality at the seed production and postharvest phase, to ensure seeds are of maximal quality before they reach the grower and then maintain quality on farm. A date is scheduled for autumn 2018 to discuss R&D strategies with key Levy payers towards future project development. Society benefits of new technologies and programs to optimize seed quality are reduced resource wastage - such as labour, fertilisers, irrigation, mechanisation and crop protection materials - and therefore a positive image of the industry as having sustainable produce.

Keywords

Up to 10
Vegetable industry; seed quality; seed viability; seed vigour; seed longevity; non destructive techniques;

Introduction

Historical Background

Vegetable crops that are field established from seed, such as corn, beans, carrots and spinach, require excellent seed quality as the primary and essential starting point of the production program. Poor quality seeds propagate a substandard crop, resulting in essential farm inputs and investments being lost or wasted. This is true for any scale of operation regardless of the size of the enterprise (George, 2009).

The vegetable industry Levy and HIA are funding a confidential program titled **"***Sowing success through transformational technologies to boost productivity and commercial outcomes"* (VG15021) to develop technologies that optimise seed longevity and seedling establishment success for the Australian vegetable industry. Specifically, naturally occurring compounds and slow release technologies for improved vegetable crop performance are being developed with a view towards commercialization over a 4 year timeframe (2015-2020).

This current project, VG16028: "*On farm evaluation of vegetable seed viability using non destructive techniques"*, will complement and build upon the VG15021 program as there are clear opportunities to share and/or optimise technologies from one project to the other. Since VG15021 is already developing transformational on farm crop establishment technologies for the vegetable industry, the two projects combined will build a holistic approach to seed quality assurance for vegetable growers and future mechanisation, field robotics and/or precision agriculture will ideally be optimised simultaneously.

Project Rationale and Objectives

VG16028 is a multifaceted project. At project onset a review of Australian vegetable industry needs from face-to-face grower surveys identified pressing on farm seed quality issues. A global review of new technologies, opportunities and/or future program activities to overcome the identified seed quality issues has since been completed using information from industry, literature and with input from new research allies who have the capacity to develop the most promising technologies. The key project focus has been a review of emerging non destructive and cost effective techniques to screen viable seed and maximise germination and vigour once planted. Information and recommendations from the VG16028 review will inform future R&D investment strategies. A meeting with key Levy payers is scheduled for autumn 2018 where future project investment will be determined, for example towards long term programs to optimise genetic and environmental influences pre- and post-harvest to maximise vegetable seed quality before seeds reach the grower and/or develop of robotics, intelligent systems and sensor technologies to maximise seed viability pre planting.

Significance for Industry

Program logic analysis (see Outcomes section below) identified that future R&D investment for VG16028 promises a significant **productivity boost** for industry, for example via (a) higher profits from enhanced crop establishment and uniformity resulting in improved crop growth and harvest outcomes, (b) reduced costs of production via enhanced resource efficiency, such as through less resource wastage if labour, fertilisers, irrigation, mechanisation and crop protection materials are not wasted, (c) reduced biosecurity risk, for example, if non destructive technologies are developed that can detect diseases that would otherwise be transmitted on farm from seeds and (d) enhanced breeding programs since successful germination and growth of difficult new lines will open currently unusable germplasm, providing a competitive advantage and reduced risk. Indeed new germplasm can be vital during disease outbreaks and if climatic extremes escalate. **New technologies and products** with new uses may arise from this project. For example, the Australian vegetable industry may invest in the development of technologies to non destructively grade seeds for high viability, which can then provide royalties to the vegetable Levy from IP and sale of technologies. **Spill-over benefits for society** may include improved resource use efficiency on-farm, reduced biosecurity risks and less resource wastage.

Thus key linkages to the Australian vegetable industry **Strategic Plan** are through Pillar 2: Market and Value Chain Development, by developing promising novel technologies (SIP strategy 2.4.2) and giving Australian products a competitive advantage over imports (2.3.4); Pillar 3: Improved Farm Productivity, Resource Use & Management by developing transformational R&D to enhance the productivity of the Australian Vegetable industry (3.1), reducing the costs of inputs such as labour, fuel, energy, fertiliser and other costs (3.5) and improving biosecurity by proactively managing biosecurity risks to industry productivity (3.6) and Pillar 1: Meeting consumer needs both domestically and internationally by maintaining a positive image of the industry through society benefits (1.4). Further, knowledge and recommendations have been communicated to Industry through multiple networks for increased industry engagement (SIP strategy 4.2) such as an industry field day in the Sydney Basin, two industry bulletins and a strategic R&D planning day scheduled for 2018.

Methodology

The vegetable industry Levy and HIA are funding a confidential program titled **"***Sowing success through transformational technologies to boost productivity and commercial outcomes"* (VG15021) to develop technologies that optimise seed longevity and seedling establishment success for the Australian vegetable industry. This current project - VG16028: *On farm evaluation of vegetable seed viability using non destructive techniques* - complements and builds upon the VG15021 program as there are clear opportunities to share and/or optimise technologies from one project to the other. A Monitoring and Evaluation Plan was completed for VG16028 at project onset, as shown in Table 1. An updated M&E plan, with progress against each activity, is provided in the Outcomes section below.

This project (VG16028) has a multifaceted approach for maximum industry impact, including:

(1) An industry review component that identified grower needs and opportunities: At project onset a review of Australian vegetable industry needs from face-to-face grower surveys identified pressing on farm seed quality issues. Responses have been collated and will be reported to industry via a bulletin and/or magazine article.

Specifically, on-farm visits and surveys of 10 leading growers and 2 industry affiliates within the Lockyer and Fassifern Valleys (Qld), Sydney Basin and Bathurst (NSW) vegetable growing areas have determined that seed viability, purity and/or quality issues are a major concern for industry. Many growers described quality seeds at their most important farm input and detailed grower responses are collated and attached as 'Output 1'.

(2) A global review of new technologies, opportunities and/or future program activities to overcome the identified seed quality issues was then completed using information from industry, literature and with input from new research allies who have the capacity to develop the most promising technologies. Grower recommendations to overcome issues are collated and attached as 'Output 1' and summarised in the Evaluation and Discussion Section below.

Literature review

The Australian vegetable industry needs high quality seeds to ensure high seedling emergence rates and a uniform crop for a successful harvest. Levy payers across industry identified that seed viability, purity and/or quality issues are a major concern for industry, hence a comprehensive literature review, attached as 'Output 2', has been completed to provide R&D solutions from literature or provide recommendations towards the development of such solutions.

(2a) Emerging non destructive and cost effective techniques to screen viable seed and maximise germination and vigour once planted were the main literature review focus and were compared without bias to one another. The tests and technologies to grade seed quality that were reviewed included: destructive tests that are used in accredited laboratories around the world and new tests that are emerging from research facilities (Section 3 in the literature review), currently available machinery to process seeds for improved quality (Section 4) and new non destructive technologies that use innovative computer-assisted analysis systems for real time automation of seed quality grading (Section 5). Industry recommendations were provided and are summarised in the Evaluation and Discussion Section below.

(2b) A vegetable seed longevity review component was completed since VG15021 identified a lack of seed longevity knowledge about Australian vegetable crops. Taxonomic trends for seed longevity exist; for example, the seeds of many crops (as well as wild and weedy plants) can be characterized as short- to long-lived according to their order, family (Probert *et al.*, 2009), genus (Hay *et al.*, 2006; Kochanek *et al.*, 2008, 2009) and species (Schoeman *et al.*, 2010; Kochanek *et al.*, 2011). Thus Section 6 reviewed factors that determine the germination and vigour peak that can be attained by a seed lot at physiological maturity and factors that determine the rate of subsequent seed deterioration including: genetic effects, pre-harvest parental effects, seed maturity at harvest and postharvest conditions.

Additional industry reviews

(2c) An on-farm seed storage review explored whether poor seed storage options may contribute to poor seed quality on farm. Poor seed storage conditions, including high relative humidity and high temperatures, result in rapid seed quality decline (Kochanek *et al.* 2010, 2011). For example, seed storage in a hot shed can kill short lived crop seeds within one month. This review occurred during on-farm grower interviews, and recommendations are summarized in the Evaluation and Discussion Section.

(3) Input from new research allies who have the capacity to develop the most promising technologies has been sought. Specifically, a relationship has been formed with researchers at The Australian Centre for Field Robotics (ACFR) at the University of Sydney and their input sought with a view to a potential collaboration to progress non destructive and cost effective techniques to screen viable seed via future R&D Levy investment.

(4) Technology transfer activities to ensure widespread communication of project findings to vegetable Levy Payers included one field day in the Sydney Basis, completed during March 2017, and two industry bulletins that detail (1) grower survey outcomes and (2) recommendations for technology and future project development. Furthermore, a date is scheduled for autumn 2018 to discuss R&D strategies with key Levy payers towards future project development.

Table 1. The monitoring and evaluation (M&E) plan for project VG16028 documenting a schedule for activities and outputs and short-term to intermediate outcomes.

Project Activities and Outputs	Achievement timeline		
	3 months	6 months	*Discussion upon project completion
Grower needs & future technology development			
i. Do growers confirm that there are seed viability issues? What are they? How large is the problem? Which crops are particularly problematic?	50%	100%	
ii. Can there be improvements made in seed storage practices on-farm? Are the technologies available to fix these problems or do new technologies need to be developed?	50%	100%	Required if gaps identified during project
iii. Are technologies developed during VG15021 for on-farm seed viability screening potentially useful for industry? How do they compare to currently used technologies and those identified in the literature review?	50%	100%	
iv. Are there gaps in current technologies on-farm for real time grading of seed for viability pre planting? What opportunities are there in Australian field robotics and precision agriculture to help growers into the future?	50%	100%	Required if gaps identified during project
v. Could a long-term program to optimise seed quality (via pollen quality) and seed longevity (via maternal plant health) through environmental growth optimisation at the seed production phase solve certain grower issues?			Required if gaps identified during project
vi. Are there other solutions, such as engaging new seed suppliers or working with suppliers to supply better quality seeds to growers?			Required if gaps identified during project
Vegetable seed longevity review			
Is there information in the literature to categorise vegetable crops as having short- to long-lived seeds?	50%	100%	
Is a future project to classify key Australian vegetable lines as short to long-lived useful for industry?			Required if information is inadequate
Literature review of techniques to assist growers in maximising seed vitality on-farm			
Are techniques identified in the literature useful and realistic for Australian growers? How do techniques compare against each other?	50%	100%	
Are future projects to validate techniques required for Australian growers and under Australian conditions?			Required if gaps identified during project

*The project leader (Kochanek) will report progress and discuss future opportunities with Levy payers from the Australian vegetable industry and Hort Innovation at project completion (post final report submission).

Outputs

(1) The detailed industry review component that identified grower needs and opportunities is attached as **'Output 1'.** This includes (a) a detailed summary of grower issues, (b) outcomes from the on-farm seed storage review to explore whether poor seed storage may contribute to poor seed quality, (c) grower recommendations towards overcoming on farm seed quality issues.

In summary, 10 vegetable growers and 2 industry affiliates (vegetable transplant and canning industry representatives) were interviewed during a field day or on-farm visits in the key growing areas of the Lockyer and Fassifern Valleys (Qld), Sydney Basin and Bathurst (NSW) (Plates 1-5). Many growers described quality seeds at their most important farm input. While certain suppliers typically supplied excellent quality seeds, others commonly provided substandard seeds (and were named repeatedly by growers). Seed issues from such suppliers included poor germination percentage and non-uniform emergence, disease transmission via seeds, varietal impurity, non-uniform seed size, damage to seeds and 'seed enhancements' such as priming, pelleting and hot water treatments reducing seed quality rather than enhancing it. Seed supplier concerns, lack of lines bred or grown for Australian conditions, disease resistance not holding up, inadequate or inaccurate seed packet labelling and long lead-in times for seed delivery were identified as additional issues of concern. Grower recommendations for seed related issues are summarized in the Evaluation and Discussion Section.

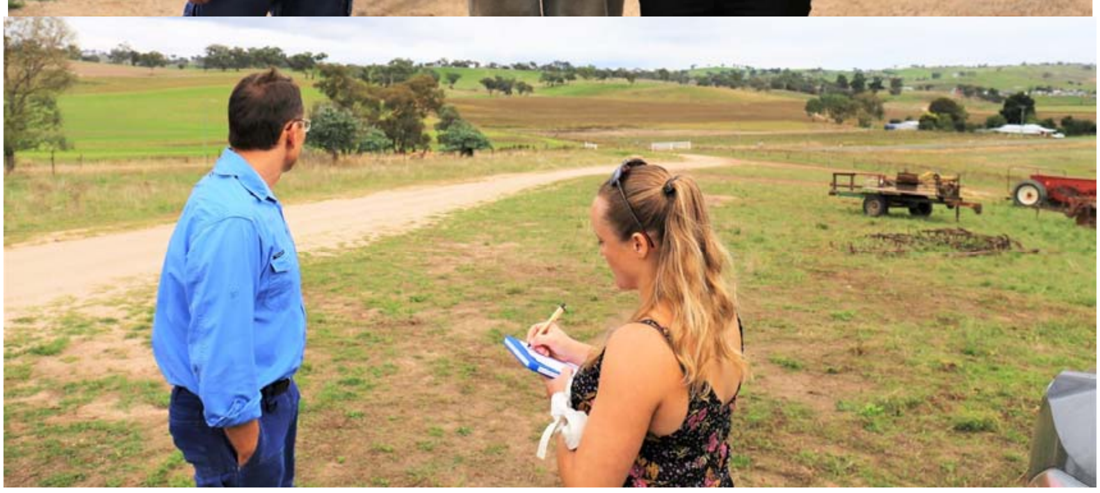

Plate 1. Grower Jeff McSpeddin from the Bathurst NSW growing area was interviewed on farm by the report author, Dr Jitka Kochanek, in March 2017. Matt Plunkett from the Greater Sydney Local Land Services generously organized and participated in grower visits.

Plate 2. Matt Plunkett and Jitka Kochanek interviewed grower Michael Willott at Ravenswood Farm in the Bathurst NSW vegetable growing area. Various crops were sown as seed which had been sold as the wrong variety and thus could not be harvested.

Plate 3. NSW extension officers Bill Dixon and Peter Conasch from the Greater Sydney Local Land Services providing a tour of the Sydney Basin demonstration farm with the report author.

Plate 4. Seedling producer John Vella, Matt Plunkett and Jitka Kochanek during on site interviews at Leppington Seedlings in the Sydney Basin, NSW.

Plate 5. On farm grower interview with grower Brock Sutton at Sutton Farms in the Lockyer Valley, Qld. Brock is shown demonstrating his farm sowing machinery to Jitka and her UQ research team (January 2017).

(2) The literature review provides information about R&D solutions or recommendations towards the development of such solutions is attached as **'Output 2'**.

Tests and technologies to grade seed quality were reviewed in the literature survey, including:
(a) Destructive tests that are used in accredited laboratories around the world and new tests that are emerging from research facilities (Section 3),
(b) Currently available machinery to process seeds for improved quality (Section 4) and
(c) New non destructive technologies that use innovative computer-assisted analysis systems for real time automation of seed quality grading (Section 5). Included is a summary of future R&D recommendations for Industry (Section 5.5).

Section 6 reviewed factors that determine the germination and vigour peak that can be attained by a seed lot and that influences the rate at seeds subsequently deteriorate. Specifically, genetic effects, pre-harvest parental effects, seed maturity effects and postharvest handling and storage conditions that influence seed viability, deterioration rate and longevity are comprehensively reviewed. Recommendations for future project R&D investments are provided in Section 6.3.

(3) Extension and communication to Levy Payers from project VG16028 is via:

(a) **Output 3** – an information sharing field day in the Sydney Basis, organized by NSW extension officers from the Greater Sydney Local Land Services and completed in March 2017 (Plate 6). We are especially grateful to Bill Dixon and Matthew Plunkett who were so generous with their time and help towards VG16028.
(b) **Output 4*** – Industry Article 1: Industry needs and recommendations from VG16028 survey will be summarised, introduction to VG15021 in the Vegetables Australia magazine and/or the Hort Innovation magazine (Aug 2017).
(c) **Output 5*** - Industry Article 2: Technology & future project recommendations from VG16028 will be summarised in the Vegetables Australia magazine and/or the Hort Innovation magazine (Aug 2017).
(d) **Output 6* -** Industry Technical Bulletin: Optimized seed storage conditions needed to ensure maximum seed viability is maintained during seed storage and on farm. Location of publication to be confirmed (completed before mid 2018).
(e) **Output 7** – More information pertaining to grower issues and R&D needs will be collected in Sep 2017 – March 2018 to inform the 2018 R&D Strategy meeting (Output 8). Growers will be encouraged to send information to a designated email and information will be collated prior to the 2018 meeting.
(f) **Output 8 -** A date is scheduled for autumn 2018 to discuss R&D strategies with key Levy payers towards future project development.

* Drafts will be reviewed by Hort Innovation prior to publication in industry magazines or bulletins.

Plate 6. An information sharing field day in the Sydney Basis was organized by NSW extension officers from the Greater Sydney Local Land Services in March 2017. Here the report author is presenting to growers as part of the field day. Grower interviews followed this presentation.

(4) New research collaboration: A relationship has been formed with researchers at The Australian Centre for Field Robotics (ACFR) at the University of Sydney and their input sought with a view to a potential collaboration to progress non destructive and cost effective techniques to screen viable seed via future R&D Levy investment. The report author met with team members in Sydney in March 2017 (Plate 7).

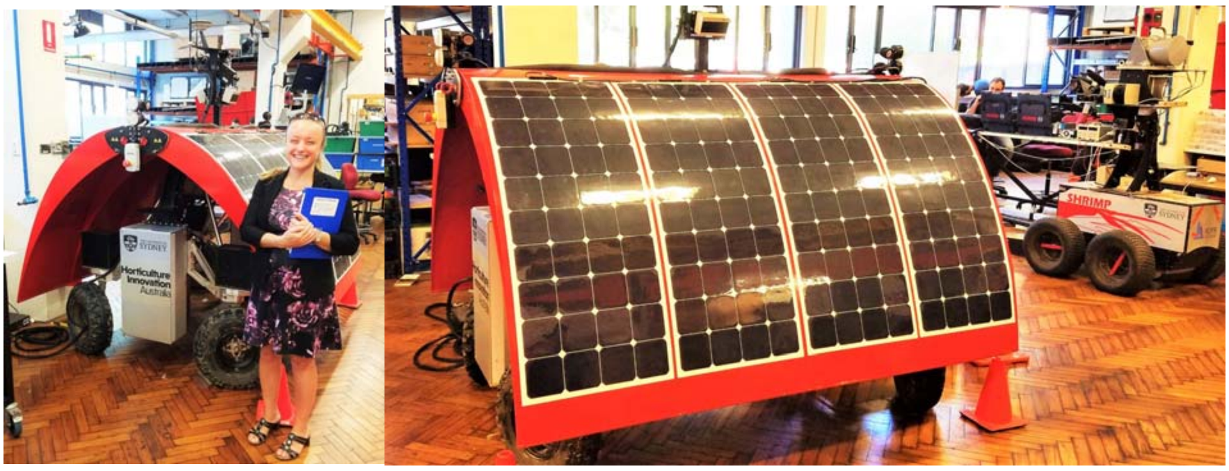

Plate 7. A relationship has been formed with researchers at The Australian Centre for Field Robotics (ACFR) at the University of Sydney. The report author is shown standing beside their infamous 'Ladybird' mobile ground robot.

(5) Recommendations for development of novel technologies via new R&D investment/s, are summarised in the Evaluation and Discussion and Recommendations sections. A date is scheduled for autumn 2018 to discuss R&D strategies with key Levy payers towards future project development.

Outcomes

1. PROJECT RESULTS AND OUTCOMES

All intended outcomes were successfully achieved, as shown in the Monitoring and Evaluation (M&E) Plan in Table 2. This includes recommendations for new R&D investment/s towards the development of novel technologies with the potential for real time grading to maximize vegetable seed quality and a long-term program to optimise seed quality at the seed production and postharvest phase, to ensure seeds are of maximal quality before they reach the grower and then maintain quality on farm.

Table 2. The Monitoring and Evaluation (M&E) Plan for project VG16028 documenting the activity and output schedule and the outcomes and/or next steps arising from each activity.

Project Activities and Outputs	Complete	Outcomes and next steps
Grower needs & future technology development		
i. Do growers confirm that there are seed viability issues? What are they? How large is the problem? Which crops are particularly problematic?	Yes	Outcomes from the grower survey to be communicated via an industry bulletin
ii. Can there be improvements made in seed storage practices on-farm? Are the technologies available to fix these problems or do new technologies need to be developed?	Yes	Opportunity identified for future R&D - to be discussed at 2018 strategy meetings*
iii. Are technologies developed during VG15021 for on-farm seed viability screening potentially useful for industry? How do they compare to currently used technologies and those identified in the literature review?	Yes	Growers not keen on technology, prefer to outsource to seed laboratories
iv. Are there gaps in current technologies on-farm for real time grading of seed for viability pre planting? What opportunities are there in Australian field robotics and precision agriculture to help growers into the future?	Yes	Literature review completed. Opportunity identified for future R&D - to be discussed at 2018 strategy meetings. Findings communicated via industry bulletin
v. Could a long-term program to optimise seed quality (via pollen quality) and seed longevity (via maternal plant health) through environmental growth optimisation at the seed production phase solve certain grower issues?	Yes	Opportunity identified for future R&D - to be discussed at 2018 strategy meetings*
vi. Are there other solutions, such as engaging new seed suppliers or working with suppliers to supply better quality seeds to growers?	Yes	Opportunity identified for future R&D - to be discussed at 2018 strategy meetings*
Vegetable seed longevity review		
Is there information in the literature to categorise vegetable crops as having short- to long-lived seeds?	Yes	Literature review completed
Is a future project to classify key Australian vegetable lines as short to long-lived useful for industry?	Yes	Opportunity identified for future R&D - to be discussed at 2018 strategy meetings*
Literature review of techniques to assist growers in maximising seed vitality on-farm		
Are techniques identified in the literature useful and realistic for Australian growers? How do techniques compare against each other?	Yes	Literature review completed
Are future projects to validate techniques required for Australian growers and under Australian conditions?	Yes	Opportunity identified for future R&D - to be discussed at 2018 strategy meetings*

*The project leader (Kochanek) will report progress and discuss future opportunities with Levy payers from the Australian vegetable industry and Hort Innovation in autumn 2018 at a strategy meeting with key Levy payers with a view to planning future R&D project development and investment.

2. ECONOMIC, SOCIAL AND ENVIRONMENTAL IMPACTS THAT HAVE RESULTED OR MAY RESULT INTO THE FUTURE FROM THE PROJECT

The detailed and integrated program logic model for VG16028 is provided as Table 3.

Table 3. Program Logic for project VG16028.

<table>
<tr><td>Broader goals
Long-term goals: HIA, Australian Veg Industry & Government</td><td><u>Government</u>
Enhanced productivity & adding value

<u>Australian Vegetable Industry & HIA</u>
Market and Value Chain Development
Develop promising novel technologies (2.4.2)
Give Australian products a competitive advantage over imports (2.3.4)
Improved Farm Productivity, Resource Use & Management
Transformational R&D to enhance the productivity of the Australian Vegetable industry (3.1)
Reduce the costs of inputs such as labour, fuel, energy, fertiliser and other costs (3.5)
Biosecurity - Proactively manage biosecurity risks to industry productivity (3.6)
Knowledge and recommendations communicated to Industry
Communication to growers and other industry stakeholders through multiple networks for increased industry engagement (4.2)
Meeting consumer needs both domestically and internationally
Maintain a positive image of the industry through society benefits (1.4)</td></tr>
<tr><td>End-of-program outcomes
(i.e. with future R&D investment)</td><td>New technology development
New technologies and products with new uses may arise from this project,
For example, The Australian Vegetable Industry may choose to invest in the development of technologies to non-destructively grade seeds for high viability, which can then provide royalties to the Vegetable Levy from IP and sale of technologies.
Significant productivity boost from enhanced seed quality, for example
Higher profits via enhanced crop establishment and uniformity resulting in improved crop growth and harvest outcomes,
Reduced costs of production via enhanced resource efficiency, for example, through less resource wastage when poor seed viability no longer hinders product quality,
Enhanced breeding programs since successful germination and growth of difficult new lines will open currently unusable germplasm, providing a competitive advantage and reduced risk (e.g. new germplasm can be vital during disease outbreaks and into the future if climatic extremes escalate),
Reduced biosecurity risk, for example, if non-destructive technologies are developed that can detect diseases that would otherwise be transmitted by seeds.
Spill-over benefits for society
By overcoming early crop losses a myriad of potential spill-over benefits for society can be obtained such as improved resource use efficiency on-farm, reduced biosecurity risks and less resource wastage,
High quality seeds mean that essential farm inputs and investments - such as labour, fertilisers, irrigation, mechanisation and crop protection materials - are not lost or wasted, as can be the case if poor seed quality results in crop failure,</td></tr>
</table>

	o This promotes industry with a positive and sustainable image in the public eye.

Intermediate outcomes	The project leader will report progress and discuss future opportunities with Levy payers from the Australian Vegetable Industry and Hort Innovation at project completion.
	Possible future projects, as identified from grower interviews:
	• Development of technologies for non-destructive real time grading of seed for viability pre planting
	  o For example, to ensure variety/cultivar purity, seed uniformity in terms of size and germinability, seeds free from disease, seeds that maintain their viability across seasons etc.
	• Classification of key Australian vegetable lines as short to long-lived
	  o To aid growers and allied industries in seed storage decision-making.
	• Improvements to and increased knowledge about seed storage practices for growers to maintain optimal seed quality.
	• A long-term program to optimise seed quality and seed longevity for growers.
	• Development of Australian Standards for seed quality that must be adhered to by seed suppliers.
	• Programs to produce seeds in Australia and develop lines specifically for Australian conditions (e.g. Centre for Vegetable Excellence in southern Qld).

Immediate outcomes (July 2017)	Provide recommendations to Industry for development of novel technologies and/or practical solutions for future R&D investment consideration. The primary objective will be to ensure seeds supplied to growers are of a high quality (or the grower can seek compensation and/or pay a lower price). Two information fact sheets or industry bulletins summarising findings from industry, literature and future technology reviews will be distributed to Industry at project completion.

Influence activities	Activities to 'set the scene' delivered
	• Growers interviewed in Lockyer and Fassifern Valleys (Qld), Sydney Basin and Bathurst (NSW)
	• Seed issues and problem crops identified and collated
	• Recommendations to overcome key issues identified and collated such as:
	  o Engage new seed suppliers,
	  o Develop new varieties specifically for local conditions,
	  o Centre for Vegetable Excellence (e.g. in southern Qld) for genetic improvement,
	  o Development of Australian Standards that must be adhered to by seed suppliers,
	  o Need for better/truthful labelling on seed packaging,
	  o Development of technologies to non-destructively grade seeds for high viability.
	• Literature review has identified promising non-destructive techniques to assist growers in maximising seed vitality on-farm.

Foundational activities	Funding obtained for VG16028, building upon project VG15021. Relationships developed with (a) Leading growers in key Australian vegetable growing areas (i.e. Lockyer and Fassifern Valleys (Qld), Sydney Basin and Bathurst (NSW)); (b) Researchers at The Australian Centre for Field Robotics (ACFR) at the University of Sydney, QUT Australian Centre for Robotic Vision and QDAFF Society of Precision Agriculture with a view to possible future collaboration towards development of technologies identified in VG16028; and (c) Extension officers from the Greater Sydney Local Land Services.

In summary, longer term outcomes from VG16028 promise:

a. New technology development

New technologies and products with new uses may arise from this project. VG16028 provides recommendations for development of novel technologies via new R&D investment/s with the potential for real time grading of seed for viability pre planting but also the option to ensure seeds are of maximal quality even before they reach the grower and maintain their quality on-farm.

b. Significant productivity boost for growers

Project VG15021 showed that enhanced crop establishment technologies could realistically be adopted by *c.* 50% of the vegetable industry within 7-8 years. Key financial or social benefit estimates that align with VG16028 are shown below:

Higher profits via enhanced crop establishment, growth and yield: (a) Enhanced crop establishment: Project VG15021 showed that seed costs account for *c.* $260m p.a. for the Australian vegetable industry. Assuming expensive and problem lines account for 10% of seed stock, a 20% increase in germination of problem lines accounts for $5.2m p.a., while $5 extra produce harvested for each extra germinated seed provides $52m p.a. (b) Enhanced crop productivity. Assuming a conservative 2% increase in total yield with better seed viability outcomes for 50% of the levied vegetable industry provides $18.5m p.a.

Reduced costs of production via enhanced resource efficiency. For example, assuming labour accounts for 17% of total costs and a 2% reduction in labour costs, this accounts for $6.3m annually for 50% of the industry; assuming fertiliser costs account for 9% of total costs and a 3% reduction in their use, this accounts for cost savings of $5m p.a. for 50% of industry.

Enhanced breeding programs: Successful germination and growth of difficult new lines will open currently unusable germplasm, providing a competitive advantage and reduced risk (e.g. new germplasm can be vital during disease outbreaks and into the future if climatic extremes escalate).

c. Spill-over benefits for society

This project aims to overcome early crop losses for industry, which have a myriad of potential spill-over benefits for society. One key benefit to society is improved resource use efficiency on-farm, hence less resource wastage. High quality seeds mean that essential farm inputs and investments - such as labour, fertilisers, irrigation, mechanisation and crop protection materials - are not lost or wasted, as can be the case if poor seed quality results in crop failure.

Evaluation and discussion

<u>Grower Survey - Issues and Recommendations:</u>

To identify grower needs and opportunities, 10 vegetable growers and 2 industry affiliates (vegetable transplant and canning industry representatives) have been interviewed during a field day or on-farm visits in the key growing areas of the Lockyer and Fassifern Valleys (Qld), Sydney Basin and Bathurst (NSW). A summary of the key points raised within the survey:

Certain suppliers typically supplied excellent quality seeds and the same companies were repeatedly praised by growers. Future programs should begin by understanding why some suppliers are able to provide excellent seeds while others are not.

All growers reported seed viability, purity and/or quality issues from certain suppliers and/or for certain cultivars

- Many growers described quality seeds at their most important farm input
    - Without quality seeds all other resources are wasted,
    - Growers are happy to pay extra for high quality seeds.
- Some growers have resorted to importing their own seeds because Australian seed suppliers do not meet the quality and quantity standards needed.
- Growers commonly observed seed viabilities of < 85% – ideally 98% viability is the target.
- Currently vegetable growers are price takers of seeds – ideally would like to become price setters.
- Growers and other seed users (e.g. transplant suppliers) are often forced to use seeds even if they are of poor quality because they need that specific variety to meet market demands.

Seed issues

- Poor germination percentage and non-uniform emergence
    - Identified in certain varieties of sweetcorn, cabbage, cauliflower, lettuce, beetroot and other crops.
- Disease transmission via seeds
    - Overseas seed production was perceived as a potential biosecurity threat,
    - Growers suspect many diseases are entering production systems via infected seeds,
    - Diseases of concern were *Botrytis spp.* fungus, verticillium wilt fungus (*Verticillium spp.*), *Alternaria spp.* fungus, *Rhizoctonia spp.* fungus, black rot bacteria (*Xanthomonas spp.*) and cucumber green mottle mosaic virus (*Tobamovirus genus*).
- Varietal impurity
    - For example, non-hybrid seeds are mixed into hybrid lines, multiple varieties/cultivars are mixed together or the entirely wrong variety is supplied to the grower.
- Non-uniform seed size
    - Larger seeds were perceived to have higher vigour,
    - Uniform seed size is needed for optimal machinery performance (e.g. to avoid sowing of 2 seeds into one location).
- Damage to seeds
    - Cleaning practices often damage seeds; better cleaning practices are needed.
- Seed enhancements need improvement
    - Techniques such as priming, pelleting and hot water treatments need to be improved,
    - Presently many reduce seed quality rather than enhance it.

Other key issues (from certain suppliers):

- Seed supplier insincerity from certain suppliers was a key issue
    - Behaviour deemed ‘unprofessional’ from certain seed suppliers towards growers. For example, the grower must just ‘accept what they get’ even if seed quality is poor and compensation is rarely provided,
    - Truth in labelling is needed as often the grower cannot trust what is written on the packet, e.g. 95% germination is on the packet but only 70-80% of seeds germinate,

    - Some seeds are sourced from inappropriate locations, such as developing countries, hence seed quality is poor OR from inappropriate climates so seeds/crops have poor outcomes in Australia (e.g. deserts of California, cool regions of New Zealand).
- Lines are generally not bred or grown in conditions that resemble Australian conditions hence do not perform well in Australian conditions.
- Large companies have bought many of the local/smaller companies with consequences for Australian growers
    - The Australian market is too small to justify investment in breeding programs for Australian conditions,
    - Massive skills gap within the market,
    - Many breeding programs (including international) have been shut down by these companies.
- Disease resistance is not holding up in many available lines.
- Labelling needs more information and that information needs to be accurate.
- New lines are not being made available on the Australian market.
- Lead-in times for seed are very long, seeds are not available on-hand.

Grower recommendations to overcome key issues

- Engage more seed suppliers who can provide growers with what they need, for example:
    - Bring in new companies that are willing to do breeding in Australia or at least under climatic conditions similar to those in Australia,
    - It was perceived that there are not enough seed producers/suppliers so if a bad season hits the grower 'gets what they get'.
- Develop new varieties specifically for local conditions
    - Seed production in Australia was seen as a high priority by most growers,
    - Overseas seed production was perceived as a potential biosecurity threat.
- Centre for Vegetable Excellence (e.g. in southern Qld)
    - Genetic improvement was viewed as a key priority,
    - Growers suggested that the biggest industry suppliers of key crops in Australia be involved to develop varieties for the Australian climate and market needs.
- Development of Australian Standards for seed quality
    - Understand why certain suppliers can supply excellent seeds while others cannot,
    - Development of 'A' and 'B' grade seed standards that give the grower a choice to pay more for premium 'A grade' seeds or pay less for poorer 'B grade' seed lots,
    - Learn from the 'good suppliers' and construct seed standards with their participation,
    - Explore penalties for seed suppliers if seed quality parameters on the label are not met.
- Need better/truthful labelling on seed packaging.
- Screening trials
    - Engage a body such as the DPI or UQ to undertake screening trials with seed companies and engage growers to do final proof-of-concept trials for new varieties.
- Development of technologies to non-destructively grade seeds for high viability
    - Growers suggested that the Vegetable Industry could invest in the development of these technologies and royalties from IP and sale of technologies would return into the Vegetable Levy,
    - Possible partnerships with providers such as GRDC who face similar problems,
    - Maintenance of IP in Australia a key priority,
    - Machinery itself bought and owned by seed suppliers.

Other key points

- A long-term program to optimise seed quality (via pollen quality) and longevity (via maternal plant health) through environmental growth optimisation at the seed production phase was viewed highly favourably by growers
    - Viewed as a real opportunity to maximise seed quality for the Australian vegetable industry,
    - Kochanek was the first researcher to discover this phenomenon (Kochanek *et al.*, 2010, 2011) and will engage growers at project conclusions to determine feasibility of this research.
- The UQ-developed 'seed pouch' and app to destructively determine seed quality on-farm was <u>not</u> deemed useful for growers

- Growers would prefer to outsource such services to seed testing laboratories and/or have confidence in quality from seed suppliers in the first place.
- Seed storage practices on-farm
    - Most growers store seeds for <1 year, generally in air-conditioned rooms, hence seed deterioration on-farm was generally not a major issue,
    - Nonetheless some growers kept discontinued lines or excess seeds between seasons,
    - Hence the final project report will make recommendations to industry about optimal seed storage conditions to optimise seed longevity.
- A future project that classifies key Australian vegetable varieties/cultivars as short to long-lived was deemed useful for industry
    - Seeds of some varieties were noted to live longer than others within a crop,
    - Knowing inherent seed longevity for a given line would mean fewer repeat germination tests and an ability to keep lines between seasons,
    - Industries that could particularly benefit are, for example, baby leaf cut lettuce and spinach industries, sweet corn and beetroot canning industries and others.

Literature Review Recommendations:

Levy payers across industry identified that seed viability, purity and/or quality issues are a major concern, hence the literature review has compiled R&D solutions or provided recommendations towards the development of such solutions.

The definition of a high quality seed lot from grower surveys is one that is disease-free and genetically pure, with high germination (>95%) and uniform seedling establishment and with seed sizes and shapes that fit well into existing machinery.

1) Promising non destructive technologies for real time grading of seed quality

The most promising technologies to grade seed quality non destructively, in real time and across most of the areas of concern for growers were reviewed in the literature. Innovative computer-assisted analysis systems to grade seed quality in real time - based on external and internal seed attributes such as surface texture and colour, light reflectance and fluorescence, seed size, shape, density and more – are emerging and promising to be faster, easier and more accurate than traditional seed viability analysis by technicians or rudimentary seed grading machinery (Cantliffe, 2003; Dell'Aquila, 2009; Huang *et al.*, 2015). The review covered computer vision, electronic nose and thermal imaging techniques and various optical analysis techniques, including infrared spectroscopy, hyperspectral imaging, chlorophyll fluorescence, X-ray imaging and biospeckle laser techniques. Of these, those that quantify seed optical properties and thermal dynamics were deemed the most useful to address grower needs.

Hyperspectral imaging was identified as the most useful technology because it combines spectroscopic imaging and computer vision to simultaneously determine interior and exterior seed qualities. Its rapid data acquisition capacity and ability to gather multiple complex attributes at high resolution simultaneously and under variable conditions makes it the most promising technology for conveyer belt commercial-scale uses. It is also the only currently available technology able to deal with specific seed sorting realities and complexities, such as overlapping and clumped seeds and distinguishing between seeds with similar sizes, colours and shapes. The main limitation hindering commercial use of hyperspectral imaging has been the huge amount of data it generates, which slows and overcomplicates the seed classification process. This is now being overcome by researchers selecting specific effective wavebands to build more simple imaging systems that are slightly less accurate but still meet the quality requirements of the grower (ElMasry & Sun, 2010; Dumont *et al.*, 2015; Fahlgren *et al.*, 2015; Rahman & Cho, 2016).

Thermal imaging was also identified as a promising technology for automated non destructive seed sorting, being a highly sensitive, non-contact and affordable technique with a high resolution in spectral and spatial dimensions and that is completely safe for the seed and user. Currently, the drawbacks limiting its usefulness for real time seed sorting are its requirement for a long data acquisition window of around 15 seconds, need for environmental stability and inability to sort clustered or overlapping seeds; on a conveyor belt this would mean stopping the production line to gather seed quality data. However, given that thermal imaging is a much newer technology than hyperspectral imaging, thus without the R&D background, thermal imaging limitations may be overcome with future R&D investment (Kranner *et al.*, 2010; Dumont *et al.*, 2015; Rahman & Cho, 2016).

R&D Challenges and Future Direction

Future R&D will need to overcome seed lot complexity and variability if new technologies to grade seed quality in real time for growers are to become a reality. Artificial intelligence is already used in horticulture and agriculture for simple and repetitive on farm tasks such as weed management (Ball *et al.*, 2015) and yield prediction (Underwood *et al.*, 2016). Thus, given that seeds are complex and variable living organisms, seed quality grading success will come with building upon simple systems. A future project to develop such technologies may require, for example:

- Time to learn intricacies of seed lots for each crop or line of interest, such as subtleties in seed external appearance and internal chemical and physical composition. Indeed, these traits will vary between seasons and crops and sometimes between varieties or cultivars of a single crop.
- Time to learn how seed features relate to biological attributes that are important for growers, such as in-field seed viability and vigour to ensure uniform seed emergence and crop growth,
- A long phase of evaluation and validation for each new trait to be assessed and sorted, with significant learning needed to correlate the image-extracted traits to biologically relevant quality attributes of seeds (Fahlgren *et al.*, 2015),
- For each new application or crop line a new process of learning and expertise building will be needed to ascertain the meaning of measurements and to put them into the correct biological context (Braga *et al.*, 2005).

Complex traits may require a multi-step sorting process with several techniques used one after the other or multiple techniques used simultaneously to grade seed quality to the precision required by industry (Pannico *et al.*, 2015). Indeed, this may even entail combining currently used seed sorting machines with novel techniques, such as new hyperspectral imaging techniques with presently used gravity tables (Hansen *et al.*, 2017).

(2) Maximising Seed Viability and Longevity for Industry

Section 6 of the literature survey determined that scarce research has been undertaken into understanding vegetable seed viability and longevity characteristics or how these seed quality traits can be maximised through pre- and post-harvest cultural practices.

Thus key areas for future R&D investment identified in this review include:

(a) A definitive classification of key vegetable crops as short to long lived to inform storability decisions for seed producers and vegetable growers. This would entail a holistic comparison of the most economically important cultivars and varieties for the Australian vegetable industry.

(b) Significant opportunity to improve vegetable seed viability and longevity by optimising:

(i) The pre-harvest crop growing environment. This work would follow on from the author's ground-breaking research that was the first to determine that paternal and maternal plant health plays a combined and cumulative role in significantly improving seed viability and longevity. Future research would identify those conditions that optimise pollen quality and maternal health for industry's most economically important cultivars and varieties with a view to significantly improving seed viability and longevity for the grower.

(ii) The timing of seed harvest. Future research would identify optimal seed collection windows for industry's most economically important cultivars and varieties to maximise seed viability and longevity at harvest and thus for the grower in the longer term.

The review also highlighted the need for appropriate seed storage conditions to ensure maximum seed viability is maintained during seed storage and on farm. A technical bulletin will communicate this information to industry over the coming months.

Concluding Remarks

The next steps for project VG16028 will be grower consultation to prioritise R&D activities. Since each challenge requires unique solutions, grower seed quality issues have been divided into six Pillars: germination, viability, seed aging, uniform emergence and vigour (Pillar 1), seed-borne disease (2), varietal impurity (3), damage to seeds (4), seed mass, fill and density (5) and seed size, uniformity of size and shape of seeds (6). Levy payers will be consulted via a strategy meeting in 2018 to ascertain which of the six seed quality Pillars are their first priority. Future R&D activities will thus follow.

Recommendations

CONTEXT FOR RECOMMENDATIONS

Growers require high quality seed for long term crop performance and management on farm. Hence the Australian vegetable industry tendered project VG16028 to (a) identify grower seed quality issues and (b) provide recommendations for future R&D investment into technologies, activities or techniques that can evaluate and improve seed viability prior to planting on farm. The University of Queensland (UQ) Plant Growth and Productivity Optimisation team delivered the project.

At project onset a review of Australian vegetable industry needs from face-to-face grower surveys identified pressing on farm seed quality issues. Growers described quality seeds as their most important farm input. Certain suppliers typically supplied excellent quality seeds and were repeatedly praised by growers. Other suppliers commonly supplied substandard seeds. Future programs should begin by understanding why some suppliers are able to provide excellent seeds while others are not.

Key seed quality issues

- Poor germination percentage and non-uniform emergence,
- Seed-borne disease transmission – potentially critical biosecurity issue if seeds are imported from overseas,
- Varietal impurity,
- Non-uniform seed size,
- Damage to seeds,
- ‘Seed enhancements’ reducing seed quality (e.g. priming, pelleting and hot water treatments),
- Other concerns: certain seed supplier insincerity, lack of lines bred or grown for Australian conditions, disease resistance not holding up, inadequate or inaccurate seed packet labelling, long lead-in times for seed delivery.

A global review of new technologies, opportunities and/or future program activities to overcome the identified seed quality issues was then completed using information from industry, literature and with input from research allies with the capacity to develop the most promising technologies.

RECOMMENDATIONS TO INDUSTRY

1. Development of Australian Standards for seed quality
   Understand why certain suppliers can supply excellent seeds while others cannot,
   Learn from the ‘good suppliers’ and construct seed standards with their participation to:
   - Address the critical need for better and/or truthful labelling on seed packaging,
   - Give the grower a choice to pay more for premium ‘A grade’ seeds and less for poorer ‘B or C grade’ seeds,
   - Explore the use of penalties if seed quality parameters on the label are not met.

2. Development of technologies to non-destructively grade seeds in real time for high viability

   - Machinery would be bought and owned by seed suppliers; royalties from IP and sale of technologies would return into the Vegetable Levy,
   - A comprehensive literature review compared emerging artificial intelligence (AI) technologies for grading seed quality to currently available destructive tests and machinery for processing seeds,
   - Artificial intelligence technologies promise to be far superior to currently available technologies for real time seed quality grading automation, ensuring the high precision and accuracy required by growers,
   - Of the new technologies, hyperspectral imaging (HSI) was the most promising. Using a combination of spectroscopic imaging and computer vision, HSI is able to simultaneously determine interior and exterior seed qualities while being the only technology reviewed that is able to deal with seed sorting realities and

complexities (e.g. overlapping and clumped seeds, distinguishing between seeds with similar sizes, colours and shapes),
  - Thermal imaging was also identified as a promising technology for automated non destructive seed sorting but is a newer technology hence requires more R&D prior to being useful commercially,
  - Researchers at The Australian Centre for Field Robotics (University of Sydney) were identified as potential collaborators to deliver technologies with the UQ team via future R&D Levy investment,
  - Technology development could be in partnership with providers who face similar problems (e.g. Grains Research and Development Corporation).

3. A long-term R&D program to improve vegetable seed viability and longevity for industry

   - Growers unanimously agreed that programs to better understand and maximise vegetable seed viability and longevity presented real opportunities to improve seed standards for industry,
   - The literature survey determined that scarce research has been undertaken into understanding how vegetable seed viability and longevity can be maximized,
   - The UQ team has the capacity to deliver this R&D for industry.

   Three significant R&D opportunities were identified

   (i) A long term R&D program to determine the influence of environmental conditions and planting times of parent lines to maximise seed quality for industry's most economically important lines. This would follow on from ground-breaking UQ research that has determined that pollen and maternal plant health can be enhanced by optimising growing conditions prior to seed harvest, with a cumulative flow-on effect that then significantly improves seed viability and longevity.

   (ii) Identify optimal seed collection windows for industry's most economically important cultivars and varieties. Currently immature or over-mature seed harvesting is resulting in poor seed quality and more information is needed to address this issue.

   (iii) Classify the most economically important vegetable lines as short to long lived to inform storability decisions for seed producers and vegetable growers. Seeds of a given crop or line can be classified as short to long lived, however scarce research has been undertaken into understanding these trends for vegetables.

4. Programs to develop new varieties for local conditions

   - Developing new varieties for local conditions was a high priority for most growers,
   - Discussions are needed to ascertain best strategy forward. Strategies suggested by growers:
     (i) Engaging seed suppliers who are willing to undertake breeding programs in Australia or under climatic conditions similar to those in Australia, as a means of insurance against bad seasons, and/or
     (ii) Creation of a Centre for Genetic Improvement to undertake this research in Australia, possibly as a collaboration between growers, researchers, breeders and seed suppliers.

The next steps

- Growers have been invited via two industry bulletins to submit more seed quality information directly to the UQ team (seedqualitystudy@uq.edu.au),
- Following this second phase of data gathering, Levy payers will be invited to a strategy meeting in autumn 2018 to prioritise seed quality issues and future R&D activities to bring the greatest benefits and profitability across the Australian vegetable sector,
- Since sister project VG15021 is already developing transformational technologies for the vegetable industry to optimise seed quality, the two projects combined will build a holistic approach to seed quality assurance for vegetable growers and future mechanisation, field robotics and/or precision agriculture will ideally be optimised simultaneously.

Scientific refereed publications

None to report.

Intellectual property/commercialisation

No commercial IP was generated.

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Appendices and attachments

Output 1 – GROWER INTERVIEWS: Key issues and recommendations from face-to-face grower interviews
Output 2 – LITERATURE REVIEW: On farm seed viability and ways to overcome key issues
Output 3 – Industry Bulletin #1: Turning seed quality failure into consistent success: How widespread is the problem?
Output 4 – Industry Bulletin #2: Turning seed quality failure into consistent success: The R&D journey begins

Literature Review

On farm evaluation of vegetable seed viability using non-destructive techniques

Dr Jitka Kochanek and Dr Santi Krisantini
The University of Queensland

Project number: VG16028

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1. PROJECT BACKGROUND

1.1 HISTORICAL BACKGROUND

Vegetable crops that are field established from seed, such as corn, beans, carrots and spinach, require excellent seed quality as the primary and essential starting point of the production program. Poor quality seeds propagate a substandard crop, resulting in essential farm inputs and investments being lost or wasted. This is true for any scale of operation regardless of the size of the enterprise (George, 2009).

The vegetable industry Levy and HIA are funding a confidential program titled **"***Sowing success through transformational technologies to boost productivity and commercial outcomes"* (VG15021) to develop technologies that optimise seed longevity and seedling establishment success for the Australian vegetable industry. Specifically, naturally occurring compounds and slow release technologies for improved vegetable crop performance are being developed with a view towards commercialization over a 4 year timeframe (2015-2020).

This current project, VG16028: "*On farm evaluation of vegetable seed viability using non destructive techniques"*, will complement and build upon the VG15021 program as there are clear opportunities to share and/or optimise technologies from one project to the other. Since VG15021 is already developing transformational on farm crop establishment technologies for the vegetable industry, the two projects combined will build a holistic approach to seed quality assurance for vegetable growers and future mechanisation, field robotics and/or precision agriculture will ideally be optimised simultaneously.

1.2 PROJECT RATIONALE AND OBJECTIVES

VG16028 is a multifaceted project. At project onset a review of Australian vegetable industry needs from face-to-face grower surveys identified pressing on farm seed quality issues. A global review of new technologies, opportunities and/or future program activities to overcome the identified seed quality issues has since been completed using information from industry, literature and with input from new research allies who have the capacity to develop the most promising technologies. The key project focus has been a review of emerging non destructive and cost effective techniques to screen viable seed and maximise germination and vigour once planted. Information and recommendations from the VG16028 review will inform future R&D investment strategies. A meeting with key Levy payers is scheduled for autumn 2018 where future project investment will be determined, for example towards long term programs to optimise genetic and environmental influences pre- and post-harvest to maximise vegetable seed quality before seeds reach the grower and/or develop of robotics, intelligent systems and sensor technologies to maximise seed viability pre planting.

1.3 SIGNIFICANCE FOR INDUSTRY

Program logic analysis identified that future R&D investment for VG16028 promises a significant **productivity boost** for industry, for example via (a) higher profits from enhanced crop establishment and uniformity resulting in improved crop growth and harvest outcomes, (b) reduced costs of production via enhanced resource efficiency, such as through less resource wastage if labour, fertilisers, irrigation, mechanisation and crop protection materials are not wasted, (c) reduced biosecurity risk, for example, if non destructive technologies are developed that can detect diseases that would otherwise be transmitted on farm from seeds and (d) enhanced breeding programs since successful germination and growth of difficult new lines will open currently unusable germplasm, providing a competitive advantage and reduced risk. Indeed new germplasm can be vital during disease outbreaks and if climatic extremes escalate. **New technologies and products** with new uses may arise from this project. For example, the Australian vegetable industry may invest in the development of technologies to non destructively grade seeds for high viability, which can then provide royalties to the vegetable Levy from IP and sale of technologies. **Spill-over benefits for society** may include improved resource use efficiency on-farm, reduced biosecurity risks and less resource wastage.

Thus key linkages to the Australian vegetable industry **Strategic Plan** are through Pillar 2: Market and Value Chain Development, by developing promising novel technologies (SIP strategy 2.4.2) and giving Australian products a competitive advantage over imports (2.3.4); Pillar 3: Improved Farm Productivity, Resource Use & Management by developing transformational R&D to enhance the productivity of the Australian Vegetable industry (3.1), reducing the costs of inputs such as labour, fuel, energy, fertiliser and other costs (3.5) and improving biosecurity by proactively managing biosecurity risks to industry productivity (3.6) and Pillar 1: Meeting consumer needs both domestically and internationally by maintaining a positive image of the industry through society benefits (1.4). Further, knowledge and recommendations have been communicated to Industry through multiple networks for increased industry engagement (SIP strategy 4.2) such as an industry field day in the Sydney Basin, two industry bulletins and a strategic R&D planning day scheduled for 2018.

2. SEED QUALITY

2.1 DEFINING SEED QUALITY

A **high quality seed lot** is one that is genetically pure, not mixed with seeds of other crops, is free from disease and has a high viability and vigour. A **vigorous seed lot** is one that has a high planting value and performs well even under environmental conditions that are not optimal for that crop (Dumont *et al.*, 2015; ISTA, 2013). More specifically, **seed quality** comprises elements of (a) **genetic quality**, which is the 'trueness to type' or cultivar/varietal purity of a seed lot, (b) **physical purity**, which is the presence of contaminants such as seeds of other crops or weeds, soil or unwanted plant debris, (c) **seed health**, which is the presence of seed-borne pathogens such as fungi, bacteria and viruses, pests such as nematodes and insects and physiological conditions such as those that arise from trace element deficiency, (d) **viability**, which is the potential germination and subsequent production of a seedling of the correct cultivar or variety, (e) **vigour**, which is the planting value in a wide range of environments and/or the storage potential of a seed lot, including the rate and uniformity of seed germination and seedling growth, emergence ability of a seed lot under unfavourable conditions and the seed lot performance after storage, (f) **moisture content** of the seed lot and (g) end-user-driven attributes such as seed size, shape and colour as required, for example, by sowing machinery or consumers (George, 2009; ISTA, 2013; Huang *et al.*, 2015; Dumont *et al.*, 2015).

Seeds reach a maximal germination and vigour peak at their physiological maturity, after which time their quality declines until germination is entirely lost. This seed quality peak can be influenced by conditions before the seed is developed. Specifically, conditions that change the pollen quality and maternal health of the parent plant(s) determine the quality and longevity of a seed lot and therefore how long that quality can be maintained over time. The report author was the first researcher in the world to discover this phenomenon, whereby specific growing conditions were shown to drastically improve or harm seed quality and longevity for plant species (Kochanek *et al.*, 2010, 2011). How quickly seeds deteriorate after they reach peak quality is influenced by genetics, since an inherent longevity exists for a given species, crop or line (Kochanek *et al.*, 2009; Probert *et al.*, 2009; Nagel *et al.*, 2015) and the seed post-harvest environment, such as seed handling and seed storage conditions, including seed moisture content, storage temperature and oxygen pressure, pest damage and internal and external seed pathogen contamination (Dell'Aquila, 2009).

2.2 LITERATURE REVIEW SCOPE

The Australian vegetable industry needs high quality seeds to ensure high seedling emergence rates and a uniform crop for a successful harvest. Levy payers across industry have identified that seed viability, purity and/or quality issues are a major concern for industry, hence the following Sections review R&D solutions from literature or provide recommendations towards the development of such solutions. Tests and technologies to grade seed quality are reviewed first, including: destructive tests that are used in accredited laboratories around the world and new tests that are emerging from research facilities (Section 3), currently available machinery to process seeds for improved quality (Section 4) and new non destructive technologies that use innovative computer-assisted analysis systems for real time automation of seed quality grading (Section 5). Section 6 reviews factors that determine the germination and vigour peak attained by a seed lot at physiological maturity and the rate at seeds subsequently deteriorate including: genetic effects, pre-harvest parental effects, seed maturity at harvest and postharvest conditions.

3. DESTRUCTIVE TESTS TO DETERMINE SEED QUALITY

3.1 DESTRUCTIVE TESTS IN ISTA ACCREDITED LABORATORIES

"Seeds are living organisms and will ultimately die, no matter how well they are stored, so it always pays to have an up-to-date test on any seed you plan to purchase or sow" (ASA, 2017).

The International Seed Testing Association (ISTA) was established in 1924 to ensure uniformity in seed testing laboratories internationally, and publishes a continually updated handbook of rules, named the International Rules for Seed Testing or ISTA Rules, for destructively determining seed quality of crops and production plants (Aveling & Blanco, 2009). Experienced technicians in seed testing laboratories across 72 countries determine seed quality and viability based on the ISTA Rules, using a combination of techniques such as (a) manual counting and grading of germinating seedlings, (b) biochemical tests that stain living seed tissue but not non-viable seeds (e.g. tetrazolium test), (c) X-ray tests to rapidly and non destructively determine filled, empty, insect-damaged and physically damaged seeds and (d) vigour tests that provide information about the planting value and storage potential of seed lots using, for example, conductivity tests which determine seed leachate quantities that increase as vigour declines, controlled deterioration and accelerated aging tests whereby seeds are rapidly aged under controlled high temperature and moisture conditions to quantify how quickly a seed lot is likely to deteriorate and radicle emergence tests (ISTA, 2013).

While ISTA tests provide vital information about seed lot quality, they are time-consuming and usually destructive laboratory-based methods that are not designed for large-scale automation and/or real-time grading of seeds (Dumont *et al.*, 2015).

3.2 NOVEL DESTRUCTIVE TESTS

Highly accurate and reliable destructive techniques are already available to detect various seed quality anomalies, for example molecular identification, DNA analysis, isotope fingerprinting and mineral element analysis to detect varietal quality and protein electrophoresis, gas chromatography and HPLC to quantify sowing quality (Huang *et al.*, 2015). Similarly, ISTA laboratories use destructive seed health tests to detect various seed-borne diseases for vegetable crops, as shown in Table 1, using an array of methods that vary in novelty, sensitivity, reproducibility and in the amount of training and equipment required. Tests range from simple assays to more complex molecular identification and DNA analysis techniques (ISTA, 2017a).

Table 1. Seed-borne diseases of vegetable crops that can be detected using destructive ISTA laboratory seed health tests (ISTA, 2017a,b).

Crop	Seed-borne diseases detected by destructive ISTA tests
Carrot	*Alternaria spp.* fungi that causes leaf blight, *Xanthomonas hortorum* that causes bacterial blight
Brassica spp.	*Phoma lingam* fungus that causes blackleg disease, *Xanthomonas campestris* pv. *campestris* bacterium that causes black rot
Beans	*Colletotrichum lindemuthianum* which causes anthracnose or black spot disease, Xanthomonas axonopodis that causes bacterial bean blight, *Pseudomonas savastanoi* that causes bacterial halo blight
Cucurbits	Squash mosaic virus (SqMV), Cucumber green mottle mosaic virus (CGMMV) and Melon necrotic spot virus (MNSV)
Corn salad (*Valerianella locusta*)	*Acidovorax valerianellae* that causes bacterial leaf spots

Species and variety testing can also be determined in ISTA laboratories if an authentic standard sample of the correct variety or species is available for comparison. Laboratory tests utilise morphological, physiological, cytological, chemical, bio-molecular (using DNA, RNA, protein or other specific metabolic products) and germination tests as appropriate (ISTA, 2013).

Limitations of these techniques are that they are expensive per seed lot, take a long time to complete and require high operator skills to perform (Huang *et al.*, 2015). Further, their destructive nature means that they are not suitable for real time grading and automation and hence are beyond the scope of this current review. Nonetheless, such techniques may be explored in subsequent projects if Industry suggest that they warrant development, for example for biosecurity purposes such as to ensure imported seeds are not infected with pathogens.

4. TRADITIONAL NON DESTRUCTIVE MACHINERY FOR SEED GRADING

Seed conditioning or processing is the name given to equipment that upgrades seed quality by physical criteria; in a horticultural context with a view to ensuring uniform germination and high seedling densities on farm. This equipment, for example, removes contaminants such as seeds from weeds and unwanted crops, inert material and poor quality seeds such as those that are immature, damaged, contaminated or undersized (Cantliffe, 2003; George, 2009; Dumont *et al.*, 2015). Rudimentary machines to non destructively upgrade seed quality are widely available commercially and are briefly reviewed below.

4.1 PRE-CLEANING

Pre-cleaning is used prior to seed upgrading and includes processes such as:

- Winnowing: Following threshing and seed drying, debris and less dense seeds are removed by air movement, such as with air from an electric fan. A skilled operator can remove almost all debris and empty seeds with this process (Chaplin, 1985; George, 2009).
- Scalping: Vibrating and rotating sieves, usually with an air flow to remove light debris, separate out plant debris and other non-seed materials and de-clump seed clusters (George, 2009).
- Removal of surrounding plant parts for certain crops, for example:
    - Shelling machinery passes sweetcorn cobs through a drum with a rotating beater to separate the kernels from the cob which are then passed through a screen (George, 2009).
    - Debearding or de-awning machines remove appendages that otherwise result in seed clustering, such as for carrot and dill seeds, or de-clump seeds that are removed from wet fruit, such as for tomato and cucumber seeds (George, 2009).
    - Brushing machines use rotating brushes against mesh surfaces to separate plant parts, such as to detach carrot seeds from their umbels, stalks from lettuce seed inflorescences and can be used to clean small seed lots (George, 2009).

4.2 SEED UPGRADING

Seed upgrading is the process of improving the quality of a seed lot by removing low quality seeds, such as those that are cracked, insect damaged, broken or injured and/or of inferior quality, such as having a low density (McDonald & Copeland, 1997). Grading by gravity, magnetic, electrostatic, air and colour separation are briefly discussed below.

4.2.1 Gravity separation

Other names: gravity table, gravity separator

Gravity separation utilises fans and vibration along a sloping deck to sort seeds for their bulk density and size by moving heavier seeds up the deck slope and lighter seeds down the deck (Figure 1). Thus this process sorts the seed into higher and lower quality fractions, with the lighter seeds being of lower quality, for example, having a lower bulk density and/or being damaged, empty, insect-infested, diseased or sterile (Krueger *et al.*, 2007; George, 2009).

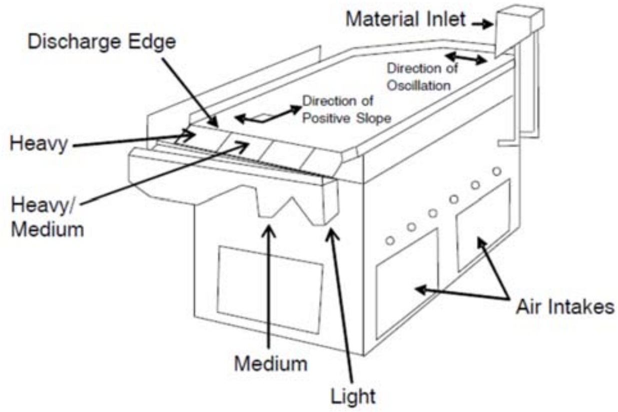

Figure 1. A gravity table used to separate broken kernels and foreign material from corn (Oliver model 50; Krueger *et al.*, 2007). Dense/heavy seeds are collected at the top of the slope and light material at the lowest part of the sloped deck.

4.2.2 Electrostatic separation

Other names: electrical separators, electrostatic separators

Electrostatic separators use differences in the electrical characteristics of seeds to sort seeds of different crops and species or with different seed qualities, such as damaged versus undamaged seeds. The technique electrically charges the seeds and allows separation based on their different electrostatic charges (Salam *et al.*, 2004; Butunoi *et al.*, 2011; Basiry & Esehaghbeygi, 2012). The technique may not be useful for all crops, showing no differences in germination between sorted and unsorted wheat and canola seeds, but a 17% higher germination for barley seeds post sorting when compared to pre-sorting with an electrostatic separator (Basiry & Esehaghbeygi, 2012). An example experimental electrostatic separator is shown in Figure 2.

Figure 2. An electrostatic separator used for experimental purposes to separate wheat, canola and barley seeds with high and low germination (Basiry & Esehaghbeygi, 2012).

4.2.3 Air separation

Other names: air-stream separator, aspirator, precision air classifier, vacuum separator

Aspirators use a rising air-stream to separate seeds and chaff with different specific gravities and sizes (Figure 3). A skilled operator manipulates the rate of feed and airflow velocity and volume to optimise cleaning results for different crops and seed lots (George, 2009; McDonald & Copeland, 1997).

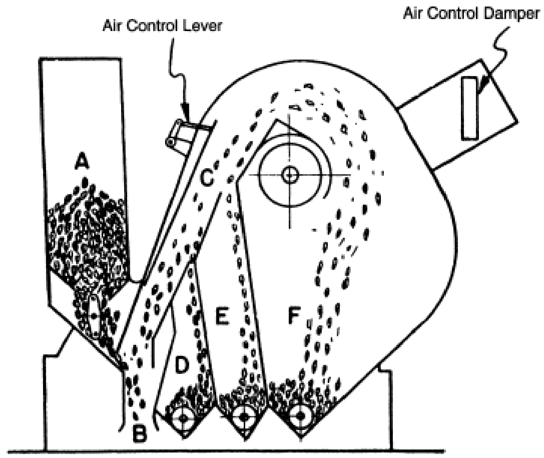

Figure 3. A fractionating aspirator that uses air to separate quality seeds from poor quality seeds and unwanted materials based on their specific gravities. Seeds fall from a hopper and the heaviest and highest quality seeds fall into bin B, while the poorest fraction, often with debris, chaff and empty seeds, fall into bin F (McDonald & Copeland, 1997).

4.2.4 Electronic colour separation

In certain crops, seed coat colour can indicate variable levels of seed quality, such as for watermelon cv. Crimson sweet (Mavi, 2010), canola (Zhang et al., 2013) and snap beans (Lee *et al.*, 1998). For lines where these colour trends are consistently associated with seed quality, such as for pea and bean seeds or any seeds infected with halo blight, colour separators are used to remove off-colour seeds to increase seed lot quality. The seeds move past a photoelectric cell that senses and removes the off-colour seed with an air jet (Figure 4; George, 2009).

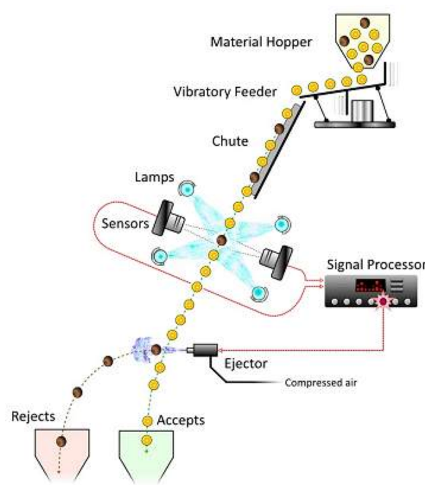

Figure 4. A chute type colour sorter for sorting ergot, wheat, rice, beans and other pulses by their seed coat colour (Satake Australia, 2017).

4.2.5 Other seed grading technologies

Other seed grading technologies used for vegetable seed separation and grading (George, 2009):

- Disc and cylinder machines use discs and cylinders to catch seeds, removing them from unwanted debris.

- Spiral separators use inner and outer spirals to separate spherical from irregularly-shaped seeds, such as to separate damaged seeds and unwanted materials from clean and intact *Brassica* seeds.
- Needle drum separators use needles inside a revolving drum to catch and separate insect damaged pea and bean seeds from clean lots.
- Magnetic separators separate rough from smooth surfaced seeds. In this process all seeds are coated in water or oil and iron dust and are passed over a magnetised roller; seeds with a rough coat adhere more iron dust and can be removed from the seed lot.

4.3 RUDIMENTARY MACHINES VERSUS NEW TECHNOLOGIES

The problem with currently available seed sorting machines is that their precision often does not meet the demands of growers (Dumont *et al.*, 2015) who aim for high germination percentages (ideally >95%,) uniform seed size and shape to fit into sowing machinery, uniform seedling establishment, varietal purity and disease-free seed lots (Output 1, grower interview summary). Promising new technologies that use computer-assisted systems with the aim of grading seeds in real time and with the high precision required by growers are reviewed in the following Section.

5. NEW NON DESTRUCTIVE TECHNOLOGIES FOR REAL TIME SEED GRADING

This Section reviews novel seed grading technologies and is the principle focus of this literature review. These new techniques utilise **artificial intelligence**, defined as “intelligent machines that perform tasks as well as, or better and faster than, humans can….using math- and computer-based solutions to solve problems”. Indeed, artificial intelligence is a well-researched field benefitting from algorithm development in wide disciplines, with applications ranging from computer-generated imagery (CGI) in movies and numberplate and facial recognition sensors to advanced systems for stopping credit card fraud (Harris, 2011).

For applications in horticulture and agriculture, fully automated and integrated robotic systems are still some years away. This is because the farm environment is complex and variable, presenting scientists developing such systems with ever-changing conditions such as dust, rain and wind that complicate mathematical models. Likewise, automation of harvesting or grading produce is complicated because plants or plant parts vary considerably, for example changing in colour, texture or size from season to season or across different lines (Geller, 2016). Nonetheless, artificial intelligence can already assist growers with more simple tasks that are highly repetitive such as weed management (Ball *et al.*, 2015), yield prediction in fruit orchards (Underwood *et al.*, 2016) and driverless farm machinery (Ball *et al.*, 2016). Similarly, innovative computer-assisted analysis systems to grade seed quality in real time - based on external and internal seed attributes such as surface texture and colour, light reflectance and fluorescence, seed size, shape, density and more – are emerging and promising to be faster, easier and more accurate than traditional seed viability analysis by technicians or seed grading machinery (Cantliffe, 2003; Dell'Aquila, 2009; Huang *et al.*, 2015). Reviewed here are computer vision, electronic nose and thermal imaging techniques and various optical analysis techniques, including infrared spectroscopy, hyperspectral imaging, chlorophyll fluorescence, non-lethal X-ray imaging and biospeckle laser techniques. Recommendations on the usefulness and applicability of each technique for real time seed grading for the Australian vegetable industry are presented in Section 5.5.

5.1 COMPUTER VISION

Other names: machine vision, computer image processing (Huang *et al.*, 2015).

Computer vision is a form of artificial intelligence that simulates human vision, usually using the visible light spectrum of 380 to 780 nm. Computer vision identifies and grades seeds based on image features including, for example, their size (using the number of pixels), shape (using the target boundary), colour (intensity of red, green, blue pixels) and texture (variations in pixel intensity; Huang *et al.*, 2015).

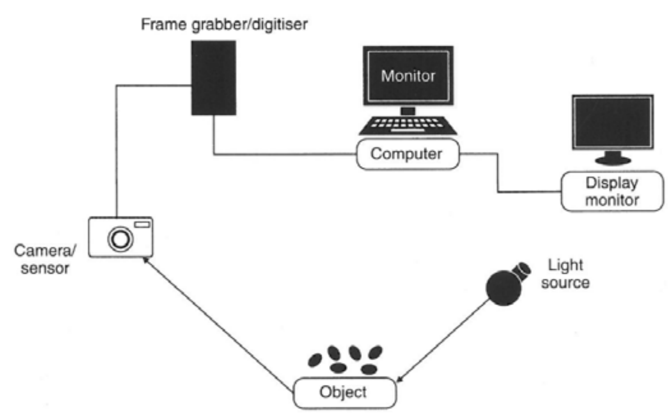

Figure 5. Steps involved in the computer vision process (from ElMasry & Sun, 2010).

How computer vision works: Important steps in the computer vision process, shown in Figure 5, translate the raw image into useful information for further analysis and involve the acquisition of an image by a camera or sensor, image pre-processing, which enhances the image quality, image segmentation, which partitions the imagine into multiple parts so it is easy to analyse and feature extraction, which simplifies the image into a reduced set of features that can then be analysed individually (Huang *et al.*, 2015).

Seed quality applications: Computer vision technology has been used for seed quality processing applications such as purity detection using morphological and colour features, for example to identify unwanted varieties within a seed lot (Arefi *et al.*, 2011; Nasirahmadi & Behroozi-Khazaei, 2013), exterior damage and injury detection and location of such issues within the seed (Tan *et al.*, 2014). It has also been used to detect seed-borne disease (Tan *et al.*, 2014), quantify seed maturity (Rodriguez-Pulido *et al.*, 2012) and for general seed grading purposes based on attributes such as seed colour, size, moisture content, crease depth and others (Kilic *et al.*, 2007; Razavi *et al.*, 2010; LeMasurier *et al.*, 2014; Huang *et al.*, 2015).

Computer vision limitations: There are certain attributes of computer vision that limit its applicability for grading seed quality. For example, internal seed structure and chemical information is not detected because the image registers only the external view of the seed, hence it cannot detect potentially important quality attributes such as chemical composition or invisible defects. Also, it can be inefficient for measuring seeds of a similar colour or for multiple complex traits and attributes (ElMasry & Sun, 2010; Huang *et al.*, 2015).

5.2 MEASURING OPTICAL PROPERTIES TO ASSESS SEED QUALITY

Optics is the discipline of studying light and the interaction of light, or electromagnetic radiation, with matter. Emerging techniques that quantify seed **optical properties** are among the most promising for non destructive quality assessment (ElMasry & Sun, 2010). These methods measure the response of a seed or seed lot to incident electromagnetic radiation (Figure 6) and are particularly useful where several quality attributes need to be determined simultaneously. These technologies grade seeds based on their transmission, reflectance, absorption or scattering of radiation and rely on inferior quality seeds having different optical properties compared to high quality seeds. Spectral instruments detect and measure these optical differences and computer-assisted analysis systems interpret and analyse the data as changes in selected seed attributes (ElMasry & Sun, 2010; Huang *et al.*, 2015). Currently, the greatest challenge to developing these promising new technologies into industrially useful seed grading tools, and the area that requires substantial R&D input, is the correlation of the image-extracted traits to biologically relevant quality attributes of seeds (Fahlgren *et al.*, 2015).

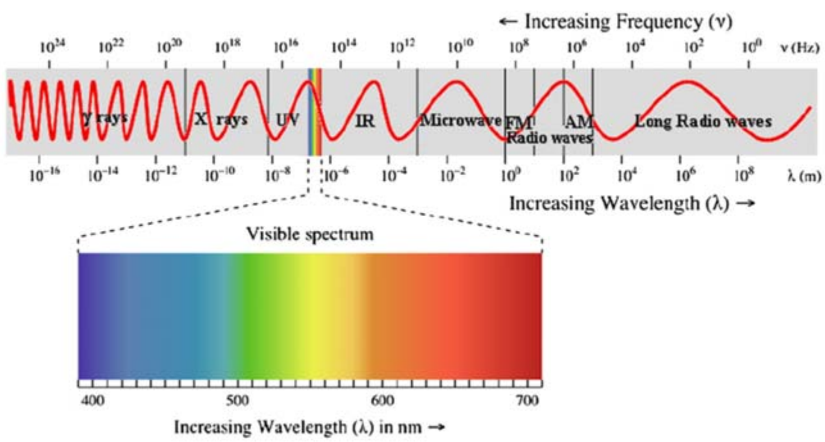

Figure 6. The spectrum of electromagnetic radiation showing wavelengths of gamma rays (γ), X-rays, ultraviolet radiation (UV), visible light (VIS), infrared radiation (IR) - divided into near infrared (NIR), mid infrared (MIR), and far infrared (FIR) regions - microwaves and FM and AM radio waves (ElMasry & Sun, 2010).

5.2.1 Spectroscopy

Spectroscopy is a technology that provides a spectral fingerprint for a seed or seed lot by describing the light intensities emerging from its molecules at different electromagnetic wavelengths which can manifested as, for example, reflectance, transmittance, absorbance, phosphorescence and fluorescence (ElMasry & Sun, 2010; Rahman ad Cho, 2016).

a. Infrared (IR) Spectroscopy

Infrared (IR) spectroscopy specifically deals with the infrared region of the electromagnetic spectrum, using infrared radiation to analyse a seed lot (Huang *et al.*, 2015). **Near-infrared (NIR)** is the most commonly used spectroscopy for seed quality grading (spectrum 780-2500 nm). While mid-infrared spectroscopy (MIR, 2500-25000 nm) has also been used, NIR penetrates deeper into the seed (Huang *et al.*, 2015), hence is discussed here.

How near-infrared spectroscopy works: NIR technology consists of a spectrometer, computerized control of the spectrometer and data acquisition, and the use of multivariate mathematical and statistical computer algorithms to analyse the data (Dell'Aquila, 2009; ElMasry & Sun, 2010).

Seed quality applications: NIR technology is best used for the determination of internal chemical seed composition, such as nutritional value, oil, moisture, mineral, protein and polyphenol content, as well as food perception attributes such as aroma, mealiness and flavour (Huang *et al.*, 2015; Rahman & Cho, 2016). Specifically for seed quality related parameters, it has been used to detect internal seed properties such as fungal contamination (Wang *et al.*, 2004), seed viability (Farhadi *et al.*, 2015; Daneshvar *et al.*, 2015; Ambrose *et al.*, 2016a), seed density, fill and weight (Velasco *et al.*, 1999; Wu & Shi, 2004; Farhadi *et al.*, 2015), seed defects and deterioration due to excessive storage (Pannico *et al.*, 2015) and insect damage (Chelladurai *et al.*, 2014; Moscetti *et al.*, 2014). Further, it has applications for seed identification, such as to determine whether seeds are GM or not and for crop origin identification (Huang *et al.*, 2015). While NIR is already used for batch evaluation of grain and bean seeds, R&D into individual seed analysis is required to meet the seed lot quality, uniformity and purity needs of growers (Agelet & Hurburgh, 2014).

NIR advantages: NIR is rapid, non destructive, relatively easy to implement and is able to measure multiple complex seed attributes simultaneously (Dell'Aquila, 2009; ElMasry & Sun, 2010).

NIR limitations: The main limitation of IR technology is that it is difficult to know the position or location of a defect within a seed or seed lot. By contrast, computer vision can detect the location of a defect but cannot detect internal seed parameters. Hence, infrared spectroscopy is now being combined with computer vision to identify and classify seeds with different exterior and internal qualities in a technology called hyperspectral imaging (ElMasry & Sun, 2010). Indeed, hyperspectral imaging has been shown to be far superior to NIR for certain applications, such as detecting certain seed-borne diseases (Olesen *et al.*, 2011) and varietal purity (Vresak *et al.*, 2016).

b. Hyperspectral Imaging

Other names: imaging spectroscopy, imaging spectrometry; images can be called image cubes, hypercubes, spectral cubes, datacube (ElMasry & Sun, 2010; Huang *et al.*, 2015).

Hyperspectral imaging is the technology that shows most promise for non destructive, automated, real-time seed sorting on an industrial scale. It is highly sensitive, rapid and low-cost to use, has a high resolution and does not pose any risk to the user. Further, it does not require a stable environment and hence can readily be automated and eventually used, for example, for high throughput conveyor belt industrial seed sorting (Dumont *et al.*, 2015).

How hyperspectral imaging works: Hyperspectral imaging combines the spectral information of spectroscopy with spatial distribution data from computer vision to create a 3D image 'hypercube' that classifies seeds based on their external and internal quality characteristics (Figure 7; ElMasry & Sun, 2010).

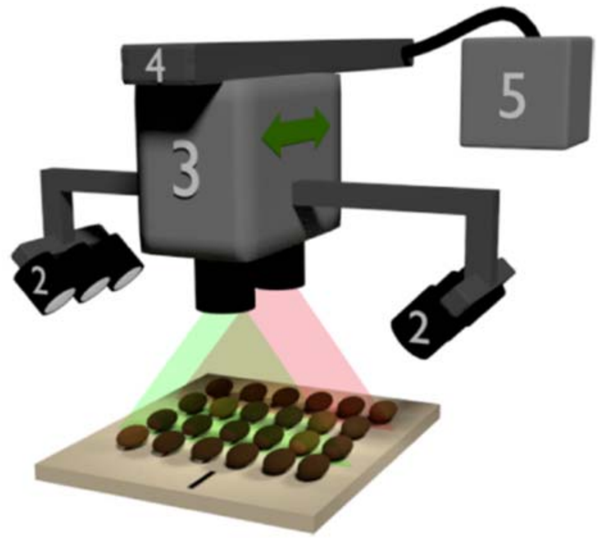

Figure 7. Hyperspectral imaging combines the strong points of infrared spectroscopy with computer vision to create a 3D image that classifies seed quality based on external and internal characteristics. The diagram shows hyperspectral imaging equipment used to classify Norway spruce seeds as viable, empty or infested with 93-99% accuracy (Dumont *et al.*, 2015). Numbering shows (1) the seed lot, (2) halogen lamps, (3) hyperspectral cameras, (4) the linear conveyor and (5) the control unit used to process data**.**

Seed quality applications: Hyperspectral imaging has been used for seed viability grading, often with accuracies at or above 95% (Ahn *et al.*, 2012; Mo *et al.* 2014; Dumont *et al.* 2015; Ambrose *et al.*, 2016b), for insect damage detection (Chelladurai *et al.*, 2014; Dumont *et al.* 2015), to detect a myriad of seed-borne diseases (Olesen *et al.*, 2011; Lee *et al.* 2016a., Lee *et al.* 2016b; Vresak *et al.*, 2016), for seed size sorting (to aid germination success; Shetty *et al.*, 2012), for varietal purity detection and grading (Vresak *et al.*, 2016; Vu *et al.*, 2016), for seed age determination (Mo *et al.* 2014; Nansen *et al.*, 2015; Dong *et al.*, 2017), to detect genetically modified versus non-GM seeds (Liu *et al.*, 2014) and to determine internal seed composition such as grain hardness, fat, protein, chemical and moisture content (Huang *et al.*, 2015).

Hyperspectral imaging advantages: Hyperspectral imaging does not require sample preparation and is a completely non-invasive, non destructive, chemical-free assessment method, hence completely safe for the user. Once the calibration model has been built and validated, it is a simple analysis that provides both qualitative and quantitative information for multiple characteristics simultaneously, being able to detect hundreds of spectral bands simultaneously and with very high nm-level resolution. These characteristics thus allow seeds of a similar colour, morphology or overlapping seeds to be analysed due to large amounts of information residing in each image. Further, the detection of the biochemical make-up of seeds, such as fat and protein content, is also possible, thus allowing chemical mapping for pricing and labelling (ElMasry & Sun, 2010; Dumont *et al.*, 2015; Fahlgren *et al.*, 2015; Rahman & Cho, 2016).

Hyperspectral imaging limitations: The main limitations hindering commercial use of hyperspectral imaging has been the high cost of hyperspectral cameras and very large amounts of data generated that make the process slow and computationally challenging (ElMasry & Sun, 2010; Fahlgren *et al.*, 2015). Nonetheless, researchers are overcoming such issues by selecting only a few effective wavebands for building a more simple multispectral imaging system that is less accurate but still able to meet the speed requirements of production lines. For example, to classify Norway spruce seeds as viable, empty or infested, 21 wavebands resulted in a sorting accuracy of 99%, seven wavebands >98% and >93% accuracy with only three wavebands (Dumont *et al.*, 2015).

c. Chlorophyll Fluorescence

Fluorescence occurs when absorbed light is re-emitted from seed tissues, usually at a longer wavelength (ElMasry & Sun, 2010). **Chlorophyll fluorescence (CF)** analysis irradiates seeds with electromagnetic radiation of a suitable wavelength and measures the amount fluoresced from the seed coat (Jalink, 2000).

Seed quality applications: CF is a method of sorting seeds for their maturity and therefore quality. For the majority of species, the amount of chlorophyll in the seed coat decreases during maturation and hence the presence of high chlorophyll indicates immature seeds that will have a shorter longevity and hence poorer quality (Jalink *et al.*, 1998; Kenanoglu *et al.*, 2013). The CF analysis method and apparatus for sorting seeds for maturity and quality have been patented (Jalink, 2000).

Chlorophyll fluorescence advantages are that it is a non destructive, rapid and highly sensitive technique, particularly well suited to many vegetable crops since their seed tends to mature over time as a result of prolonged flowering and fruit set and hence for which the variation in seed maturity within a lot is high (Jalink *et al.*, 1998; Jalink, 2000; Kenanoglu *et al.*, 2013).

Chlorophyll fluorescence limitations are that the technique is not effective for species with seeds that have little or no chlorophyll in their seed coat or pericarp, such as aubergine (*Solanum melongena*), maize (*Zea mays*) and sunflower (*Helianthus annus*), and it has limited applications for certain species that have high variation in seed coat chlorophyll content or colour between seed lots, such as for *Brassica napus* (Kenanoglu *et al.*, 2013).

5.2.2 Biospeckle Laser Technologies

Biospeckle laser technologies utilise laser investigative tools for seed analysis (Figure 8). These tools illuminate a rough surface with coherent laser light to create a distinct interference pattern – or 'speckle' - that is measured and analysed, thereby providing information about the object being studied, in this case a seed or seed lot. If the sample has biological activity, the speckle varies with time. This dynamic phenomenon is called a 'biospeckle', which is the time varying speckle pattern from the biological specimen (Braga *et al.*, 2003; Retheesh *et al.*, 2016; LIGO Laboratory, 2017).

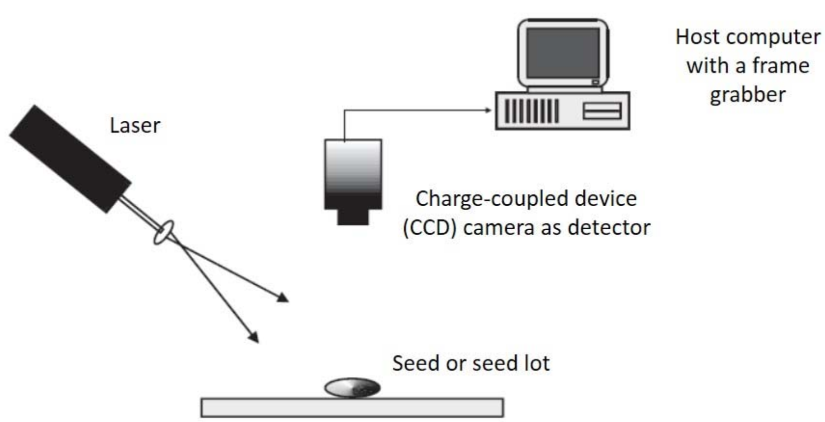

Figure 8. Biospeckle laser technologies utilise laser investigative tools for seed analysis. The laser illuminates the seed sample, the CCD camera captures the image and the computer analyses and interprets the image into data about the sample seed viability (Braga *et al.*, 2003).

How biospeckle laser technologies work: When coherent light is scattered by a seed, that scattering pattern can be measured and analysed, providing information about the activity of that seed. The technique generates a map of activity, whereby dark regions identify low activity associated with low seed viability and bright regions high activity associated with high viability (Figure 9; Braga *et al.*, 2003).

Seed quality applications: The biospeckle technique has been used to sort viable and non-viable seeds (Braga *et al.*, 2003) and detect fungal contamination (Braga *et al.*, 2005) in bean seeds (*Phaseolus vulgaris* L.). For each new application a process of learning and expertise building is needed to ascertain the meaning of measurements and to put them into the correct biological context. For example, two types of fungi were successfully detected in beans (*Aspergillus* and *Colletotrium*) while a third (*Sclerotinia*) was not detected (Braga *et al.*, 2005).

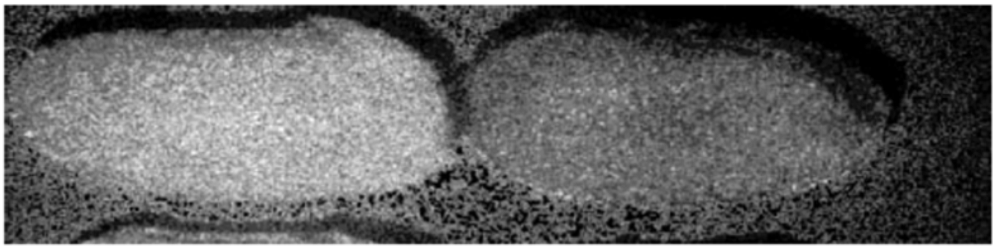

Figure 9. The biospeckle display for viable (left) and non-viable (right) bean seeds. Dark regions identify low activity associated with low seed viability and bright regions high activity associated with high viability (Braga *et al.*, 2003).

Biospeckle advantages: The technique is simple and rapid to use in the laboratory. The equipment, comprising a laser and standard digital imaging components, is relatively cheap to purchase and implement with the correct know-how (Braga *et al.*, 2003).

Biospeckle limitations: While the biospeckle test is non destructive, seeds must be soaked before testing which reduces their seed viability over the longer term. Hence the technique is useful for laboratory viability analysis (for example as a fast alternative to time-consuming laboratory tests such as the Tetrazolium biochemical test that destructively stains living seed tissues; Braga *et al.*, 2003), but is not yet applicable for real time seed grading.

5.2.3 X-ray inspection

X-ray technology utilises non destructive radiographic inspection of seed internal and external morphology in combination with digital imaging, as shown in Figure 10 for spruce seeds. Low-energy X-rays are used for small objects such as seeds (ISTA, 2013).

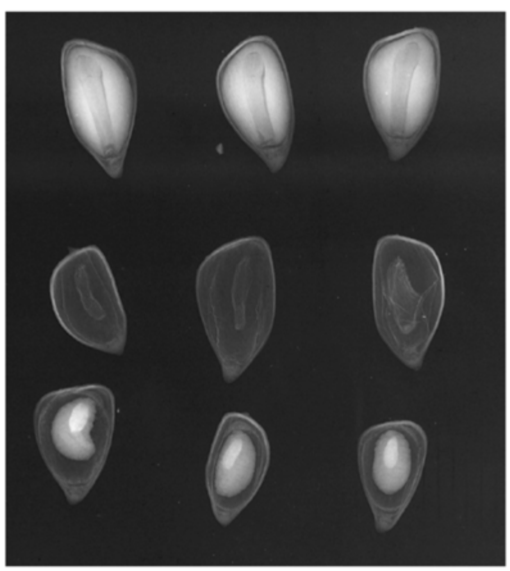

Figure 10. X-ray images of Norway spruce seeds showing viable (top row), empty (middle row) or insect infested (lowest row) seeds (Dumont *et al.*, 2015; Photo copyright: Natural Resources Institute Finland/Seed Laboratory).

Seed quality applications: X-rays are most useful for inspection of internal seed features, such as seed density and empty cavity space (versus embryo/endosperm size), key traits that determine seed quality in many fruit and vegetable seeds such as tomato (Zhao *et al.*, 2016), capsicum (Dell'Aquila, 2007), squash, melon and watermelon (Gomes *et al.* 2012) and internal damage, for example from insect infestation, deterioration from seed aging and mechanical damage (Chelladurai *et al.*, 2014; Arruda *et al.*, 2016). Other applications have been for determining seed maturity and the presence of pathogens in seed tissues (Dell'Aquila, 2009).

X-ray inspection limitations: While seed sorting with the X-ray technique is useful for laboratory applications where high accuracy is required, it is currently a time consuming process that takes 3-5 seconds to produce an image while possibly being harmful to seeds hence is not yet usable for industry-scale seed sorting (Dumont *et al.*, 2015; Rahman & Cho, 2016).

5.3 ELECTRONIC NOSE

Other names: E-nose, olfactometer (Henderson *et al.*, 2010; Zhou *et al.*, 2012).

The electronic nose is an instrument that senses and recognises volatile compounds existing in the headspace of a seed lot at parts-per-million (ppm) to parts-per-billion (ppb) levels via an array of electronic and chemical sensors (Henderson *et al.*, 2010; Zhou *et al.*, 2012; Ying *et al.*, 2015; Rahman & Cho, 2016).

How the electronic nose works: The E-nose works by producing a characteristic 'aroma-pattern' for a given sample which distinguishes it from other samples. Optimised sensors precisely distinguish odours in complex and simple samples, detecting a broad range of volatile chemical compounds such as alcohols, aldehydes, esters, hydrocarbons and volatile sulfur compounds (Zhou *et al.*, 2012; Rahman & Cho, 2016).

Seed quality applications: The electronic nose has been used to distinguish crop varieties, for example distinguishing between seed lots harvested from different wheat varieties (Zhou *et al.*, 2012), to detect pathogens in seed lots, for example distinguishing between four *Fusarium* fungal species in wheat seeds with ≥83% accuracy (Eifler *et al.*, 2011) and detecting early mould in rice, oat and red bean seeds with a 94% accuracy (Ying *et al.*, 2015) and detecting internal insect damage, for example detecting stink bug damage to cotton seeds with 100% accuracy (Henderson *et al.*, 2010). Further, it may have some potential for distinguishing seed provenance or source, for example to determine the origin of a seed lot (Tahri *et al.*, 2016).

Electronic nose advantages: Positive attributes are that the E-nose is mobile, inexpensive and a relatively fast operating electronic device (Eifler *et al.*, 2011).

Electronic nose limitations: The E-nose does not provide information about specific compound identity or compound properties; much more complex laboratory instruments such as GC-MS are needed for this (Zhou *et al.*, 2012).

5.4 THERMAL IMAGING

Other names: infrared lifetime imaging, thermal lifetime imaging, infrared thermography (Dumont *et al.*, 2015), pulsed thermography (Kim *et al.*, 2013).

Thermal imaging uses an infrared camera to capture the thermodynamic properties of seed tissue to provide information about seed quality (Kim *et al.*, 2013; Dumont *et al.*, 2015). Certain techniques measure the temperature of the seed surface, subsurface and internal heat changes after a light pulse to provide information about the viability of the seed (Figure 11; Dumont *et al.*, 2015). Other techniques do not rely on an illumination source and simply use a thermal camera to map seed surface temperature variations (Rahman & Cho, 2016).

Figure 11. Thermal imaging equipment that was used to collect information about viability of Norway spruce seeds, used to classify seeds as viable, empty or infested with 98-99% accuracy (Dumont *et al.*, 2015). Numbering shows (1) the seed lot, (2) halogen lamps that pulse light onto the seeds, (3) an infrared camera that captures the thermal images, (4) the control unit that processes the data.

Seed quality applications: Thermal imaging has successfully classified seeds as highly viable, aged or dead based on heat flows within the seed for lettuce (Kim *et al.*, 2013), garden pea, wheat and rape seed (Kranner *et al.*, 2010) and pea, field pea and navy bean (Baranowski *et al.*, 2003) and as viable, empty or infested for Norway spruce seeds (with 98-99% accuracy; Dumont *et al.*, 2015). Further, the technique successfully classified healthy versus fungus-infected pistachio kernels with a 99% accuracy (*Aspergillus flavus* fungi; Kheiralipour *et al.*, 2015). Early work required seeds to be imbibed prior to imaging (Baranowski *et al.*, 2003; Kranner *et al.*, 2010), but this has since been superseded by dry seed imaging (Dumont *et al.*, 2015).

Thermal imaging advantages: Together with hyperspectral imaging, thermal imaging is one of the most promising emerging technologies for automated non destructive seed sorting, being a highly sensitive, non-contact, rapid and affordable technique with a high resolution in spectral and spatial dimensions and that is safe for the user (Kranner *et al.*, 2010; Dumont *et al.*, 2015). For imaging that uses a thermal camera, the equipment is easy to handle and highly accurate temperature measurements are possible (Rahman & Cho, 2016).

Thermal imaging limitations: Thermal imaging does not have the research background of hyperspectral imaging hence is not yet ready for high-throughput seed sorting on a conveyor until a more sophisticated feature extraction method is developed. For example, current thermal imaging technologies that use a light pulse require a 15 second data acquisition window under a stable environment, which would mean stopping the production line during this time. Further, this technique currently requires seeds to be spatially separated while on a conveyor belt they are likely to clump, cluster or overlap (Dumont *et al.*, 2015). Conversely, thermal imaging systems that do not rely on a light pulse are influenced by environmental and weather conditions, thus limiting the technology applications (Rahman & Cho, 2016).

5.5 USEFULNESS OF NEW TECHNOLOGIES TO OVERCOME GROWER ISSUES

5.5.1 Promising Technologies to Meet Industry's Needs

Surveys of leading growers and industry affiliates from southern Queensland and central NSW have determined that seed quality issues are a major concern from certain suppliers and Table 2 (pages 19-23) illustrates specific examples where new non destructive techniques have shown promise to overcome each specific issue. Since each challenge requires unique technological solutions, grower issues are divided into six Pillars: germination, viability, seed aging, uniform emergence and vigour (pillar 1), seed-borne disease (2), varietal impurity (3), damage to seeds (4), seed mass, fill and density (5) and seed size, uniformity of size and shape of seeds (6).

The most promising technologies to grade seed quality non destructively, in real time and across most of the six areas of concern for growers are those that quantify seed optical properties and thermal dynamics.

Of these, hyperspectral imaging is proving to be the most useful because it combines spectroscopic imaging and computer vision to simultaneously determine interior and exterior seed qualities. Its rapid data acquisition capacity and ability to gather multiple complex attributes at high resolution simultaneously and under variable conditions makes it the most useful and promising technology for conveyer belt commercial-scale uses. It is also the only currently available technology able to deal with specific seed sorting realities and complexities, such as overlapping and clumped seeds and distinguishing between seeds with similar sizes, colours and shapes. The main limitation hindering commercial use of hyperspectral imaging has been the huge amount of data it generates, which slows and overcomplicates the seed classification process. This is now being overcome by researchers selecting specific effective wavebands to build more simple imaging systems that are slightly less accurate but still meet the quality requirements of the grower (ElMasry & Sun, 2010; Dumont *et al.*, 2015; Fahlgren *et al.*, 2015; Rahman & Cho, 2016).

Thermal imaging is also a highly promising emerging technology for automated non destructive seed sorting, being a highly sensitive, non-contact and affordable technique with a high resolution in spectral and spatial dimensions and that is completely safe for the seed and user. Currently, the drawbacks limiting its usefulness for real time seed sorting are its requirement for a long data acquisition window of around 15 seconds, need for environmental stability and inability to sort clustered or overlapping seeds; on a conveyor belt this would mean stopping the production line to gather seed quality data. However, given that thermal imaging is a much newer technology than hyperspectral imaging, thus without the R&D background, thermal imaging limitations may be overcome with future R&D investment (Kranner *et al.*, 2010; Dumont *et al.*, 2015; Rahman & Cho, 2016).

5.5.2 R&D Challenges and Future Direction

As discussed in Section 5.0, fully automated and integrated robotic systems for applications in horticulture and agriculture are still some years away. The ever-changing nature of farming systems and variability across different crop lines and between seasons introduces complexity and variability into mathematical models that can complicate the design of artificially intelligent machines for applications such as automated harvesting, sorting and grading of produce (Geller, 2016).

Challenges for Real Time Seed Quality Grading

Seeds are complex and variable living organisms, with their external appearance and internal chemical and physical composition changing between crops, with different varieties and cultivars and between seasons; indeed genetics and the pre- and post-harvest environment and handling conditions all play a role. Thus the success of using new computer-assisted techniques to grade seed quality will depend on their ability to make sense of and provide useful information about the quality attributes that need to be determined with the level of precision and accuracy that is required by the grower.

As revealed in the grower survey, a disease-free seed lot that is genetically pure, with high germination and uniform seedling establishment and with seeds sizes and shapes that fit well into existing machinery is the aim and definition of a 'quality' seed lot for the Australian vegetable industry (Output 1, grower interview summary). Thus future R&D will need to overcome seed lot complexity and variability if new technologies to grade seed quality in real time for growers are to become a reality.

Future R&D to Overcome Challenges

Artificial intelligence is already used for simple and repetitive on farm tasks such as weed management (Ball *et al.*, 2015) and yield prediction (Underwood *et al.*, 2016). Similarly for seed quality grading, success will come with building upon simple systems and may require, for example:

- Time to learn intricacies of seed lots for each crop or line of interest, such as subtleties in seed external appearance and internal chemical and physical composition,
- Time to learn how seed features relate to biological attributes that are important for growers, such as in-field seed viability and vigour,

- A long phase of evaluation and validation for each new trait to be assessed and sorted, with significant learning needed to correlate the image-extracted traits to biologically relevant quality attributes of seeds (Fahlgren *et al.*, 2015),
- For each new application or crop line a new process of learning and expertise building will be needed to ascertain the meaning of measurements and to put them into the correct biological context (Braga *et al.*, 2005).

Future R&D will also need to focus on rapid individual seed analysis, rather than batch analysis, if automated machines are to meet the seed quality, uniformity and purity needs of growers (Agelet & Hurburgh, 2014). Complex traits may require a multi-step sorting process with several techniques used one after the other or multiple techniques used simultaneously to grade seed quality to the precision required by industry (Pannico *et al.*, 2015). Indeed, this may even entail combining rudimentary machines with novel techniques, such as hyperspectral imaging with currently used gravity tables (Hansen *et al.*, 2017).

The next steps for project VG16028 will be grower consultation to prioritise R&D activities. Since new technologies that utilise artificial intelligence to grade seeds will need to be built from simple systems, vegetable Levy payers will be consulted via a strategy meeting in early 2018 to ascertain which of the six seed quality Pillars are their first priority. Future R&D activities will thus follow.

Table 2. Key grower seed quality issues as identified during project VG16028 interviews and examples from literature of new non destructive techniques that show promise to overcome each specific issue. Technology abbreviations are CV = computer vision, HSI = hyperspectral imaging, EN = electronic nose, NIRS = near infrared spectroscopy, CF = chlorophyll florescence, TI = thermal imaging, BLT = biospeckle laser technology, Spec = spectroscopy.

Grower seed quality issue	Tech	Seed quality parameter(s); plant species, crop or line	Usefulness and/or accuracy of technology	Reference
Pillar 1: Germination, viability, seed aging, uniform emergence and vigour	HSI	Classified seeds as viable to non-viable following accelerated aging; capsicum (*Capsicum annuum L.*)	Discrimination accuracies from 97 to 100% with different techniques. Potentially applicable to high-quality pepper seed sorting	Mo *et al.* 2014
		Detection of seed viability as affected by heat treatment, such as overheating during drying; corn, three varieties	Classification of viable and non-viable seeds had >83% accuracy	Ambrose *et al.* 2016
		Discrimination of viable and non-viable seeds; radish	Accuracy of 95%	Ahn *et al.*, 2012
		Discrimination of viable and nonviable seeds that were microwaved; corn	Accuracy of >97% (calibration) and >95% (prediction)	Ambrose *et al.*, 2016b
		Seed aging during storage over a 5 year timeframe; wheat	Detected decreasing moisture and protein content during storage, accuracy ranged from 82-97%	Dong *et al.*, 2017
		Seed germination after accelerated aging; three native Australian tree species (*Acacia cowleana*, *Banksia prionotes* and *Corymbia calophylla*)	Germination of *Acacia* and *Corymbia* seeds could be classified with over 85% accuracy and 80% accuracy for *Banksia* seeds	Nansen *et al.*, 2015
	CF	Seed germination, seedling emergence and vigour of seeds produced immature to over-mature fruits; four cultivars of pepper (*Capsicum annuum* L.)	Increased germination, seedling emergence, and seed vigour, especially for seeds harvested from immature and overmature stages - up to 21% improved seedling emergence. Sorting discarded 25 to 35% of seeds.	Kenanoglu *et al.* 2013
		Maturity and quality of seeds; cabbage cv. Bartolo *(Brassica oleracea* var. *capitata*)	Successfully identified less mature seeds, useful non destructive marker to determine maturity of seeds	Jalink *et al.* 1998
	TI	Predict whether a seed will germinate or die; garden pea (*Pisum sativum*), wheat (*Triticum aestivum*), rape seed (*Brassica napus*)	A potential tool for advancing studies of the molecular basis of seed aging and development	Kranner *et al.*, 2010
		Classified seeds as highly viable, aged or dead; lettuce		Kim *et al.*, 2013
		Identified seed germination capacity during very early stages of germination; pea, field pea and navy bean	Considerable differences in temperature were noted at seed swelling following imbibition, pea seeds that were viable showed a temperature decline	Baranowski *et al.*, 2003

	HSI/TI	Identified viable vs empty seeds and seeds infested by *Megastigmus sp*. Larvae; Norway spruce (*Picea abies* (L.) Karst.)	HSI accuracy was >93% with 3 wavelengths, 99% with 21 wavelengths; 98-99% accuracy with TI	Dumont *et al.* 2015
	EN	Seed deterioration - naturally- and artificially-aged seeds vs not aged; cabbage and onion	Acetaldehyde and ethylene may be a positive marker for seed deterioration because they increase with deterioration so could be useful, rapid and non-destructive indices of viability (once refined). Ethane and CO_2 are unlikely to be useful indicators since they decline.	Klein *et al.* 2004
	BLT	Sorted viable and non-viable seeds; beans		Braga *et al.*, 2003
	CV	Assessment of germination rate using germinating seedlings (i.e. destructive); tomato seeds	>95% correct classification	Skrubej *et al.*, 2015
		Seed maturity based on colorimetric and morphological parameters analysed by image analysis, compared to phenolic compound analysis; grape seeds	Technique was a useful and rapid tool for making decisions at seed harvest time; correlation coefficient of 0.97 for predicting the maturity stage	Rodriguez-Pulido *et al.*, 2012
	NIRS	Fourier transform near-infrared (FT-NIR) and Raman spectroscopy used for evaluating seed viability, compared to corn viability test and classification; white, yellow, and purple corn	FT-NIR spectroscopy was far superior to Raman spectroscopy, correctly classified viable and nonviable seeds for all the three categories of corn with an accuracy of 100% and a predictive ability of >95%	Ambrose *et al.*, 2016a
		Viable vs non-viable seeds; timber crop Larch (*Larix sibirica*)	100% accuracy. Spectral differences were attributed to differences in seed moisture content and storage reserves	Farhadi *et al.*, 2015
		Viable vs. non-viable seeds (empty, insect-attacked and shrivelled); juniper seeds (*Juniperus polycarpos*)	Discrimination of viable vs. non-viable seeds had 98% and 100% accuracy, respectively	Daneshvar *et al.*, 2015
Pillar 2: Seed-borne disease	HSI	Cucurbit diseases caused by cucumber green mottle mosaic virus[1,2] (CGMMV); Watermelon cv. Sambok Honey	Discriminated virus-infected seeds from healthy seeds with 83% accuracy	Lee *et al.* 2016a.
		Bacterial fruit blotch (BFB, e.g. *Acidovorax avenae* subsp. *Citrulli*); Watermelon cv. Speed Plus	Discriminated 336 bacteria-infected seeds from healthy seeds with *c.* 90% accuracy	Lee *et al.* 2016b.
		Three *Fusarium* species and one *Alternaria* infection; winter wheat, winter triticale	Distinguished infected parts of seeds from uninfected ones by reflection intensity of pixels. Accuracy not given.	Vresak *et al.*, 2016
		Distinguished between uninfected and infected seeds for five common fungal diseases (*Verticillium spp.*, *Fusarium spp.*, *Stemphylium sp.*, *Cladosporium spp*., *Alternaria spp.*); babyleaf spinach	80-100% accuracy using multispectral imaging with 395-970 nm wavelengths. NIRS accuracy was much lower at 26-88%. To more accurately distinguish between diseases, a microscope camera could be used.	Olesen *et al.*, 2011
	TI	Classified healthy versus fungus-infected pistachio kernels (*Aspergillus flavus* fungi)	99% accuracy	Kheiralipour *et al.*, 2015

	EN	Distinguished between four *Fusarium* fungal species; wheat seeds	≥83% accuracy	Eifler *et al.*, 2011
		Detected early mould in rice, oat and red bean seeds	94% accuracy	Ying *et al.*, 2015
	BLT	Detected fungal contamination in bean seeds (*Phaseolus vulgaris* L.)	Two types of fungi were successfully detected (*Aspergillus* and *Colletotrium*) while a third (*Sclerotinia*) was not detected	Braga *et al.*, 2005
	CV	Identified two diseases that can be transmitted via seeds (frogeye leaf spot fungus, *Cercospora sojina,* and mildew fungus, *Peronospora manshurica*); soybean	Accuracy >95%	Tan *et al.*, 2014
	NIRS	Classified healthy and fungal-damaged seeds and discriminated among various types of fungal damage; soybean	Classification accuracy was >99% when the wavelength region of 490–1690 nm was used. Classification accuracies were 100% for healthy seeds and 84-99% to correctly classifying disease (*Phomopsis, Cercospora* kikuchii, soybean mosaic virus, and *Personospora manshurca* Syd or downy mildew)	Wang *et al.*, 2004
Pillar 3: Varietal impurity	EN	Simple variety identification system with less complexity for bulk sample testing (not single grain analysis); wheat, several varieties	Correct classifications were analysis dependent, 83 to >90%	Zhou *et al.* 2012
		Distinguishing seed provenance or source, for example to determine the origin of a seed lot	Some potential	Tahri *et al.*, 2016
	CV	Identified varieties based on seed coat colour; beans	Sensitivity was >96% and specificity 97%	Nasirahmadi & Behroozi-Khazaei, 2013
		Identification of four wheat varieties based on grain morphology and colour	96% accuracy. Colour alone could not distinguish varieties due to colour overlap, hence it was necessary to use morphology and colour features together.	Arefi *et al.*, 2011
	HSI /NIRS	Variety classification; winter wheat, winter triticale	For HSI: one variety was classified with >97% accuracy; for the other varieties classification accuracy was below 67% due to surface similarities. NIRS did not work for this function.	Vresak *et al.*, 2016
	HSI	Variety classification; rice	Automatically detected unwanted seeds from other varieties within a seed batch. By adding spectral data to shape-based features, accuracy increased from 74% to 84%	Vu *et al.*, 2016

Pillar 4: Damage to seeds	CV	Identified worm-eaten and damaged seeds; soybean	Accuracy 92%	Tan *et al.*, 2014
	NIRS	Detection of flawed seeds (mould and browning of kernel) and chemical composition; hazelnut (*Corylus avellana* L.)	It was possible to use NIR to separate hazelnuts into different quality classes, accuracy for flawed seeds not provided.	Pannico *et al.*, 2015
		Detection of internal damage from insects; chestnut (*Castanea sativa,* Miller)	Results had a 55% improvement over a traditional flotation sorting system	Moscetti *et al.*, 2014
		Detection of early stages of cowpea weevil infestation; soybean	>86% classification accuracy for uninfested and infested seeds, respectively, with NIRS. However, combining with soft X-ray and using HSI greatly increased accuracy.	Chelladurai *et al.*, 2014
	HSI	Identified seeds infested by *Megastigmus sp*. Larvae; Norway spruce (*Picea abies* (L.) Karst.)		Dumont *et al.* 2015
	X-ray	Internal seed damage; *Crotalaria juncea* seeds	Successfully identified mechanical, stink bug and tissue deterioration damage	Arruda *et al.*, 2016
	EN	Internal insect damage, for example detecting stink bug damage; cotton seeds	100% accuracy	Henderson *et al.*, 2010
Pillar 5: Seed mass, fill and density	X-ray	Internal seed morphology to evaluate physical seed quality; squash, melon and watermelon	Useful in identifying viable seeds with reduced embryo size and seeds with high embryonic area. Low average density was expressed as poor germination.	Gomes *et al.* 2012
		Determined the internal morphology of the seed, empty cavity area was correlated with seed quality; tomato	Provided a perfect view of the internal seed parts; the larger the area of the endosperm and the embryo (i.e. the less internal cavity area), the greater was the probability of healthy seedling growth without abnormalities	Zhao *et al.*, 2016
		Determined the internal morphology of the seed, empty cavity area; capsicum	Free space area was an excellent indicator of germination potential and was related to abnormal seedlings and advancing deterioration in the seed population.	Dell'Aquila, 2007
	NIRS	Estimation of seed weight by near-infrared reflectance spectroscopy; rapeseed (*Brassica napus* L.)	Coefficient of correlation between NIRS and reference methods of 0.92 for seed weight	Velasco *et al.*, 1999
		Seed weight analysis for brown and white rice for breeding purposes	More useful for brown rice than white rice weight (coefficient of correlation between NIRS and reference methods of 0.71 and 0.67 respectively), much more useful for chemical composition than weight	Wu & Shi, 2004
		Seed fill; timber crop Larch (*Larix sibirica*)	Accuracy 82%	Farhadi *et al.*, 2015

Pillar 6: Seed size, uniformity of size, shape of seeds	CV	Size and colour quantification; beans	The overall accuracy was 91%, with the system correctly classifying 99% of white beans, 93% of yellow–green damaged beans, 69% of black damaged beans, 75% of low damaged beans and 94% of highly damaged beans	Kilic *et al.*, 2007
		Seed size grading by analysis of three-dimensional digital image information on single seeds; lentils	Seed Size Index (SSI) was highly correlated with physical measurements (>0.98). Gave more detailed and precise descriptions of grain size and shape than manual assessment	LeMasurier *et al.*, 2014
		Evaluated geometrical properties of small seeds and compared to measurements obtained by a micrometer; wild sage (*Salvia macrosiphon*)	Useful method for measurement of some small seed dimensions; correlation with manual micrometer measurements ranged from 64-99%	Razavi *et al.*, 2010
	HSI	Classified large seeds from small-size and medium-size seeds; Baby leaf spinach	HSI successfully determined seed size which correlated with germination of seeds, whereby large seeds showed better germination. Accuracy not provided. NIRS alone was not reliable.	Shetty *et al.*, 2012
Other	NIRS	Resistance to premature sprouting (germination) in the field, wheat	Sensitivity greater than human eye inspection and destructive techniques	Smail *et al.* 2006
	CV	Colour classification into whitish, cane green, green, and bluish-green; coffee beans	Classification accuracy of 100%; can be used by coffee growers to analyse green coffee beans and the method can be extended to other crops	de Oliveira *et al.*, 2016
	Spec	Chemical composition of seeds: • highly accurate for protein (corn, maize, beans, rice, soybean, peanuts, rapeseed, sunflower, canola, cotton, millet, flax, safflower, sesame, palm); • useful for fibre (soybean, corn, rapeseed), sucrose (soybean) and amino acids (rapeseed, peanuts, rice, millet); • not useful for carbohydrates (maize, rice, millet, soybean). Also useful for seed oil content (peanuts, maize, safflower, rapeseed, sunflower, cotton, canola, corn, soybean), fatty acid (peanuts, soybeans, safflower, rapeseed, sunflower, jatropha, canola, flax), moisture content (soybean, sunflower, peanuts, flax, safflower, cotton), pH (cocoa), mineral content (K, Mg, Ca and P in peanuts), ethanol		Rahman & Cho, 2016
	HSI	Chemical composition of seeds: useful for crude protein and fat (soybean), protein (wheat), alpha-amylase (wheat); not useful for some other chemical characteristics. Seed oil content (corn, maize).		Rahman & Cho, 2016

6. FACTORS THAT INFLUENCE THE GERMINATION AND VIGOUR POTENTIAL OF SEEDS

Seeds reach a maximal germination and vigour peak at their physiological maturity, after which time their quality declines until germination is entirely lost. The following Section reviews those factors that determine the seed quality peak and how rapidly a seed lot will lose that quality. Factors discussed are genetics and the pre- and post-harvest environment, including seed storage conditions.

Around 85% of land plant species, including almost all vegetable crops, display **orthodox** seed behaviour, meaning their seeds are able to tolerate drying to a low moisture content of *c.* 2 to 5% without harm (Roberts, 1973; Tweddle *et al.*, 2002) and can tolerate freezing once sufficiently dry (Copeland & McDonald, 2001). Most annual and biennial and many perennial plants display orthodox behaviour (Tweddle *et al.*, 2003). What makes orthodox seeds unique is that they are *cryptobiotic organisms*, meaning that in the dry state their rate of viability loss can be significantly slowed (Walters, 1998b), with seeds of some plant species potentially surviving for many tens, hundreds or thousands of years if stored under appropriate conditions (Copeland & McDonald, 2001).

Seeds that do not tolerate drying are referred to as **recalcitrant** (or intermediate); moisture contents below *c.* 12 to 31% (Roberts, 1973; Tweddle *et al.*, 2003) will kill these kinds of seeds. Recalcitrant behaviour is not discussed in this review since these plants tend to be large seeded trees and shrubs from moist and warm environments (Tweddle *et al.*, 2003). Hence all reviewed seed behaviours refer to orthodox seeds.

6.1 SEED VIABILITY, DETERIORATION AND LONGEVITY THEORY

It is possible to compare the seed longevity of seed lots because seed populations age in a predictable way (Roberts, 1973). When germination proportion is plotted against time at a given temperature and relative humidity, a seed lot will display a characteristic *seed survival curve* as seed viability is lost, as shown in Figure 12. Equations can then be used to calculate the viability, deterioration rate and longevity of that seed lot and compare these parameters with other seed lots (Ellis & Roberts, 1980).

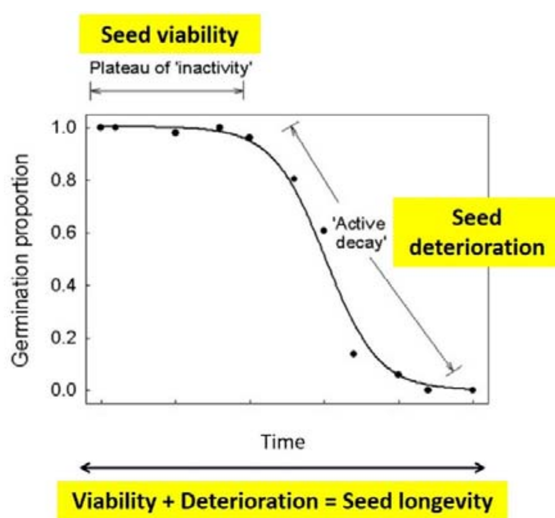

Figure 12. A seed survival curve, where seed germination is plotted over time and the seed lot longevity is recorded (Kochanek, 2008). The seed viability of the seed lot is depicted by the 'plateau of inactivity' and the rate of seed deterioration is depicted by the 'active decay' phase; combining these parameters provides the seed lot longevity.

Two distinct phases are a key feature of seed survival and longevity (Walters *et al.*, 2005; Kochanek, 2008):

(a) The initial seed germination of a seed lot represents its **seed viability.** For many species there is an initial phase where seeds remain completely viable and germinate at 100% for a period of time, which is depicted by the 'plateau of inactivity' in Figure 12. Short-lived species may have a short plateau and seeds that have started to deteriorate may display no plateau (Figure 13) or may already be in the 'active decay' phase. Equations take all three scenarios into account to provide a seed viability value for a given seed lot.

(b) A phase of active viability decline where seeds are deteriorating is depicted by the 'active decay' phase in Figure 12. The slope of this deterioration curve represents the rate of seed lot decay; longer lived seed lots will have a flatter slope and shorter lived seed lots will have a sharper slope (Figure 14).

The overall **longevity of a seed lot**, or its life span, is thus a combination of the two phases, including both the initial seed viability and subsequent seed deterioration phase (Walters *et al.*, 2005). Predictions for a range of plant species indicate that seed longevity varies by at least two orders of magnitude, even when seeds are stored under identical conditions (Ellis & Roberts, 1980). Seed viability and the rate of seed deterioration can behave independently of one another (Kochanek *et al.*, 2011), sometimes seed longevity varies as a result of differences in viability alone (Figure 13), sometimes only the deterioration rate changes (Figure 14) and sometimes both can change simultaneously.

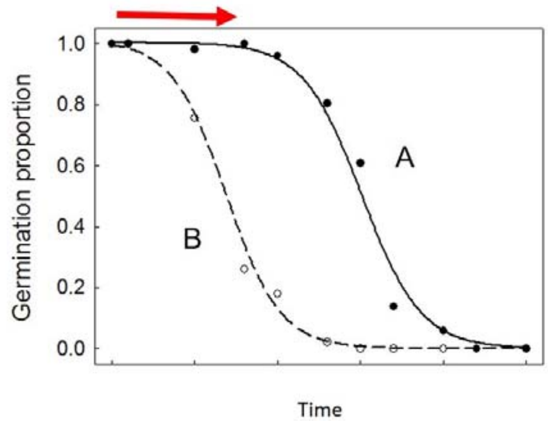

Figure 13. Two seed lots showing differences in their **seed viability**. Seed lot A has a significantly longer storability because its seed viability is much greater than that of seed lot B. Both seed lots have the same rate of seed deterioration (Kochanek, 2008; Kochanek *et al.*, 2011).

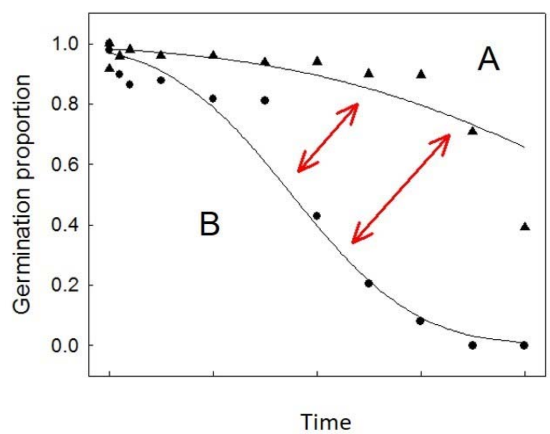

Figure 14. Two seed lots showing differences in **seed deterioration rate**. Seed lot A has a significantly longer storability because its seed deterioration is much slower than that of seed lot B. Both seed lots have the same initial seed viability (Kochanek, 2008; Kochanek *et al.*, 2011).

The next Section explains how harvest maturity, genetics and the pre- and post-harvest environment can change each aspect of seed viability, deterioration and longevity.

6.2 FACTORS THAT INFLUENCE SEED LONGEVITY, VIABILITY AND DETERIORATION

6.2.1 Seed Maturity at Harvest

Seed viability increases as seed lots mature until a maximum attainable viability is reached; the more immature the seed lot the lower its viability. This has been observed for many crops including bean (Sanhewe & Ellis, 1996), soybean (Zanakis *et al.*, 1994), rice (Ellis & Hong, 1994; Ellis *et al.*, 1993; Rao & Jackson, 1996a), carrot (cv. Alvorada; Nascimento *et al.*, 2003), hot, sweet and red pepper (Alan & Eser, 2008; Vidigal *et al.*, 2009) and tomato (Dias *et al.*, 2006). In some fleshy-fruited crops, such as tomato and pepper, a period of post-harvest fruit maturation can improve seed viability if fruits were harvested before seeds were fully mature (although if they are too immature even this does not improve viability; Dias *et al.*, 2006; Alan & Eser, 2008; Vidigal *et al.*, 2009).

The phenomenon is somewhat complicated because the developmental stage at which maximum viability is reached is genotype-specific. Some crops, such as beans (Sanhewe & Ellis, 1996), reach maximum viability after the end of seed-filling while others reach this point earlier or later. For example, there were no differences in viability for rice seeds harvested 28, 35 and 42 days after flowering (Rao & Jackson, 1996b), wheat attained maximum viability when seeds reached maximum dry weight, pearl millet and carrot at one week after reaching maximum dry weight (Pieta Filho & Ellis, 1991; Nascimento *et al.*, 2003) and hot and red pepper at two weeks after maximum dry weight (Alan & Eser, 2008). Also, the pattern by which viability increases during plant development can vary with genotype. For example, for barley, carrot and pepper the viability increased to a point and then declined (Pieta Filho & Ellis, 1991; Nascimento *et al.*, 2003; Alan & Eser, 2008), in rice the patterns changed, sometimes increasing, sometimes decreasing and sometimes not changing as the growth environment changed (Rao & Jackson, 1996b).

It is important that seeds do not remain on the plant for longer than required as seed viability will eventually begin to decline due to aging on the mother plant (Ellis and Hong, 1994; Alan & Eser, 2008).

6.2.2 Postharvest Handling and Seed Storage

After harvest, orthodox seed deterioration is a consequence of ‘time, temperature and moisture content’ (Ellis & Roberts, 1980) and seed handling. Seeds that are immature, broken, cracked, pathogen or insect infested or damaged will deteriorate more rapidly than those that are intact and healthy (Copeland & McDonald, 2001; Dell'Aquila, 2009). For intact seeds harvested at the correct maturity, the relative humidity and temperature of their storage environment are the most important factors that influence seed life span and a basic rule of thumb is:

“For each 1% reduction in moisture content or each 5°C decline in temperature, the storage life of (orthodox) seeds doubles” (Harrington, 1963).

Reducing seed moisture content is the most critical factor to improving seed longevity because dehydration reduces metabolism, slows pathogen attack, reduces food reserve depletion and reduces the collection of by-products from metabolism, thereby allowing seeds to live longer (Harrington, 1963; Vertucci & Roos, 1990). In fact, at moisture contents above 14% seeds can deteriorate even more rapidly than the rule of thumb suggests (Copeland & McDonald, 2001). Seed moisture content can be reduced by decreasing the air relative humidity around the seeds because seeds absorb or desorb water from the atmosphere until they are in equilibrium with their surroundings (provided they are not impermeable to water; Probert and Hay, 2000).

Seed biologists recommend drying seeds at 15 to 20% relative humidity and 15°C to optimise their storage longevity (Terry *et al.*, 2003).

Conditions below 15% relative humidity may damage some seeds and higher humidity will result in accelerated aging and rapid seed quality decline (Chai *et al.*, 1998; Zeng *et al.*, 1998; Walters, 1998a; Walters *et al.*, 2001). Storage of seeds with *c.* 2-6% moisture is generally considered ideal to maximise longevity (Roberts, 1973 Copeland & McDonald, 2001; Tweddle *et al.*, 2002). For long periods of storage, such as in gene banks, seeds that are sufficiently dry can be hermetically sealed and frozen at -20°C to maintain their longevity for as long as possible (Copeland & McDonald, 2001).

6.2.3 Taxonomic Trends for Seed Longevity

Taxonomic trends for seed longevity exist; for example, the seeds of many crops (as well as wild and weedy plants) can be characterized as short to long lived according to their order, family (Probert *et al.*, 2009), genus (Hay *et al.*, 2006; Kochanek *et al.*, 2009) and species (Schoeman *et al.*, 2010; Kochanek *et al.*, 2011). In general, wild plant species have greater variation between seed collections for longevity than crop species because wild plants are generally more genetically variable than crops and their seed collections less homogenous (Ellis et al., 1989; Hay et al., 1997).

The storability characteristics of key vegetable crop seeds are shown in Table 3. Not a great deal of research has been undertaken into understanding vegetable seed longevity trends. The work that has been conducted is generally based on uncontrolled conditions (Roos & Davidson, 1992; Priestley *et al.*, 1985; Nagel & Borner, 2010) rather than controlled laboratory conditions that allow direct comparison across crop lines (Alhamdan & Alsadon, 2004). Thus the usefulness of this research to accurately categorise vegetable seeds as short to long lived or to understand seed viability and deterioration trends is limited.

Nonetheless, certain trends can be extrapolated from the information available in Table 3. Seeds were found to be universally short lived across studies for parsley, asparagus, onion and lettuce, displayed intermediate longevities for carrot, turnip, eggplant and sweet corn and were long lived for pea, okra and tomato lines. For other crops, such as cucumber, cabbage, field bean, beetroot and spinach, the seed longevity classification varied vastly between studies. Clearly future R&D investment is needed to definitively grade vegetable crops from short to long lived to inform storability decisions for seed producers and vegetable growers. Particularly useful for the Australian vegetable industry would be a comparison of key crop longevity behaviours but with a specific focus on cultivars and varieties of most economic importance.

Table 3. Seed storability characteristics of key vegetable crops. The storability index depicts the average time taken for a seed lot to lose 50% viability for each crop under ambient storage condition (latitudes of 35-48° N.). Categories depict crops with (1) short lived seeds, with 50% viability lost after 1-2 years; (2) intermediate seeds, with 50% viability lost after 3-5 years and (3) long lived seeds, with 50% surviving for >5 years (Copeland & McDonald, 2001; Justice & Bass, 1978). The intermediate category can be further subdivided into short to intermediate, intermediate and intermediate to long lived categories. The letter beside each crop denotes the study that determined its longevity index. Crops in bold writing are those for which different studies determined a different seed storability index.

Crop	Storability Index	Crop	Storability Index	Crop	Storability Index
Chives[e] Parsley[bc] Asparagus[bc] Parsnip[b] Artichoke[b] **Celery**[c] **Cucumber**[c] Onion[ab] **Cabbage**[d] Lettuce[abcde] Capsicum[a,b] **Watermelon**[a]	1 Short lived	**Cucumber**[ab] Carrot[abe] **Field bean**[ab] **Beetroot**[a] **Cabbage**[bc] **Spinach**[ab]	2 Short lived to intermediate	**Field bean**[c] **Beetroot**[cd] Alfalfa[b] Pea[ace] Okra[ad] Tomato[ab]	3 Long-lived
		Broccoli[b] Pumpkin[b] Cauliflower[b] **Watermelon**[b] **Celery**[b]	2 Intermediate		
		Turnip[bc] **Cucumber**[e] Sweet corn[abc] Eggplant[ab] Swiss chard[a] Muskmelon[a] **Spinach**[c] Radish[bc]	2 Intermediate to long lived	References: [a]Roos & Davidson, 1992 [b]Copeland & McDonald, 2001; Justice & Bass, 1978 [c]Priestley *et al.*, 1985 [d]Alhamdan & Alsadon, 2004 [e]Nagel & Borner, 2010	

As already discussed, seed maturity, postharvest handling, seed storage conditions and genetics all play a role in determining crop seed viability and longevity. The following Section discusses the final critical factor to determine seed longevity: the effect of the pre-harvest parental environment on seed viability and longevity.

6.2.4 Pre-Harvest Influences on Seed Viability and Deterioration

The seed viability and longevity peak at physiological maturity can be influenced by environmental conditions experienced by the parent plant(s) before the seed has matured or developed. It has long been known that the environment prior to harvest can have a dramatic influence on the viability of a seed lot, whereby 'suboptimal' growth conditions can result in a lower viability in sensitive crop lines. For example, a cooler growing temperature was shown to improve seed viability for beans (Sanhewe & Ellis, 1996) and rice (Ellis & Hong, 1994; Rao & Jackson, 1996b), but warmer conditions improved viability for wheat (Sanhewe *et al.*, 1996). In fact, if growing conditions are highly suboptimal, seed viability may be so severely affected that 100% germination is never attained. For example, one rice cultivar (*Japonica*) only attained 100% germination under cool conditions, but under warm conditions the viability was much less than 100%. Conversely, for a different rice cultivar (*Indica*) 100% germination was attained under both conditions and maximum viability was unaffected (Ellis *et al.*, 1993). The mechanisms behind these genotype × environment interactions were poorly understood at the time of these early studies.

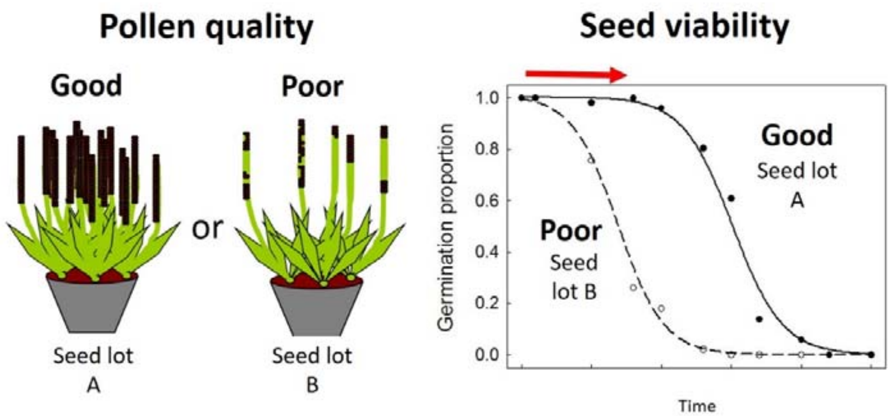

Figure 15. Pollen quality of the paternal parent directly determines the maximum attainable viability of a seed lot. These attributes also correlate with flower abortion rates, seed fill, seed yield and number of seeds per capsule (Kochanek *et al.*, 2010, 2011).

It was world-first research by the report author that pinpointed a ground-breaking phenomenon: paternal and maternal plant health play a combined role in maximising seed longevity (Kochanek *et al.*, 2011). Specifically, conditions that optimise the pollen quality of the paternal parent determine the maximum attainable viability of a seed lot (Figure 15) and are directly correlated with other pollen quality attributes, such as flower abortion rate, seed fill, seed yield and number of seeds per capsule. Conversely, conditions that determine the plant maternal health, such as the size of the maternal leaves, stems and other vegetative parts, directly determine the seed deterioration rate of a seed lot (Figure 16).

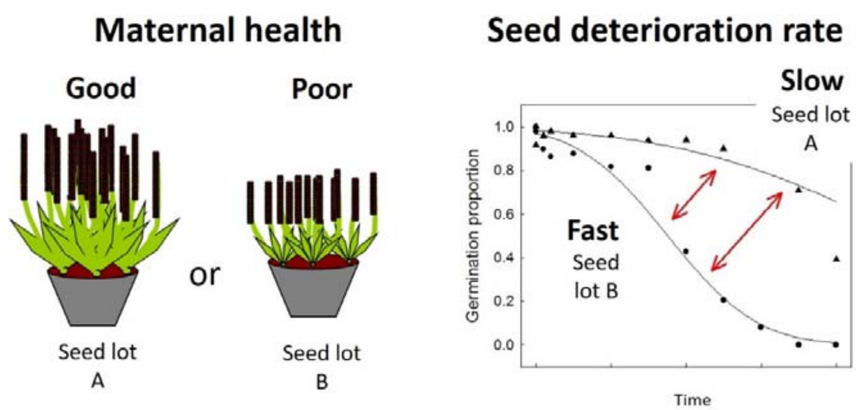

Figure 16. The plant maternal health, such as the size of the maternal leaves, stems and other vegetative parts, directly determine the seed deterioration rate of a seed lot. Healthy maternal plants result in seeds that survive for longer without deteriorating (Kochanek *et al.*, 2010, 2011).

So while seed viability and deterioration rate are each derived from a different parent, it is their combined influence that determines the overall quality and longevity for a given seed lot (Kochanek *et al.*, 2010, 2011). Recent research has reconfirmed this parental effect phenomenon for barley seed longevity (Nagel, *et al.*, 2015), hence it is likely to also be applicable to vegetable crops and warrants future R&D since this promises the ability to significantly improve seed viability and longevity for the grower.

6.3 R&D CHALLENGES AND FUTURE DIRECTION

Section 6 in this review has determined that scarce research has been undertaken into understanding vegetable seed viability and longevity characteristics or how these seed quality traits can be maximised through pre- and post-harvest cultural practices.

Thus key areas for future R&D identified in this review include:

(a) A definitive classification of key vegetable crops as short to long lived, including a holistic comparison of the most economically important cultivars and varieties for the Australian vegetable industry, to inform storability decisions for seed producers and vegetable growers.

(b) Significantly improving vegetable seed viability and longevity by optimising:

> (i) The pre-harvest parental crop growing environment. This work would follow on from the author's ground-breaking research that was the first to determine that paternal and maternal plant health plays a combined and cumulative role in significantly improving seed viability and longevity. Future research would identify those conditions that optimise pollen quality and maternal health for industry's most economically important cultivars and varieties with a view to significantly improving seed viability and longevity for the grower.
>
> (ii) The timing of seed harvest. Seeds that are collected too early and are immature have not reached their viability peak, while keeping seeds on the plant for too long will result in seed deterioration and viability decline. Thus future research would identify optimal seed collection windows for industry's most economically important cultivars and varieties to maximise seed viability and longevity at harvest and thus for the grower in the longer term.

The review also highlighted the need for appropriate seed storage conditions to ensure maximum seed viability is maintained during seed storage and on farm. A technical bulletin will communicate this information to industry over the coming months.

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