Hort Innovation

Final Report

Scanning technologies for horticultural packhouses

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Content

Summary

This project aimed to accumulate relevant knowledge about the potential of in-line scanning technology to detect market access pest and disease organisms. This knowledge will help provide additional confidence that Australian produce going to export markets is free from biosecurity risks.

Published scientific and industry literature on relevant scanning technologies was searched and summarised. A list of target market access pests and diseases of concern in Australia was compiled and information collected and summarised as to the use, or potential use, of in-line technology for detection purposes. A questionnaire survey and direct consultations were undertaken across a wide range of industry representatives, packhouse operators and packhouse equipment suppliers. Alternative statistical modalities, available with in-line scanning technologies, were studied to determine the likely biosecurity risk probabilities compared with current standard methods.

Key outcomes of the project are:

1. The recognition that the Australian horticulture commodity industries are generally well advanced in their knowledge and use of modern in-line scanning technologies. The level of adoption and use varies widely by commodity, largely determined by industry size and export value. The technologies in use are, however, almost exclusively used for quality determinations (appearance, taste, defects), driven by market demands, seldom specifically for pest and disease detection, although 'at-risk' produce will often get simply removed because of detection of symptomatic damage.

2. An awareness that in-line scanning technologies are only a latter part, and nearly 'too late', of a greater systems approach that is generally in place for pest and disease management. At-line inspections at packing are a necessity and anything to improve detection accuracy has high value, especially if it can also reduce the cost of the later mandated audits and lower the overall labour costs.

3. The generation of statistical modelling evidence detailing the significant gains in detection accuracy and efficiency achievable with in-line and/or at-line scanning technologies. Much depends on the demonstrable sensitivities (true detection rate) and specificities (true rejection rate) of the methods, statistical factors that can only be determined empirically.

4. An acknowledgement that investment in packhouse technology is primarily driven by market demands for improved quality and reduced labour costs. The grading companies are investing in technology advances, particularly in software and improved detection algorithms. Hardware advances are more challenging, the main call being for methods that can more deeply and accurately penetrate into samples to reveal internally hidden pests and diseases. Ideal future technologies might be variants of X-ray CT or MRI, that can accurately render internal structure and conditions, but these will require substantial R&D investments from beyond the grading companies alone.

The study recommends further investment in scanning technologies but within the context of each commodity and their own biosecurity challenges. A general recommendation is to examine ways to improve the accuracy and efficiency of the at-line inspections undertaken at packing. The evidence is in, from the statistical modelling, that even only moderately accurate non-destructive scanning of additional samples, supplementary to those required for destructive at-line inspections, could greatly improve accuracy and confidence in the grading and sorting results.

Keywords

Market access; pests; diseases; packhouse; detection; in-line grading; image analysis; spectra; NIR; X-ray

Introduction

In Australia, pests and diseases of quarantine concern represent a significant phytosanitary barrier for market access for fruit and vegetable commodities. This directly affects the viability of many horticultural industries. Consequently, the production of horticulture for export is reliant on affordable and effective control options in the orchard, compliance points during packing, and often end-point phytosanitary treatments. The use of multiple measures along the production pathway is referred to as a systems approach, provided at least two of them work independently of each other. This project explores the potential to increase the confidence in packing-line technology to provide additional confidence that Australian produce is free from pests and diseases.

The presence of insects on or in fruits is generally undesirable, and some insect species are subject to regulatory action in international trade. Through most of the 20th century, fumigation with various volatile chemicals (most commonly methyl bromide; MeBr) was the disinfestation method of choice. However, changes in consumer opinion and greater realisation of the unintended consequences of chemical use (e.g. climate change) have given impetus to efforts to find viable alternatives. One potential method is by detecting insect-infested fruits during grading and packing and removing them from the supply chain entirely, or redirecting them to less-sensitive markets or end-products.

Current use of in-line scanning technologies in horticulture is almost exclusively for quality grade determinations, based on external features (colour, shape, blemishes and defects) and/or internal condition (sweetness, internal defects). Two technologies have seen widespread adoption in Australia, as elsewhere in the world, and have come to dominate the grading: machine vision for external quality and near infrared spectroscopy for internal quality. Grading specifically for pests and diseases is a possibility with these technologies too, albeit a challenging one given the generally small, hidden and/or incipient nature of most pests and diseases on fresh produce at harvest grading time.

The Australian horticultural industries are seeking knowledge about the potential for in-line technology to detect market access pest and disease organisms and to provide additional confidence that Australian produce is free from biosecurity risks to export markets, ensuring that Australian horticultural industries can maximise market access opportunities. This study addresses that topic through the following aims: 1) reviewing available scanning technologies of potential to detect pests and diseases; 2) reporting on the science literature actively investigating methods for detecting known pests and diseases; 3) surveying/interviewing knowledgeable industry participants, from across the broad spectrum of Australian horticulture, to learn about specific issues and opportunities in regards to the topic; and 4) determining the statistical consequences of introducing new fast technologies, with capabilities for much larger representative sampling but at the cost of lower measurement accuracies. Knowledge generated from this project will inform further research in this area. Any resulting effective detection method will be incorporated into a systems approach for managing market access pests and diseases. Demonstration of an acceptable degree of protection from market access organisms to regulators in export markets is the end goal of the project.

Methodology

Review of technologies for detecting pests and diseases

A literature search was undertaken, through Web of Science (WoS) and Google Scholar, using the following algorithm:

TS= (postharvest* OR perishable*)

AND

("non-destructive" OR "non-invasive" OR "machine near5 handl*" OR “high speed” OR "scanning technolog*" OR “x-ray” OR Optic* OR spectroscopy OR MRI or “magnetic resonance imag*” OR “machine vision” OR “near infrared” OR “image process*” OR “near infrared interference spectroscopy" OR NIRS OR phytosanitary OR "electromagnetic radiation")

AND

TS= (Biosecurity OR "food protection" OR biosurveillance OR biocontrol* OR "Border security" OR quarantin* OR "pest detect*" OR disease detect*)

The search resulted in 123 items, mainly spanning the years 2010 onwards. There were 24 review articles in the list, most completed and published in the last 2 years, and of which a smaller number (10) appear most relevant. The literature clearly identifies machine vision and near-infrared spectroscopy as the leading contenders for advancement in terms of improved scanning technologies for pest and disease detection.

Additional literature searches were conducted for invertebrate pest and plant disease detection.

Stakeholder consultation

An online survey was created and sent out to various industries and industry leaders. To facilitate the questionnaire and data collection, the survey utilised SurveyMonkey, an electronic platform that can create user-friendly online surveys and allow researchers to receive feedback in real time. The survey had 22 questions and took approximately 8–12 min to answer. The survey questions are presented in the appendices.

Because of a relatively low response rate to the survey, additional targeted calls were made to representatives of several industries. The calls were made on Zoom and five additional questions regarding pest and disease detection were asked.

To gather information on currently used sensing technologies for pests and diseases in packing and sorting line setups, the industry survey covered a number of areas. These included:

- Type of commodity
- Line type (equipment)
- Manual packing vs current inline technology used
- Pests and diseases of greatest concern
- Market and market access issues
- Quality Control (QC) methods and restrictions.

The data were treated anonymously to allow for confidentiality. Each participant had the option to leave their name and contact information at the end of the survey to allow for follow-up conversations. However, this feature was not used by all of the participants.

The target audience for the survey was the following levy-paying industries: citrus growers, Cherry Growers Association, The Australian Almond Board, macadamia nut growers, and a variety of vegetable growers within the AusVeg association such as melons and Gippsland Vegetable Growers Association.

To aid the information gathered through the survey, a number of lead industry people were called. This method was done to ensure a wide range of industries were represented and all states included in the consultation.

The in-depth phone interviews were based on the following five questions:

1. What equipment for sorting are you using/are aware of in industry currently on your line/being used in lines, especially for blemishes, pests and diseases?
2. Why was that kind of technology/equipment chosen? (specific to pests, diseases and blemishes)
3. What kind of technologies would you/can you see be invested in if it was available and money was not an obstacle? And why?
4. What prominent pest/disease are you dealing with in your product/industry that cannot be detected with any of the available technology?
5. Where do you see the industry head to in the future in regards to sensing technologies for packing and sorting lines?

Further to engaging with packhouses and industry representatives, a limited interview process was conducted with manufacturers who produce graders and sensing technology for packhouses, including citrus, mangoes, stonefruit and pomefruit, and nuts (almonds). This includes companies that provide the most advanced sensing and scanning equipment available on the Australian market.

Questions asked to manufacturers included:

1. What sort of queries does the business get in regard to the grading and sorting for pests and diseases?
2. What have you delivered on into this pest and disease space as commercial solutions?
3. Where do you think grader technology will head in providing solutions into the pest and disease space (extension of current technologies or need development of quite new approaches)?
4. How much attention, as grower feedback, might you be able to give in terms of the information content available with grading?

Outputs

There are four main outputs from this study, posed here as questions that are then answered. The first asks what technologies exist and answers with a brief but comprehensive overview of the main scanning technologies considered either capable, or potentially so, of detecting common pests and diseases. Scanning technologies already in use in Australian packhouses are given emphasis with further explanation of their operational principles and known limitations. The second question asks what market access concerns there are in Australia and answers with a list of specific pests and diseases plus an attempt to match many of them individually with suitable scanning technologies. The third question is about learning what some of the main industry players think about the topic, answered through summarising stakeholder consultations resulting from a widely distributed questionnaire survey and in-depth industry participant interviews. The last question simply queries the current statistical methodology that industry uses and what impact new technologies could have, answering by exploring changes that might result if scanning technologies were more widely used.

Output 1. What technologies exist for detecting pests and diseases?

A range of non-invasive technologies have been implemented in other fields, notably in the medical field over the last decades, and attempts made to transfer such technologies to the fruit and vegetable sector. Fruit packlines moved from mechanical (e.g. diverging belts) to electronic beginning in the 1970s, first with adoption of load cells for sorting of fruit on weight. A watershed time came in the 1980s with use of machine vision applications. By the early 1990s there was sufficient research activity on a large variety of relevant technologies and instrumental methods for a number of specialist conferences to be held, and review papers to be written, on the subject of non-destructive technologies for fruit and vegetable quality evaluation (BARD 1993; Abbott et al. 1997; NRAES 1997; Abbott 1999).

To provide the very latest perspective, a comprehensive search was undertaken of the contemporary science research literature on the topic of non-invasive assessment of fresh produce with a focus on pest and disease detection. This search was undertaken through Web of Science and Google Scholar, spanning the years since 2010. This field is topical, with four reviews on non-invasive assessment of fruit published this very year (2020 – and still counting!), with one specifically reviewing the technological options for detection of insect infestations in fruit and vegetables (Adedeji et al. 2020). That review was well written and the range of technologies it considered was nearly complete in terms of the possible scientific arsenal available for dealing with pest and disease detection in any more general sense (i.e. beyond insects and not limited to in-line application). The review finished with a useful summary table that critically compared the different available non-destructive methods (aka scanning technologies). The general form of the summary table is reproduced here (Table 1), where it is greatly amended in content, and/or with additional comments, to reflect the perspectives of the current authors here.

Table 1: A summarised comparison of the scanning technologies reviewed in this report.

Method	Advantages	Disadvantages	Additional Comments	Possibility for On-line Pest and Disease Detection	Research Needs for in-line development	Recent References
Machine Vision (MV)	• Measures external properties • Fast, cost effective, widely available for grading • Multispectral (UV, Visible, NIR) capability	• Only applicable to external surface and near surface regions • Strong defect contrast required	Practical spatial resolution probably limited to the order of a few millimetres	Yes (if pest or disease symptoms observable at surface = not often the case)	• Improved image tracking and/or 3D model rendering • Improved feature recognition (e.g. using AI tools) • Further multispectral explorations and developments	Cubero et al. 2016
Point Spectroscopy (mainly NIR spectroscopy)	• Predicts internal properties • Fast, cost effective, widely available for grading	• Intensive model training required • Can be data heavy • Diffuse signal means limited spatial information	Practically limited to generalised properties such as average sugar content or sizeable defects such as large rots	Yes (in theory but limited success in practice, beyond large rot detection, due to diffuse nature of signal)	• Reductions in the training demand • Improved spatial resolution. • Improved sensitivity to size of symptom or defect	Walsh et al. 2020
Imaging Spectroscopy (e.g., hyperspectral imaging)	• Combines high spatial imaging with large spectral range (typically visible to NIR)	• Costly hardware • Too slow for modern graders • Very data heavy • Extensive model training required	Efficient method for informing multispectral choices for use with machine vision	No	• Hardware cost reduction • Improved speed • Efficient data handling pipelines and modelling	Pu et al. 2015
X-ray Imaging	• Sensitive to internal defects resulting in density changes • Fast (for 2D imaging) • Available for grading although not widely used	• Costly hardware • Density differences often too small • Ionising radiation (safety hazard and regulatory requirements)	Limited applications thus far: • Hollow heart in potatoes • Recently needles in strawberries	Yes	• Reduced hardware costs	Haff & Toyofuku 2008
CT X-ray	• 3D structure	• As for X-ray imaging	Some strong research activity in recent times	No but may have potential	Faster speed and lower costs	Van de Looverbosch et al. 2020
Laser light Backscatter Imaging (LLBI)	• Near-surface measurement of light scattering properties (texture related changes) • Simple setup • Fast	Spatially localised, single spot	Richer possibilities exist in use of multiple scanned lasers for multispectral NIR spectroscopy	Unlikely as single laser system	Spatial scanning required to achieve good surface coverage	Sanchez et al. 2020
Biospeckle Imaging	• Laser light interference patterns due to internal biological activity • Simple Setup	• Slow • Spatially localised, single spot	Requires many seconds of recordings	No	Unlikely	Pieczywek et al. 2018

Method	Advantages	Disadvantages	Additional Comments	Possibility for On-line Pest and Disease Detection	Research Needs for in-line development	Recent References
Dielectic & Impedance Spectroscopy (DS, IS)	• High frequency (microwave, RF) electrical measurement • Very sensitive to average water content	• Complex analysis • Shape sensitive • Setup sensitive	Probably best for continuous or in-storage monitoring where sensitivities to shape and setup can be voided	No	Unlikely	Sanchez et al. 2020
NMR (Nuclear magnetic resonance)	Sensitive to internal properties, particularly water relationships	• No spatial information • High hardware costs • Slow	Long held as a potential method but sensitivity to water activity, rather than say water concentration, makes quantification difficult	No	Unlikely	Burdon et al. 2014
MRI (magnetic resonance imaging)	Visualisation of internal 3D structure. Large aperture systems (e.g. apple box loads at once)	• Very high hardware costs • Very slow scan speeds • Data heavy • Poor quantification of image features	• Like with NMR, quantification is difficult beyond revealed structural information • Useful for experimental design, enabling pre-trial classifications of samples	No	Very unlikely (given need for greatly reduced hardware cost and greatly increased scan speeds)	Adedeji et al. 2020
Thermal Imaging	• Sensitive to heat patterns at surface, either created or pre-existing. • Can be low cost	• Sample conditioning required. • Slow • Best results with high cost systems	The advent of inexpensive solid state systems is spurring some developments but difficult to see it progressing much further	No	Unlikely Proved unsuccessful in comprehensive study into detecting wood-boring moth larvae inside wooden sticks (Hoffmann et al. 2013)	Adedeji et al. 2020
Acoustic	• Sensitivity to insect movement • Inexpensive	• Slow • Requires precise signal processing to overcome background noise	• More suited as a monitoring technique • Non-contact measurement with laser Doppler vibrometry	No	Unlikely	Adedeji et al. 2020
Electronic Olfaction Devices (PID, E-Nose)	• Sensitive to volatiles • Can be inexpensive (PID) • Fast response to volatile, once captured	• PID (photoIonisation Detector) is non-specific (VOC only) • E-Noses require extensive training • Detection speed limited by head-space capture time	The generally long time (seconds to minutes) required to collect a suitable headspace means grader applications are not possible	No	Box consignment level detection is a possibility	Li et al. 2019

Given this level of review of the scientific literature, in this report we focus on an explanation of the underpinning technologies with existing or clear prospects for on-line scanning for pests and diseases (machine Vision, near-infrared (NIR) spectroscopy, X-ray, magnetic resonance imaging (MRI) and E-nose technologies, as per Table 1), with their strengths and weaknesses for pest and disease detection, and the state of commercial implementation for fruit assessment.

In-line vs at-line

Control points

Assessment of defect (pest and disease) fruit after harvest and before phytosanitary inspection adds to the security of the value chain. In-line inspection allows for the inspection of every piece of fruit, at the compromise of working at very high speed (typically <100 ms per fruit) and consequently the risk of failure to detect the defect of interest (false negative). This time limitation is the primary difficulty for application of technologies such as X-ray computed tomography (CT) and MRI, along with cost.

Conversely, lot assessment of a sample of fruit per consignment provides more time for assessment of each item of fruit, but with sampling error risk (i.e. that the sample does not well represent the consignment). Current phytosanitary inspection regimes rely on this procedure. Operator fatigue is an issue for a manual process, however, and there is scope to employ a greater range of technologies for at-line assessment, given available time, than for in-line assessment.

In-line

The development of high-speed, in-line grading and sorting of fresh produce has been underway for many decades, coupled closely to continuous and rapid advancements in electronic instrumentation and computing power. Small companies dominated early but, as with most industries, increasing sophistication of product has been accompanied by consolidation of suppliers, as seen in recent times with the acquisition of Australasian manufacturers Colour vision Systems and Compac by MAF (France) and Tomra (Norway), respectively. A list of recognised grader manufacturers with products in these technology spaces, many prominent in Australian horticulture, is provided in Appendix 3. An example installation of a scanning system for citrus is displayed in Figure 1.

Figure 1: An eight-lane grading system for citrus with a row of eight NIR spectroscopy measurement heads (reflectance systems) immediately in front of a large machine vision system (spectrim – blue cabinet).

However, only the non-invasive assessment technologies of machine vision and NIR spectroscopy have been truly commercialised and become widely available on commercial packlines. Other technologies are still variously being explored but not with the same application focus or intensity of effort as has been seen with machine vision or NIRS. An example is nuclear magnetic resonance (NMR), which in the 1990s was holding some good promise for non-destructive measurement of internal fruit condition such as the presence of pests and diseases (Tollner et al. 1994; Kim et al. 1997).

The current advantage of in-line sorting in the context of pests and diseases of phytosanitary significance is primarily an indirect one, through removal of fruit with defects such as cuts and bruises. Such fruit are more likely to harbour a pest or pathogen of concern.

At-line

Some in-line manufacturers have made their sensors available for use off-line (at-line). For example, Aweta (Holland) produces a bench-top version of their firmness sensor. Other technologies are not available on-line but could be deployed at-line, as discussed in subsequent sections.

Available technologies

Machine Vision

Machine vision technology is widely used in packhouses for measuring external properties such as size and shape, colour and blemishes, and the presence of damage and defects. Commercial systems consist of an illumination cabinet with multiple cameras, or camera views, and the possibility of different illuminating light sources (e.g. different coloured LEDs, UV, NIR). Such systems are often referred to by different names, such camera box, camera system, imaging cabinet, vision cabinet or similar. Individual (singulated) items of produce are carried at high rates into the cabinets on a conveyor system, typically running at 1 m/s or more speeds. Multiple image captures are then taken using the cameras as the samples travel though the cabinet, often whilst they are being rotated backwards, at low angular rates, to enable full camera views of all sides during their passage through the cabinet.

The ability to detect a blemish or defect, such as an insect or insect entry hole, is determined by a number of technical illumination/camera factors that are difficult to tease apart as they convolve together in giving rise to the system optical transfer function. This means simple questions about performance limits are difficult to answer beyond such clichés as ‘if you can see it easily by eye then a camera should detect it too’.

The primary limitation to detection, be that by human eye or machine vision, is the defect contrast as delivered in the recorded images as texture (spatial patterns) and/or colours (RGB differences) with respect to the background sample surface. This contrast ultimately determines the practical limits of detection, i.e. true positive rate. An additional consideration is the presence of other objects or defects that mimic the defect of interest, such as stems or calyxes. This issue causes false positive detections.

Dealing with multiple images per sample at high speed requires image handling and processing methods using sophisticated algorithms that start with either stitching images appropriately together, as a round-the-sample strip, or by rendering the image sequences into an approximation of a 3D model of the sample. The image processing challenges involved are algorithmically deep with peculiarities pertaining uniquely to each system. This means much of the IP in the various commercial machine vision systems is simply tied up in the bespoke complex software code that implements the analysis.

More advanced systems allow for training of the machine vision to recognise a specified defect against specified backgrounds in the packhouse. The training involves presentation of positive and negative defect examples of the samples to the machine vision system followed by automated application of image processing and machine learning techniques to derive a suitable detection algorithm. Such 'on-the-go' training is sometimes presented as a 'Quiz' that the grader operator performs by tracking the known examples through the grader. The operator will generally have some control input, such as in setting of the segregation cut-points.

In most circumstances the performance of a system can only be determined empirically then, by validation trials. Such trials simply involve presenting other samples to the machine vision system and observing how successful the segregations are, e.g. by inspection of fruit at a designated defect drop point.

A rapidly growing trend in recent times has been towards multispectral imaging, using discrete-waveband light sources from the UV to the NIR range. This has been propelled in part by the increased availability of relatively inexpensive LED strips, of many different hues from UV to NIR, over the last decade. The advantage to be had with discrete waveband light sources is contrast enhancement, between the defect and the underlying fruit surface of the sample. For instance, UV illumination enables contrast enhancement if a defect feature is able to fluoresce compared with the background surface (e.g. clear rot in citrus – Figure 2). Similarly, there can be contrast advantages in the near-infrared (e.g. detection of moisture-related defects). Defect contrast in the visible range is also possible by use of selected discrete wavebands that, for example, accentuate fruit pigments so as to contrast strongly with the lack of those pigments in a defect feature.

Figure 2: Visible (left) and UV (right) illumination of a mandarin with clear rot symptoms, demonstrating improved contrast as a result of UV fluorescence.

Multispectral imaging involves the use of multiple views of an object using a limited number of wavelengths. A long-standing example is the fast laser scanners used for examining small produce items, such as macadamia and almond nuts. These systems consist of one or more laser beams that are rapidly scanned across the belt conveyor used to transport such small items. The incident laser beam is absorbed or scattered off different samples in different ways, enabling the detection of foreign samples (e.g. dirt, stones) and/or defects (e.g. broken shells). More recent developments have seen systems involve simultaneous use of multiple laser beams at different wavelengths, resulting in a signal profile with often superior performance and able to detect some internal features (e.g. The Nimbus BSI by Tomra, Norway; The Evolution by SATAKE, Japan).

Hyperspectral imaging involves the use of many more wavelengths, often 100s. It is a popular technique in many branches of science (e.g. remote sensing) as it enables the efficient collection of spectrally dense spatial data. The technique has good potential for identifying an object with a spectral fingerprint different to its background. However, data volumes can be very high, data acquisition is slow and the hardware itself is expensive – limiting factors for use on high-speed fruit graders. Such systems may also be useful for identifying wavelength choices for use in a multispectral machine vision system (Lorente et al. 2012).

In the context of biosecurity applications, as noted earlier, the current value proposition for in-line use of machine vision is the removal of damaged (e.g. cuts, bruises) produce that are more likely to suffer pests and diseases of biosecurity concern. The prospects for direct detection of these pests and diseases relies on the visibility of the defect. Basically, if a defect is on or near the surface, and easily resolvable to the order of 1 mm in dimensions (e.g. visible by unaided eye), there is potential for detection. Detection can be improved with enhanced imaging, e.g. using different light sources to accentuate contrasts, and such enhancements will improve with time. However, many pests and diseases of biosecurity concern are small and either internal to the fruit, or located in external crevices, e.g. under calyx, with the wash process removing objects from the visible body of the fruit.

There is potential to implement machine vision in at-line stations with samples handled to mimic the current biosecurity inspection, e.g. cutting of fruit or lifting of sepals.

Near Infrared (NIR) Spectroscopy

Near-infrared (NIR) spectroscopy is a technology reasonably widely used in packhouses mainly for measuring internal chemical constituents, such as dry matter content or soluble solids content, or tissue properties such as the presence of defective tissue, e.g. internal browning and rots. The term near-infrared strictly applies to a particular waveband of light, beyond the red colour end of the visible light range, but more often than not the usage is considered to include the visible range as well when applied in the context of non-destructive scanning technologies for fresh produce inspections. Various alternative acronyms are also used in the literature, such as Vis-NIR or VNIR (visible to NIR range) and SWNIR (short wave NIR).

A grader-based NIR system simply passes a sample through a bright light beam and detects the spectrum of transmitted light. The spectrum is interrogated by a suitably trained and calibrated computer algorithm, to deliver a prediction of the quantitative value or presence of the feature of interest. The fundamental spectral basis for most successful applications is claimed to be the existence of relevant light absorbing constituents (e.g. plant pigments, water) but the co-existence of many interfering spectral factors, affecting light transmission in biological materials, means the claim is largely void of meaning – successful predictive models can only be established through careful experiment. To say it is complicated is to understate the matter and only the advent of modern machine learning algorithms and thorough calibration/validation processes have made the technique practically viable in the horticultural industry.

The illuminating light source used in the commercial NIR systems is generally broadband, such as an incandescent halogen lamp, with peak emission in the NIR range. The detection sensor is typically a silicon-based optical spectrometer with good sensitivity from the blue end of the visible range (~400 nm) to the red end (~750nm) and then on a short way into the NIR (up to ~1100 nm). The spectrometers are usually quite spectrally dense, the optics build around linear sensor arrays of some hundreds of contiguous elements (diodes). Some spectrometers in use have different sensors with greater sensitivity at higher wavelengths, above 1000 nm. However, these are rarely used since light at those wavelengths has little penetration depth into fresh fruit and vegetables because of the strong moisture absorbing bands in the higher NIR regions.

The source light beam will generally illuminate one area or zone of the sample while the transmitted light spectrum from another area or zone is being simultaneously detected. If the optical source-sensor arrangement has the illumination and detection zones close by on the same side of the sample, then the remitted light will come from only a shallow part of the fruit (i.e. only part of the sample is assessed). Other systems involve a detector zone that has a substantial angular distance from the source zone, such as at 90° (partial transmission) or 180° (full transmission). These transmission systems achieve much deeper light penetration for the detected light although still with a sensitivity bias towards the near surface region of the detection zone (Figure 3). However, they have a much lower proportion of incident light detected, and so require much stronger light sources, more sensitive detectors or longer detection times, particularly for larger fruit. Which system, same-side reflectance or some form of transmission, is best to use depends on both the nature of the fruit (e.g. the presence of the thick skin on fruit such as citrus) and/or the defect (e.g. internal browning deep in an apple).

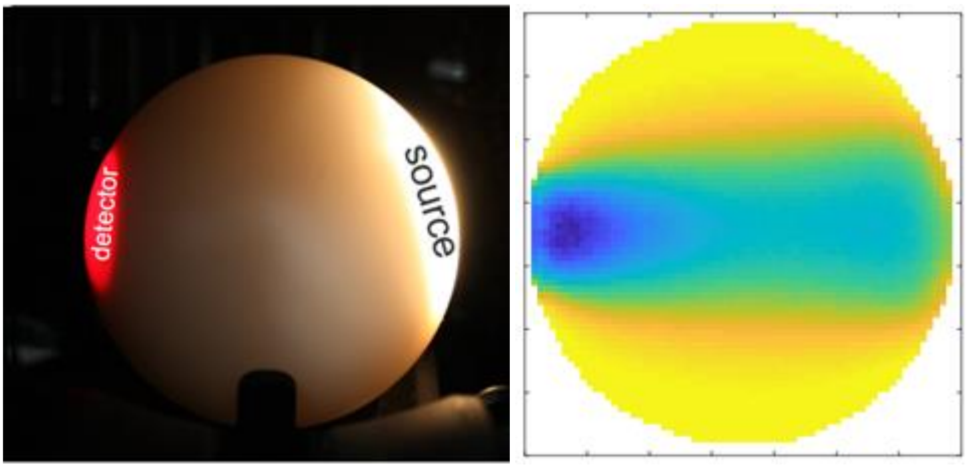

Figure 3: On the left is a phantom fruit sample, a solid white Teflon ball, photographed while passing through a NIR spectroscopy transmission system with the source and detection zones indicated (NB detection zone made visible by running red laser beam backwards through the detector optics). On the right is a computer simulation of the exact situation, the internal light transport modelled to show the relative sensitivities of the detected light to different regions of the phantom, in equatorial cross-section, from low (yellow) to high (dark blue) sensitivity (Images: Jason Sun, Plant & Food Research).

Operation at grader lines speeds, typically 1 m/s or higher, limits spectral acquisition times to well less than 100 ms, reducing the possibility for spatial resolution – the detection zone is blurred at a rate of 1 mm for every 1 ms of acquisition time. This is compounded by a generally wide illumination area (e.g. centimetres in diameter) and the strong inherently diffusive nature of the light transmission in typical biological materials such as fruit – complete scattering disorientation of the entering light beam happens within as little as 1 cm of travel. These facts severely limit the detection of small size defects also, with anything less than about 10% of sample volume being too small, even when quite close to the surface of a fruit (Sun et al. 2020. Full sample interrogation is not generally possible anyway, even with full transmission systems, as internal sample sectors beyond the main central illumination axis will have very low interaction with the transmitted light (see Figure 3 above). Multiple measurement stations would be required to provide full sample interrogation with an in-line system.

The success or failure of NIR spectroscopy, much like with the machine vision applications, can often only be confidently asserted by empirical demonstration, by trial and error measurement on an actual grader line system. Again, training and calibration of the computer algorithm is critical. The training process is a machine learning one, often called chemometrics, in which statistical tools are used to match paired spectral and standard method measurements of the quantity or quality of the produce feature of interest. Hundreds to thousands of produce samples can be required, to adequately cover variation due to fruit size, shape, origin (e.g. orchard or region), to build robust models since the training can only be secure if all likely future examples of the produce samples are included in the training.

However, while in commercial use for soluble solids content, dry matter content and internal defects such as internal browning, NIR spectroscopy has no commercial use for detection of internal disease or pest damage. This is despite some promising research on the topic, such as in the detection of fruit fly larvae in mango (Saranwong et al. 2010). This can be attributed to the small size detection limit, that in practice a defect must not only have high contrast (e.g. be strongly absorbing of NIR light compared with good tissue) but also must be at least as large as 10% by volume relative to the sample size. The diffuse nature of NIR light transmission, coupled with the poor spatial resolution, means small defects caused by pests or diseases will be simply too diluted by the signal from the intact or good tissue. There is also the salient issue of sample orientation, the defect position in the sample being unknown in advance and so the optimal light transmission path for detection cannot be ensured. There are some interesting new NIR spectroscopy prospects being researched regarding attempts to circumvent these problems, to significantly improve spatial resolution and deal with orientation issues through the use of fast scanning multi-wavelength laser systems (Sun et al. 2020).

Hyperspectral imaging in NIR wavelengths may have value for automated pest and disease detection of intact or cut fruit in an at-line context.

X-Ray Technology

Traditional X-ray imaging relies on visualisation of the attenuation of X-rays through an object. This is a function of density and path length. Unfortunately, fruit do not present a uniform thickness and the range of densities of inclusions (from skin, flesh, seed to insects) is similar, leading to relatively poor visualisation (Figure 4) except for large voids. Consequently, X-ray technology is not widely used in the horticultural industry beyond detection of foreign bodies, such as metal objects, and large internal cavities. Commercial line scanning radiographic systems are certainly available. An often quoted horticultural success has been for hollow heart in potatoes, which dates as far back as 1937 for first investigations and in automated commercial form since probably around the 1980s (Abbott 1999). The technology is in widespread use in the fresh-cut produce and consumer pack space, where there is zero tolerance for foreign bodies such as stones or, as in recent times, metal objects such as needles in fruit. (Davidson 2018).

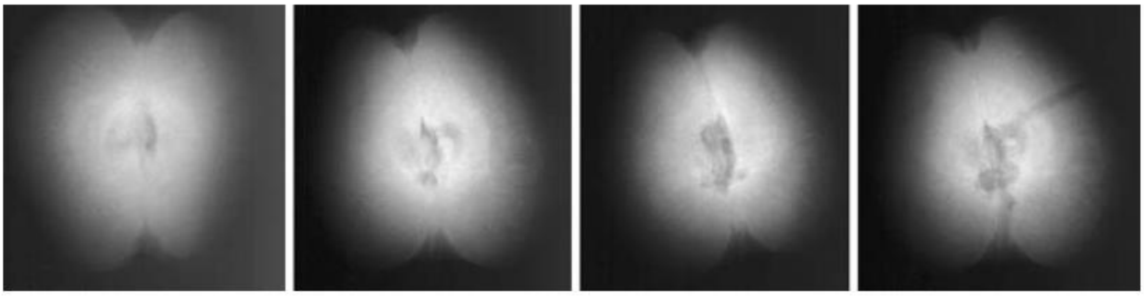

Figure 4: X-ray images of codling moth infestation in an apple, age of infestation varying from left to right over 17 days from inoculation with eggs (Haff & Toyofuku 2008).

Two main issues appear to combine to limit application of the technology in horticulture: (1) the lack of defect contrast in biological material such as fruit; and (2) the low sensitivity but high cost of the necessary digital sensors. There is also an issue of safety, X-rays being ionising radiation and thus potentially hazardous to human health, which brings extra regulatory costs into play. The lack of contrast is a result of the similar material densities involved, there simply not being enough density difference between typical defects, such as an internal insect infestation or damage, and the normal sample tissue, to be revealed on a radiograph. Open cavities present strong contrast, air being obviously much less dense than tissue, and so detection of defects such as insect tunnels is possible and has certainly been demonstrated in research applications using highly sensitive photographic plates (Haff 2006). However, current digital sensor systems for X-rays are not nearly as sensitive as standard X-ray plates and, coupled with their relatively high cost, are also a limiting factor for take-up of the technology (Haff & Toyofuku 2008).

There has been some promising recent research activity towards advancing X-ray CT for applications in horticulture (Van De Looverbosh et al. 2020). In its full form, X-ray CT requires the measurements of X-ray projections at a multiple of angular positions around the sample, with reconstruction algorithms employed to then render a 3D image of the internal structure. Higher value applications, such as in medicine or high-end industrial research, can accommodate the low acquisition speeds or the high hardware costs that are involved in standard approaches involving either precise sample rotation or large multiple source-sensor arrays. The suggestion from the recent work, and particularly an associated patent (Van Deal et al, 2015), is that costs could be substantially reduced and speed greatly improved by using prior knowledge, about shape and expected internal content, to enable reconstruction from far fewer projections. This could perhaps be just from line scan images assembled from the linear passage of a sample through an X-ray projection system. The rendered 3D internal structures would necessarily be quite crude, compared with standard medical X-ray CT, but might be sufficient for the purposes of detecting pests and diseases.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) has seen tremendous growth in the medical field, driven by ever-increasing levels of information available in using the technique. In Australia, between 1998 and 2017 the number of MRI units in hospitals and surgeries increased from 38 to 508 with it now available in regional centres not just major city hospitals (https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Community_Affairs/Diagnosticimaging/Report/c03).

MRI has been used on fresh produce but only for research purposes (e.g. Burdon et al. 2014). Typical applications of the technology with fresh produce uses a strong magnetic field to flip proton (H) nuclei, with released radiowaves used to capture information primarily about water mobility. It can produce strikingly detailed images of the internal structure of fruit and vegetables (e.g. Figure 5), much superior to standard X-ray imaging. Detection of internal pest and disease issues with high accuracy is possible (e.g. Figure 6). However, the technique is currently slow, expensive and has some risk involved in use of high-strength magnetic fields.

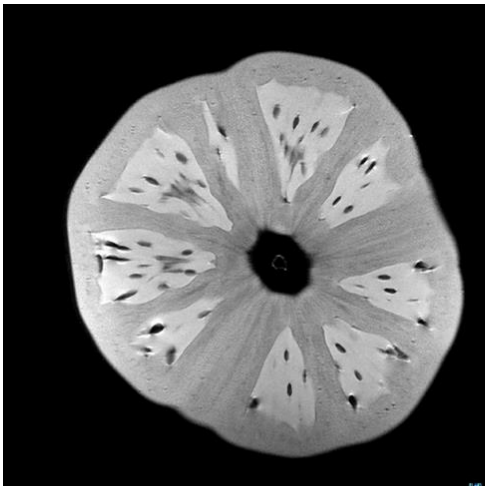

Figure 5: Magnetic resonance image of tomato fruit. Photo: Andy Ellison (image downloaded from large set available at: https://www.smithsonianmag.com/smart-news/these-mri-scanned-fruits-and-vegetables-unfold-alien-births-180951148/)

Figure 6: Magnetic resonance image of peach fruit moth larvae in fruit (Haishi et al. 2011).

However, there are some promising developments occurring that might give a little optimism about MRI application to produce inspection in the future, particularly at-line. Aspect Imaging (Shodam, Israel), a claimed leader in medical MRI, have been pushing implementation of the technology towards industrial use. They claim a point of difference in that their equipment has a low magnetic field outside the unit (e.g. the magstripe on credit cards will not be wiped clean). They have been exploring the agricultural market, developing a demonstration unit delivering a single slice image of citrus fruit at a 2 s per fruit rate, although it is unclear how seriously beyond that simple proof of concept they have taken it since 2015 (Figure 7). And for a biosecurity application a full 3D image would be required for complete assessment of the fruit, rather than a single 'slice' image.

In Australia, recent federal funding has been provided to the University of Queensland to pursue development of portable MRI systems for medical uses and beyond, where high resolution imaging is not required and safer low strength magnetic fields can be used (https://www.uq.edu.au/news/article/2020/06/1-million-develop-portable-mri-device).

The technology may never be fast enough for grading line applications, there being a physical limit to the speed with which magnetic fields can be adjusted and controlled, but slower at-line applications may be possible in the future by taking advantage of efficiencies if tray or box lots of fruit can be examined at one time. It will likely remain relatively expensive too, almost definitely out of reach in terms of single packhouse operations, but as an at-line system it could be easily shareable across an industry where harvest season timings vary greatly by locality and crop.

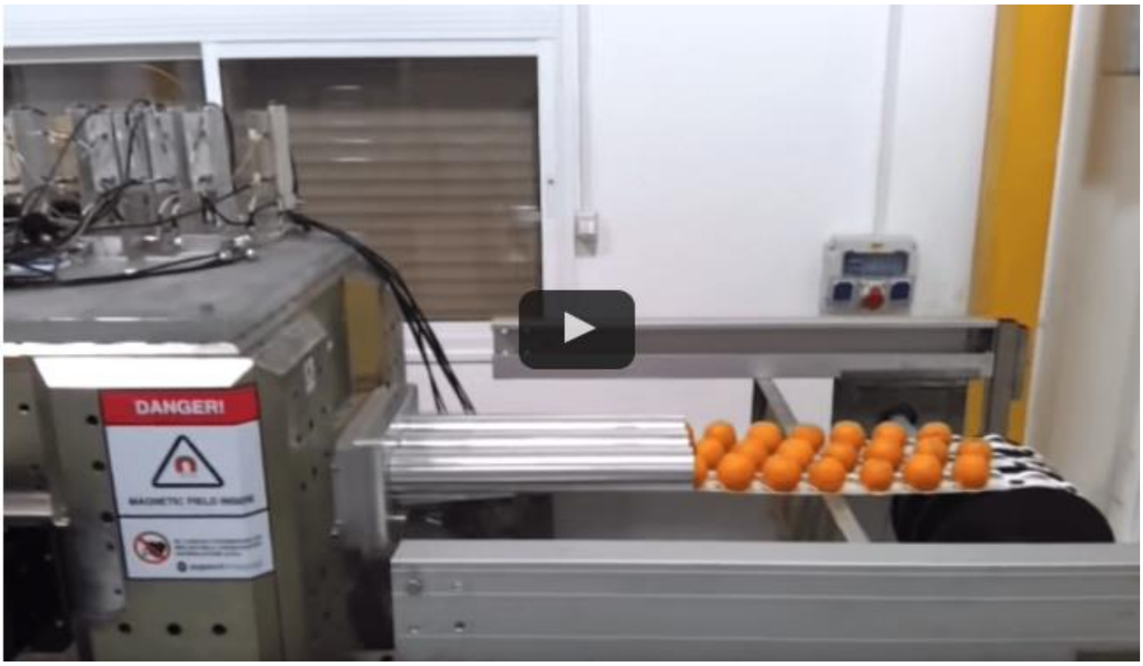

Figure 7: The Aspect Imaging system for citrus that produces a single medial magnetic resonance image per fruit in approximately 2 seconds (image from 2015 YouTube clip: https://www.youtube.com/watch?v=nV2Nuv9m4bU&feature=youtu.be).

E-nose

There is potential to 'smell' some disorders (Cui et al. 2018). An example is the detection of different diseases in plant tissue by Li et al. (2019) using a portable sensor (Figure 8).

Figure 8: E-nose for detection of disease of plant foliage (Li et al. 2019)

Such technology has not advanced into commercial application as yet. Technical difficulties include detector stability and uniqueness of the 'smell' (the odour fingerprint). Practical difficulties include speed of detection, with time required for odour to accumulate in an enclosed space. In biosecurity applications there can be a very small number of organisms of concern in a relatively large assessment lot (e.g. 1 fruit fly in 600 pieces of fruit), making detection by e-nose unlikely. The technique is therefore applicable at-line rather than in-line, and likely only for a limited number of applications.

Output 2. What are the pests and diseases of market access concern?

Biosecurity and Market Access

Tables 2–10 below list the pests and diseases of 'critical' and 'high' market access concern for Australian producers exporting to key markets (the United States, New Zealand, China, Vietnam, Japan, and Korea) created by collating information from the Australian Department of Agriculture's Pest Risk Assessments and the MICoR database (Manual of Importing Country Requirements). The commodities used for stakeholder consultation were reviewed: almond, macadamia nut, cherry, citrus, Solanaceae, and brassicas. Pests that were listed in Operational Work Plans as 'critical risk' and 'high risk' were noted.

Key items in the list are further discussed below with respect to potential scanning technologies for detection that may have been positively reported in the science literature. Most of the technologies to be mentioned have been cited above, in the technology review, but are here given specific context. For convenience, a division is made between insect pests and disease pathogens.

Table 2: Requirements for almond exports to key markets

United States	Shelled, free from pests
New Zealand	Free from all pests
China	Free from all pests
Vietnam	Free from all pests
Japan	Free from all pests
Korea	Free from all pests

Table 3: Requirements for macadamia nut exports to key markets

United States	Shelled, free from pests
New Zealand	Shelled or fumigated, free from pests
China	Free from all pests
Vietnam	Free from all pests
Japan	Free from all pests
Korea	Free from all pests

Table 4: Pests and diseases of 'high' and 'critical' risk for capsicum and tomato exports to key markets

United States	No protocol
New Zealand	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Yellow peach moth (*Conogethes punctiferalis*) Silverleaf whitefly (*Bemisia tabaci*) Banana fruit fly (*Bactrocera musae*) Northern Territory fruit fly (*Bactrocera aquilionis*) Jarvis fruit fly (*Bactrocera jarvisi*) Cucumber fruit fly (*Bactrocera cucumis*) Fruit fly (*Bactrocera bryoniae)* Fruit fly (*Bactrocera frauenfeldi)* Fruit fly (*Bactrocera kraussi)* Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Melon thrips (*Thrips palmi*)
China	No protocol
Vietnam	Prohibited
Japan	Mediterranean fruit fly (*Ceratitis capitata*) Queensland fruit fly (*Bactrocera tryoni*)
Korea	No protocol

Table 5: Requirements for Brassica exports to key markets

United States	No protocol
New Zealand	No protocol
China	No protocol
Vietnam	No protocol
Japan	Free from all pests
Korea	Free from all pests

Table 6: Pests and diseases of 'high' and 'critical' risk for potato exports to key markets

United States	No protocol. Potatoes intended for use in research purposes only
New Zealand	No protocol
China	No protocol
Vietnam	Potato cyst nematodes (*Globodera* spp.) Potato spindle tuber viroid
Japan	No protocol
Korea*	Potato cyst nematode (*Globodera* spp.) Potato spindle tuber viroid

*Victoria, Queensland and Western Australia potatoes prohibited

Table 7: Pests and diseases of 'high' and 'critical' risk for cherry exports to key markets

United States	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Light brown apple moth (*Epiphyas postvittana*) Black cherry aphid (*Myzus cerasi*) Black peach aphid (*Brachycaudus persicae*) Fuller's rose weevil (*Pantomorus cervinus*) Garden weevil (*Phlyctinus callosus*) Longtailed mealybug (*Pseudococcus longispinus*) Tortricid moth (*Epiphyas xylodes*) Plague thrips (*Thrips imagines*) Plague soldier beetle (*Chauliognathus lugubris*) Brown rot (*Monilinia fructicola*) Twig blight/crown rot (*Pseudomonas syringae*) Bacterial canker (*Pseudomonas syringae* pv. *morsprunorum*) Prunus necrotic ringspot virus
New Zealand	No protocol
China	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Light brown apple moth (*Epiphyas postvittana*) Black plague thrips (*Haplothrips froggatti*) Tubular black thrips (*Haplothrips victoriensis*) Longtailed mealybug (*Pseudococcus longispinus*) Phylloxera (*Daktulosphaira vitifoliae*) Bunch mite (*Brevipalpus californicus*) Grape lead rust mite (*Calepitrimerus vitis*) Argentine ant (*Linepithema humile*) Redback spider (*Latrodectus hasseltei*) Bitter rot (*Greeneria uvicola*) Grapevine dieback (*Eutypa lata*)
Vietnam	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Oriental fruit moth (*Grapholita molesta*) San Jose scale (*Diaspidiotus perniciosus*) Bacterial leaf blight (*Pseudomonas viridiflava*) Shot hole (*Stigmina carpophila*) Powdery mildew (*Podosphaera clandestine* var. *clandestine*) Brown rot (*Monilinia laxa*) Phytophthora root rot (*Phytophthora megasperma*)

	Bacterial canker (*Pseudomonas syringae* pv. *morsprunorum*)
Japan	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Codling moth (*Cydia pomonella*)
Korea	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Codling moth (*Cydia pomonella*) Light brown apple moth (*Epiphyas postvittana*) Tortricid moth (*Epiphyas xylodes*) Short hole (*Stigmina carpophila*)

Table 8: Pests and diseases of 'high' and 'critical' risk for citrus exports to key markets

United States	Mediterranean (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Light brown apple moth (*Epiphyas postvittana*) Brown citrus rust mite (*Tegolophus australis*) Small brown snail (*Cernuella virgate*) Pointed snail (*Cochlicella acuta*) Citrus black spot (*Guignardia citricarpa*) Citrus scab (*Sphaceloma fawcetti* var. *scabiosa*)
New Zealand	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Northern Territory fruit fly (*Bactrocera aquilionis*) Halfordia fruit fly (*Bactrocera halfodiae*) Jarvis fruit fly (*Bactrocera jarvisi*) Citrus leafminer (*Phyllocnistis citrella*) Black spot (*Guignardia citricarpa*) Citrus canker (*Xanthomonas citri* subsp. *citri*)
China	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Northern Territory fruit fly (*Bactrocera aquilionis*) Jarvis fruit fly (*Bactrocera jarvisi*) Blastobasis moth (*Blastobasis* spp.) Bunch mite (*Brevipalpus californicus*) Sorgum head caterpillar (*Cryptoblabes adoceta)* Black thread armored scale (*Ischnaspis longirostris*) Orange fruit borer (*Isotenes miserana*) Whitefly (*Aleurocanthrus valenciae)* Golden mealybug (*Nipaecoccus aurilanatus*) Island fruit fly (*Dirioxa pornia*) Carob moth (*Ectomyelois ceratoniae*) Brown rot (*Phytophthora hibernalis*) Citrus brown rot (*Phytophthora syringae)* Septoria spot (*Septoria citri*)
Vietnam	Mediterranean fruit fly (*Ceratitis capitate*) Queensland fruit fly (*Bactrocera tryoni*) Jarvis fruit fly (*Bactrocera jarvisi*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Oleander scale (*Aspidiotus nerii*) Palm scale (*Hemiberlesia lataniae*) Armored scale (*Lepidosaphes gloverii*)

	Obscure mealybug (*Pseudococcus viburni*) Citrus scab (*Elsinoë australis*) Branch canker (*Botryosphaeria ribis*) Bacterial canker (*Pseudomonas syringae* pv. *syringae*) Sooty blotch and fly speck (*Gloeodes pomigena*) Greasy spot (*Mycosphaerella citri*)
Japan	*all pests present are considered a quarantine concern
Korea	Mediterranean fruit fly (*Ceratitis capitata*) Queensland fruit fly (*Bactrocera tryoni*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Northern Territory fruit fly (*Bactrocera aquilonis*) Halfordia fruit fly (*Bactrocera halfodiae*) Jarvis fruit fly (*Bactrocera jarvisi*) Torres Strait fruit fly (*Bactrocera trivialis*) Greasy spot (*Sycosphaerella citri*) Collar rot (*Phytophthora citricola*) Brown rot (*Phytophthora hibernalis*) Septoria spot (*Septoria citri*)

Table 9: Pests and diseases of 'high' and 'critical' risk for mango exports to key markets

United States	Northern Territory fruit fly (*Bactrocera aquilonis*) Cucumber fruit fly (*Bactrocera cucumis*) Mango fruit fly (*Bactrocera frauenfeldi*) Jarvis fruit fly (*Bactrocera jarvisi*) Fruit fly (*Bactrocera kraussi)* Fruit fly (*Bactrocrea murrayi*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) False Oriental fruit fly (*Bactrocera opiliae*) Queensland fruit fly (*Bactrocera tryoni*) Mediterranean fruit fly (*Ceratitis capitata*) Mango seed weevil (*Sternochetus mangiferae)* *Cytosphaera mangiferae* Stem canker (*Lasiodiplodia pseudotheobromae*) Trunk canker (*Neoscytalidium novaehollandiae*) Stem end rot (*Phomopsis mangiferae*) *Pseudofusicoccum adansoniae* Bacterial black spot (*Xanthomonas campestris* pv. *mangiferaeindica)* Mango fruit rot (*Neofusicoccum mangiferae*) Mango dieback (*Neoscytalidium novaehollandiae*)
New Zealand	Northern Territory fruit fly *(Bactrocera aquilonis*) Cucumber fruit fly (*Bactrocera cucumis*) Mango fruit fly (*Bactrocera frauenfeldi*) Jarvis fruit fly (*Bactrocera jarvisi*) Fruit fly (*Bactrocera kraussi)* Fruit fly (*Bactrocrea murrayi*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) False Oriental fruit fly (*Bactrocera opiliae*) Queensland fruit fly (*Bactrocera tryoni*) Mediterranean fruit fly (*Ceratitis capitata*) Island fruit fly (*Dirioxa pornia*) Banana spotting bug (*Amblypelta nitida*) Oriental yellow scale (*Aonidiella orientalis*) Coconut scale (*Aspidiotus destructor*)

	Dictyosperumum scale (*Chrysomphalsu dictyospermi*) Yellow peach scale (*Conogethes punctiferalis*) Fruit-piercing moths (*Eudocima* spp.) Flower thrips (*Frankliniella schultzei*) Greenhouse thrips (*Heliothrips haemorrhoidalis*) Tea-bug *(Helopeltis clavifer)* Egyptian fluted scale (*Icerya aegyptiaca*) Mango hopper (*Idioscopus clypealis*) Mango hopper (*Idioscopus nitidulus*) Black thread scale (*Ischnaspis longirostris*) Orange fruitborer (*Isotenes miserana*) European grape berry moth (*Lobesia* sp.) Red-shouldered leaf beetle (*Monolepta australis*) Small monolepta beetle (*Monolepta divisa*) Karoo thorn mealybug (*Nipaecoccus vastator*) Erebidae moth *(Ophiusa tirhaca)* Mango tipborer (*Penicillaria jocosatrix*) Mango scale (*Phenacaspis dilatata*) Citrus mealybug (*Planococcus citri*) Cockerell's scale (*Pseudaulacapis cockerelli)* *Rastroccus* sp. Mexican black scale (*Saissetia miranda*) Redbanded trhips (*Selenothrips rubrocinctus*) Mango seed weevil (*Sternochetus mangiferae*) *Asterina punctiformis* Stem sooty blotch (*Chaetothyrina tenuissima*) Stem-end rot (*Cytosphaera mangiferae)* Mango scab (*Elsinoe mangiferae*) *Fusicoccum mangiferae* Stem-end rot (*Nattrassia mangiferae*) Grey leaf spot of mango (*Pestalotiopsis mangiferae*) Storage rot (*Pestalotiopsis mangifolia*) Mango blight (*Pestalotiopsis theae*) Mango leaf spot (*Pestalotiopsis virgatula*) Stem end rot (*Phomopsis mangiferae*) Mango powdery mildew (*Oidium mangiferae*) Schizoparme fruit rot (*Schizoparme straminea*)
China	Armoured scales (*Aulacaspis* spp.) Northern Territory fruit fly (*Bactrocera aquilonis*) Mango fruit fly (*Bactrocera frauenfeldi*) Jarvis fruit fly (*Bactrocera jarvisi*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Queensland fruit fly (*Bactrocera tryoni*) Mediterranean fruit fly (*Ceratitis capitata*) Sorgum head caterpillar (*Cryptoblabes adoceta*) Fruit moths (*Ephestia* spp.) Light brown apple moth (*Epiphyas postvittana*) Orange fruit borer (*Isotenes miserana*) Tortricid moths (*Lobesia* spp.) False mango scale (*Phenacaspis dilate*) Mango seed weevil (*Sternochetus mangiferae*) *Coniella castaneicola* Stem end rot (*Cytosphaera mangiferae*) Dothiorella 'long' *Dothiorella mangiferae* Stemphylium rot (*Stemphylium vesicarium)* Bacterial black spot (*Xanthomonas campestris* pv. *mangiferaeindica*)

Vietnam	No protocol
Japan	Queensland fruit fly (*Bactrocera tryoni*) Mediterranean frut fly (*Ceratitis capitata*) Scale insects (*Aulacaspis* spp.) Anthracnose (*Colletotrichum gloeosporioides*) Stem end rot (*Dothiorella dominicana*)
Korea	Mango seed weevil (*Sternochetus mangiferae*) Bacterial black spot (*Xanthomonas campestris* pv. *mangiferaeindica*) Stem end rot (*Cytosphaera mangiferae*) Red banded caterpillar (*Deanolis albizonali*)

Table 10: Pests and diseases of 'high' and 'critical' risk for apple exports to key markets

United States	Light brown apple moth (*Epiphyas postvittana*) Queensland fruit fly (*Bactrocera tryoni*) Mediterranean fruit fly (*Ceratitis capitata*) Leafroller (Tortricidae family) Lesser Queensland frut fly (*Bactrocera neohumeralis*) Codling moth (*Cydia pomonella*) Oriental fruit moth (*Grapholita molesta*) Woolly apple aphid (*Eriosoma lanigerum)* Fuller's rose weevil (*Naupactus godmanni*) Garden weevil/Vine calandra (*Phlyctinus callosus*) Wester flower thrips (*Frankiliniella occidentalis*) Plague thrips (*Thrips imagines*) San Jose scale (*Quadraspidiotus perniciosus*) Apple mussel scale (*Lepidosaphes ulmi*) Pear scale (*Diaspidiotus pyri*) Apple scab/black spot (*Venturia inaequalis*) Brown rot (*Monilinia frucicola*)
New Zealand	No protocol
China*	Codling moth (*Cydia pomonella*) Queensland fruit fly (*Bactrocera tryoni*) Mediterranean fruit fly (*Ceratitis capitata*) Lesser Queensland fruit fly (*Bactrocera neohumeralis*) Black plague thrips (*Haplothrips froggatti*) Fuller's rose weevil (*Naupactus godmanni)* Black peach aphid (*Brachycaudus persicae*) Pear scale (*Diaspidiotus pyri*) Garden weevil/Vine calandra (*Phlyctinus callosus*) Plague thrips (*Thrips imagines*) Carob moth (*Ectomyelois ceratoniae*) Brown rot (*Monilinia fructicola*) Crown rot (*Phytophthora syringae*) Prunus necrotic ringspot virus
Vietnam	No protocol
Japan*	Queensland fruit fly (*Bactrocera tryoni*) Mediterranean fruit fly (*Ceratitis capitata*) Codling moth (*Cydia pomonella*)
Korea	No protocol

*Exports allowed from Tasmania only

Detection of insect-infested products

The presence of insects can be detected directly, through recognition of the organism itself, or detecting various chemicals associated with it (Rajendran 2005); or indirectly by the effects of insect infestation, such as entry holes, dehydration or damage to the fruit (Wang et al. 2011; Moscetti et al. 2015). Various technologies have been used in a research context to investigate the biology and behaviour of insects that are found in concealed situations. These include radiography, X-rays, confocal laser scanning microscopy (CLSM), infrared thermography (IRT), CT, MRI and NIR spectroscopy (Johnson and Naiker 2019, 2020; Adedeji et al. 2020; Keszthelyi et al. 2020). While all of these technologies could theoretically be developed for use in the commercial space, the major barriers to overcome are issues of detection accuracy and throughput volumes. Some of the technologies listed above cannot be adapted to accommodate these requirements with current conceptions of their delivery.

The following paragraphs summarise research that has been undertaken on insect taxa that are relevant for the Australian horticultural sectors, and focus on research using technologies that could be implemented in packhouses within the next 10 years.

Fruit flies

One of the greatest pests of Australian horticulture are tephritid fruit flies, especially Queensland fruit fly (*Bactrocera tryoni*) in the eastern states and Mediterranean fruit fly (*Ceratitis capitata*) in Western Australia. Females oviposit into a wide range of fruit and the larvae develop inside. Infested fruit are inedible and unmarketable, and the potential for infestation is a major hindrance for overseas market access.

Early-instar larvae of oriental fruit fly (*Bactrocera dorsalis*) in mangoes were detected using NIR spectra between 700 and 1100 nm, but eggs could not be found with the same accuracy (Saranwong et al. 2010). NIR spectroscopy was also used to classify cucumbers infested with melon fly (*Zeugodacus cucurbitae*) larvae with about 90% accuracy, across all size classes of cucumbers tested (Lu & Ariana 2013). They found that transmittance measurements resulted in a slightly higher accuracy than reflectance measurements. Compared with manual classification, humans were able to more accurately detect infestations in small cucumbers than was achieved with spectrographic data; but spectrographic data were much more accurate than humans at finding infestations in larger cucumbers (Lu & Ariana 2013). Research on the detection of olives infested with olive fruit fly (*Bactrocera oleae*) found that fruit could be classified with about 90% accuracy, and that spectra in the 100–1250 nm and 1400–1500 nm regions were particularly informative for classification (Moscetti et al. 2015). The authors ascribed this as being associated with changes in hydroperoxide and phenolic content associated with fly damage (Moscetti et al. 2015). NIR spectroscopy was able to predict infestation of blueberries by blueberry maggot (*Rhagoletis mendax*), with an accuracy of 80% (Peshlov et al. 2009).

External damage caused by fruit fly oviposition has been successfully detected by imaging systems. These have included oriental fruit fly in mangoes (Haff et al. 2013), melon fly in cucumbers (Lu & Ariana 2013) and Mediterranean fruit fly (*Ceratitis capitata*) in oranges (Blasco et al. 2007b). However, external imaging methods are sensitive to changes in orientation of the fruit (Xing et al. 2008; Lu & Ariana 2013).

Chuang et al. (2011) provide a design for an X-ray scanner designed to detect oriental fruit fly (*Bactrocera dorsalis*) larvae in a variety of fruits. They reported accuracies of over 90% at belt speeds of 30 m/min.

Unfortunately, there has been little research conducted into detecting the species of fruit fly of direct relevance to Australia. However, it is likely that findings from the research done on these other fly species would provide a useful platform on which to base the necessary research on Australian species.

Citrus

Fuller's rose weevil (*Naupactus cervinus*) egg masses on fruit hinders access to Thailand, China and Korea. These egg masses are strongly affixed to the surface of the fruit and are difficult to remove using techniques such as high-pressure washing. Heat treatments are somewhat effective at killing the eggs, but the use of the treatment is hindered by diminished fruit quality (McCoy et al. 1994). The egg masses of these weevils are on the surface of the fruit, usually near or under the calyx, and should be readily detected using machine vision systems. However, to the best of our knowledge, the necessary research to confirm and develop these systems have not been undertaken.

Thrips damage to citrus fruit has been investigated using different methods. Algorithms using hyperspectral imaging data have been developed to identify damage to green-peel citrus fruit (Dong et al. 2014). This system used four characteristic wavelengths (523, 587, 700 and 768 nm) to accurately delimit the extent of the defects from the images. Other research found that fluorescence imaging was useful for detecting thrips damage on citrus (Blasco et al. 2007a). However, neither of these studies attempted to detect the insects directly.

Scale insects on oranges were found with some success using images captured using the RGB colour space, coupled with a region-oriented segmentation algorithm (Blasco et al. 2007b). However, the small size of the insects made segmentation difficult, requiring a neighbourhood region of 3 × 3 pixels, and resulted in high (15%) rates of undetected infestations.

Damage caused by leaf-miners on oranges was demonstrated to be visible in the orange region of the visible spectrum (600 nm) (Qin et al. 2009). The reflectance properties were similar to those of citrus canker, leading to some misclassification of the two.

Apples

Codling moth (*Cydia pomonella*) is an important pest of apples that is found in most apple-growing areas of the world. Notably, however, it is absent from some key markets for apple exports. Codling moth caterpillars develop in the flesh of apples and cherries, resulting in the build-up of tunnels and frass in the fruit. Hyperspectral imaging has been used to successfully distinguish infested from uninfested 'GoldRush' apples, with accuracies of about 82% (Rady et al. 2017). A combination of five wavelengths in the violet (434 nm, 437 nm), green (538 nm), yellow (582 nm) and NIR (914 nm) regions of the spectrum were found to result in the greatest detection accuracy. External damage caused by late-instar codling moth larvae has been detected in preliminary trials using NIR imaging (Wilkinson et al. 2017); however, additional research is required to examine the conditions in which this is possible.

NIR spectra have been used to distinguish between codling moth and the related species, oriental fruit moth (*Grapholita molesta*), with the greatest differences between species being found in the region between 1142 nm and 1338 nm (Siegwart et al. 2015). Additionally, populations of oriental fruit moth from Brazil and Italy were able to be distinguished from each other (Teixeira et al. 2015). More generally, Lepidoptera silk and webbing has been demonstrated to possess species-specific IR signatures (Boulet-Audet et al. 2015). These experiments have been conducted on naked insects, and so these species- or population-specific signals were not masked by readings from fruit. However, these results suggest that IR spectroscopy could potentially be used for in-line identification of pests as well as their detection.

Identification of adult oriental fruit moth and discrimination between this and other moth species was achieved in the field using a combined pheromone trap and NIR imaging unit (Tian et al. 2016).

Summerfruit

In tart cherries, infestations of plum curculio (*Conotrachelus nenuphar*) were able to be detected using point spectroscopy of wavelengths between 550 and 950 nm, with about 80% accuracy (Xing & Guyer 2008). They found that transmittance measurements resulted in greater classification accuracy; however, the signal was likely to be more affected by size of the fruit using this mode than when measured using reflectance.

Nuts

Carob moth (*Ectomyelois ceratoniae*) is a major pest of a range of crops in Australia, particularly almonds. NIR spectroscopy has been demonstrated to discriminate between uninfested pomegranates, and pomegranates infested with carob moth, even in the absence of external symptoms of infestation (Khodabakhshian et al. 2016, Jamshidi et al. 2019). Although very different in composition from almonds, these results suggest that a method could be developed for almonds. The lower water composition of almonds may provide greater detection accuracies.

Detection accuracy of insect-infested chestnuts increased with the number of NIR wavelengths analysed, and varied according to product orientation (Moscetti et al. 2014a).

A real-time X-ray system has been used to detect insect-derived pinhole damage to almonds (Kim & Schatzki 2001).

Tomatoes

The presence of obscure mealybugs (*Pseudococcus viburni*) on the vegetative parts of tomato plants has been successfully detected using the reflectance spectrum measured using a handheld optical spectrophotometer (Canário et al. 2017). This system was optimised to detect the stress response of the plants caused by mealybug infestation, and the authors caution that more research needs to be done to evaluate the effect of different stressors on the results.

Machine vision systems have been developed to detect whitefly infestation in glasshouses. These include a cognitive vision approach for locating whiteflies (*Trichaleurodes vaporariorum*) on images of rose leaves (Boissard et al. 2008), and an optical recognition system for classifying whiteflies (*T. vaporariorum* and *Bemisia tabaci*) collected using an aspirator from tomato crops (Bauch and Rath 2005).

Large-scale infestations of whiteflies and other sap-sucking insects in field crops have been detected using remote sensing methods combining video imagery and geographic information (Everitt et al. 1994, Yang and Everitt 2011). The detection of whitefly in fields is due to the growth of sooty mould deposits on the honeydew produced by the whiteflies as they feed.

There has not been research on detection of mealybugs or whiteflies in the postharvest area.

Mangoes

X-rays have been used to successfully detect mangoes infested with mango seed weevil (*Sternochetus mangiferae*) (Thomas et al. 1995), though this study was small-scale and required manual film exposure and examination of images to infer infestation status.

Grains

Substantial research has gone into the use of scanning technologies for detecting stored product pests in grains. This research has tested a number of different methods to detect various species of interest.

NIR spectroscopic data have been tested extensively. Initial investigations found that saw-toothed grain beetle (*Oryzaephilus surinamensis*) could be detected at population densities of 270 insects/kg (Ridgway and Chambers 1996). This technology has been found to successfully classify wheat grains as uninfested or infested with rice weevil (*Sitophilus* spp.) larvae, and successfully differentiated between weevil pupae and the pupae of the parasitoid wasp (*Anisopteromalus* sp.) that parasitises them (Baker et al. 1999). NIR spectroscopic data were also able to successfully identify a broad range of stored product pest species with reasonable accuracy (Dowell et al. 1999).

Research into the detection of rusty grain beetle (*Cryptolestes ferrugineus*) using infrared thermography inside wheat grains concluded that the temperatures of infested grains were significantly different from uninfested (control) wheat grains; however, there was a lot of variability, and classification of grain using these data had fairly low accuracies (Manickavasagan et al. 2008).

A real-time X-ray system has also been used to successfully screen wheat kernels for granary weevil (*Sitophilus granarius*) infestation (Haff & Slaughter 2004)

Summary

The studies cited above and summarised in Table 11 demonstrate that detection of insects on fresh produce using methods such as machine vision, imaging spectroscopy and point spectroscopy is technically feasible in many cases. A meta-analysis of studies investigating this topic found that (1) infestations in fruits were able to be detected with NIR spectroscopy with a mean error rate of 13.98%; (2) wavelengths above 1100 nm were optimal for detection of internal pests; and (3) intractance modes of measurement were more accurate than reflectance modes (Jamshidi 2020).

A major hurdle for the detection of pests is their small size relative to the fruit. Any signal from the insect is apt to be drowned out by noise from the fruit that it is on. Techniques for amplifying this signal and differentiating it from the background will be useful for making in-line detection of insect pests on fruit more feasible.

The literature to date has often not clearly differentiated between Type I (false positive) and Type II (false negatives) errors in detection. The trade-off between these will be an important element in the decision-making process for industry partners as they decide how to implement these technologies.

Most of the research conducted to date has been largely small-scale proofs-of-concept, with few applications available for large-scale commercial use. In this setting, the high throughput required presents significant challenges, which will need to be overcome by collaborations between researchers and providers of equipment.

Table 11: Summary of research conducted on detecting arthropod pests of importance to Australian horticulture using the technologies considered in this report. Pest or symptom detectability here refers to any scientific supporting evidence irrespective of circumstance, whether in the laboratory or the field, and does not infer commercial feasibility.

Insect pest group	**Exemplar species**	**Pest detectable?**	**Symptoms detectable?**	**Technologies**	**Comments**	**References**
Aphids	*Myzus cerasi* *Brachycaudus persicae* *Daktulosphaira vitifoliae* *Conogethes punctiferalis*	Needs more data	Needs more data	Imaging spectroscopy	Field applications studied to date. Research needs to be done regarding detection in the postharvest environment	Reisig & Godfrey 2006
Argentine ant	*Linepithema humile*	Needs more data	Needs more data	Point spectroscopy	Near-infrared used in behavioural research of other ant species. Protocols for in-line use need to be developed and validated	Newey et al. 2008
Armoured scale insects	*Diaspidiotus perniciosus* *Diaspidiotus ostreaeformis* *Ischnaspis longirostris* *Aspidiotus nerii* *Aspidiotus destructor* *Hemiberlesia lataniae* *Lepidosaphes gloverii* *Lepidosaphes ulmi* *Pseudaulacaspis cockerelli* *Aspidiotus destructor*	needs more data	needs more data	Machine vision	Small size presents challenges. Some research conducted on field detection, using plant-stress responses	Blasco et al. 2007b Alruwaili et al. 2019
Beetles	*Chauliognathus lugubris* *Monolepta australis* *Monolepta divisa* *Rhyparida limbatipennis*	Needs more data	—	—	No research. Size and colour of species gives development of detection protocols a high probability of success	—
Carob moth	*Ectomyelois ceratoniae*	yes	yes	Point spectroscopy	Research to date has been conducted on pomegranates. Protocols need to be developed for Australian crops	Khodabakhshian et al. 2016 Jamshidi et al. 2019
Citrus leafminer	*Phyllocnistis citrella*	needs more data	yes	Machine vision	Mines in fruit skins can be detected	Qin et al. 2009
Codling moth	*Cydia pomonella*	needs more data	yes	Imaging spectroscopy	External damage, especially by late-instar larvae can be detected	Rady et al. 2017 Wilkinson et al. 2017
Cushion scale insects	*Icerya* spp. *Saissetia miranda*	needs more data	needs more data	—	No research.	—
Fruit flies	*Ceratitis capitata* *Bactrocera tryoni* Other *Bactrocera* spp.	yes	yes	Imaging spectroscopy X-ray imaging Machine vision	Other species of fruit flies have been detected. Results need to be validated for Australian species	Saranwong et al. 2010 Lu & Ariana 2013 Moscetti et al. 2015 Chuang et al. 2011 Blasco et al. 2007b
Fruit moths	*Blastobasis* spp. *Cryptoblabes adoceta* *Isotenes miserana*	needs more data	need more data	—	Size of insect and results from similar species suggests detection should be possible	—

Insect pest group	Exemplar species	Pest detectable?	Symptoms detectable?	Technologies	Comments	References
	Deanolis sublimbalis *Conoethes punctiferalis* *Ophiusa tirhaca* *Penicillaria jocosatrix*					
Leafroller moths	*Epiphyas postvittana* *Epiphyas xylodes*	needs more data	need more data	—	Size of insect and results from similar species suggests detection should be possible	—
Mango hoppers	*Idioscopus clypealis* *Idioscopus nitidulus*	needs more data	needs more data	—	No research.	—
Mango seed weevil	*Sternochetus mangiferae*	yes	yes	X-ray imaging	Proof of concept has been demonstrated; however, additional research required to make the method more suitable for industry use	Thomas et al. 1995
Mealybugs	*Pseudococcus longispinus* *Nipaecoccus aurilanatus* *Planococcus minor* *Pseudococcus viburni*	needs more data	needs more data	Point spectroscopy	Field applications studied to date. Research needs to be done regarding detection in the postharvest environment	Canário et al. 2017
Mites	*Brevipalpus californicus* *Calepitrimerus vitis* *Tegolophus australis* *Brevipalpus californicus*	needs more data	needs more data	Imaging spectroscopy	Field applications studied to date. Research needs to be done regarding detection in the postharvest environment	Reisig & Godfrey 2006 Wilkin et al. 1986
Oriental fruit moth	*Grapholita molesta*	yes	needs more data	Point spectroscopy	Field applications studied to date. Research needs to be done regarding detection in the postharvest environment	Siegwart et al. 2015 Teixeira et al. 2015 Tian et al. 2016
Plant bugs	*Amblypelta lutescens* *Amblypelta nitida* *Helopeltis clavifer*	needs more data	needs more data	—	No research.	—
Snails	*Microxeromagna vestita* *Cochlicella acuta* *Cernuella virgata*	needs more data	needs more data	Imaging spectroscopy	Mollusc shells are opaque to transmitted NIR light and reflective of reflected NIR	Savazzi & Sasaki 2013
Spiders	Latrodectus hasselti	Needs more data	needs more data	Point spectroscopy	Infrared spectroscopy has been used to characterise silks. Research needed to evaluate contrast between spider silk and produce	Ene et al. 2011
Thrips	*Thrips imaginis* *Thrips palmi* *Haplothrips froggatti* *Haplothips victoriensis* *Frankliniella occidentalis*	no	yes	Machine vision	Small size of thrips makes detection of specimens challenging. Detection of surface damage to fruit has been demonstrated	Blasco et al. 2007a
Weevils	*Naupactus cervinus* *Phlyctinus callosus*	needs more data	no	—	No research. Egg masses on fruit surface should be detected using machine vision, though eggs laid under the calyx would reduce accuracy	—
Whitefly	*Aleurocanthus valenciae* *Bemisia tabaci*	yes	yes	Machine vision	Proof of concept has been demonstrated in greenhouses. This work has yet to be extended to the packhouse	Boissard et al. 2008 Bauch & Rath 2005

Detection of pathogens

Plant pathogen detection is more difficult than detection of arthropods because of the small size of fungal propagules, often in the range beyond the detection limits of currently available technology. Fungal spores are in the size range of 2–50 µm in length and/or diameter. When spores germinate, they can form protective structures known as appressoria, which can remain sitting on the outside of fruit until conditions are suitable for penetration into the fruit flesh (latent or quiescent infection). Although appressoria are slightly larger than spores, they are in the same general size range (10–50 µm), and are also below detectable limits of available technology. Once spores germinate and infection occurs, symptoms can rapidly become visible to the human eye. Historically, packhouses have installed a number of quality inspectors to visually detect defects, including fungal infections, by in-line inspection under a bank of lights. However, this method is subject to human error, and it is possible that some fruit escape inspection.

Citrus

Two closely related fungal pathogens, *Penicillium digitatum* and *P. italicum*, cause the serious postharvest citrus rots green and blue mould, respectively (Figure 9). Early symptoms cannot be detected visually because of their similarity to sound skin and are known as clear rots (Palau 2014). After the appearance of translucent skin, symptoms of firstly white thread-like fungal growth (mycelium), and then green or blue lesions, develop during coolstorage. Symptomatic fruit can contaminate adjacent fruit due to prolific production of easily spread spores, which are responsible for the blue and green colouring of the lesions. Ultraviolet light was first used to induce fluorescence in clear rots and thus detect early lesions (Ogawa et al. 2011). Blanc et al. (2013) commercialised the test by developing an in-line machine. However, this method was shown to be unreliable because of the presence of other defects that also fluoresce (Obenland et al. 2010), and lesions on different varieties of citrus reacted to different wavelengths, making it difficult to provide a standardised test (Momim et al. 2012).

Clear rots can be detected by using NIR hyperspectral imaging with 88–98.6% accuracy (Gomez-Sanchis et al. 2008; Gomez-Sanchis et al. 2013; Gomez-Sanchis et al. 2014; Folch-Fortuny et al. 2016; Li et al. 2016; Ghooshkhaneh et al. 2018). Clear rots can be reliably detected by this technology before symptoms are visible to the naked eye (Folch-Fortuny et al. 2016; Spectrim 2017).

The spots on fruit due to citrus canker, caused by the bacterium *Xanthomonas citri* subsp. *citri*, can also be detected by hyperspectral imaging (Qin et al. 2009), which was later developed into an in-line test (Qin et al. 2012). Different algorithms were developed for using hyperspectral imaging to distinguish citrus canker from other defects (Li et al. 2012).

Anthracnose caused by *Colletotrichum* spp. could also be detected by NIR spectroscopy (Blasco et al. 2007a). Laser image backscattering (Lorente et al. 2013), or laser light backscattering imaging (LLBI) has recently been used for detecting defects in citrus fruit (Adebayo et al. 2016).

Figure 9: Green and blue mould of mandarins caused by *Penicillium digitatum* and *P. italicum.*

Apples

NIR spectroscopy for apples was able to detect various disease symptoms, including side rots, flyspeck, scab, moulds, and fungal diseases described as black pox (Mehl et al. 2004). Although not specified, these diseases were probably caused by *Neofabraea* spp., *Schizothyrium pomi*, *Venturia inaequalis*, *Colletotrichum* spp., *Helminthosporium papulosum* (Sutton et al. 2014), respectively, although moulds could also be caused by *Botrytis* or *Penicillium* (Figure 10). Aneshansley et al. (1997) studying *Venturia inaequalis* infection on apple tissue, noted a reflectance reduction in the 600–930 nm waveband. Brown rot damaged tissue caused by the fungus *Monilinia fructicola* reduced reflectance at the 700–800 nm waveband.

Pieczywek et al. (2018) compared biospeckle, hyperspectral imaging and chlorophyll fluorescence for their ability to detect bull's-eye rot (*Neofabraea malicorticis*) in apples following artificial inoculations. All three methods could detect infections 2–3 days before visible symptoms, but biospeckle activity results were more detailed.

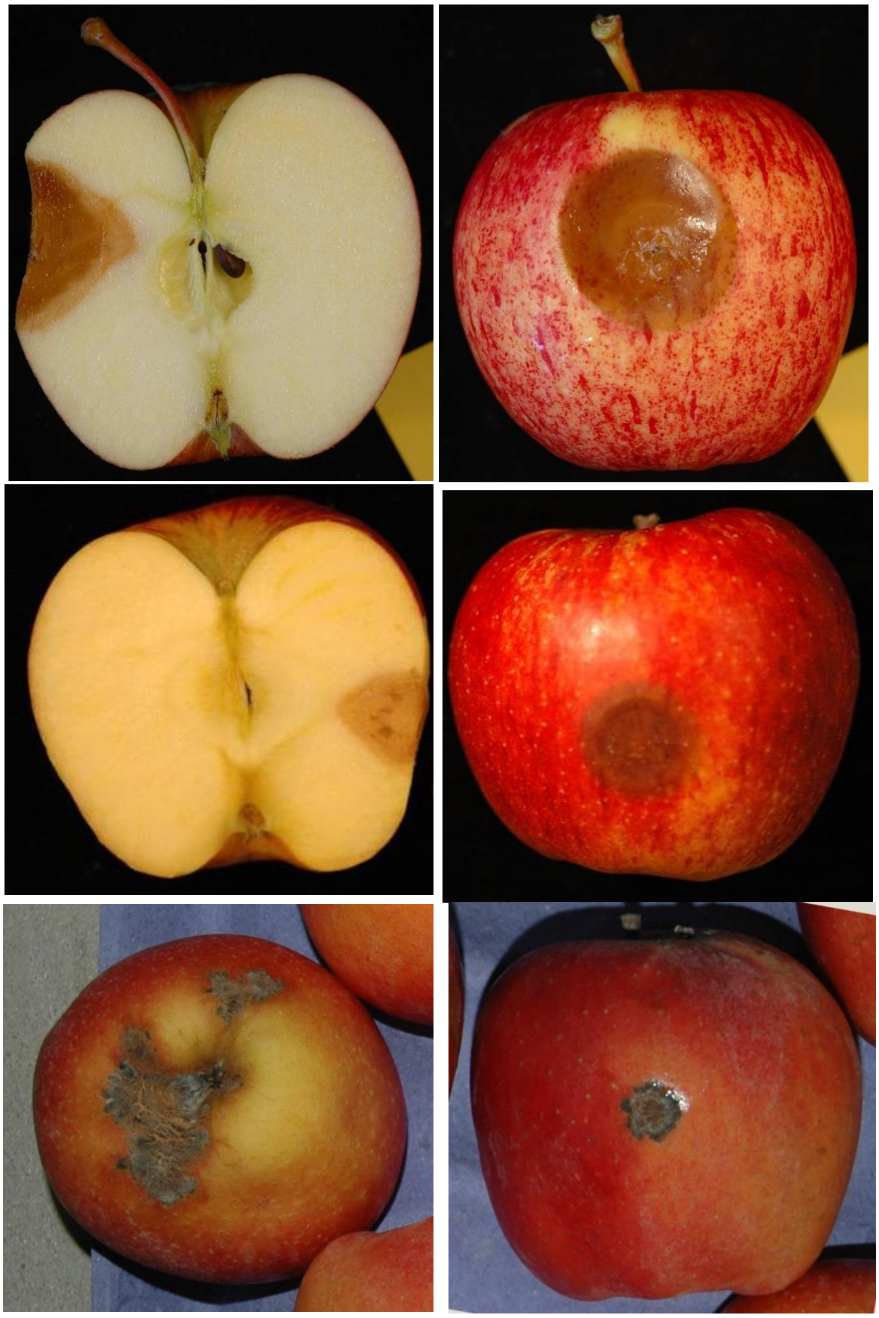

Figure 10. Symptoms of bull's-eye rot (*Neofabraea alba* syn. *Phlyctema vagabunda*) (top) bitter rot (*Colletotrichum acutatum*) (middle row) and black spot (*Venturia inaequalis*) (bottom) on apples.

NIR spectroscopy was used to detect apple mouldy core caused most commonly by *Cladosporium herbarum* and *Alternaria alternata*, but also by *Fusarium* spp. and *Penicillium* spp. Mouldy core is undetectable until the fruit is cut open or bitten into, and can cause problems with consumers and retailers. The fungi infect the fruit at flowering and disease develops inside the calyx in the orchard, more commonly in varieties with a more open calyx (Shendery et al. 2010). This technique was also tested in-line and decay was reliably detected, although 1 s per fruit was required for data acquisition (Shendery et al. 2010). Since this study, Tian et al. (2020) used NIR in transmittance mode to detect mouldy core in apples passing at 0.5m/s on-line with a 94% detection rate.

Nuts

Nuts can suffer mould problems in storage that result in poisonous aflatoxins. Markets are sensitive to aflatoxin contamination, and can require rigorous and expensive testing before consignments are accepted. Although not specifically related to aflatoxin contamination, the applicability of NIR spectroscopy to detect hidden mould infection in chestnuts has been demonstrated (Moscetti et al. 2014b). In Taiwan, diseased areca nuts were detected using a colour cameras to collect the RGB colour spectrums that were then image processed (Huang 2012).

Tomatoes

The fungus *Rhizopus stolonifer* causes a soft rot of tomatoes during cold storage, shipping and marketing resulting in economically important losses. This fungus produces distinctive dark spores that could be detected in an experimental on-line system on red tomatoes using NIR spectroscopy (Hahn 2004, Hahn et al. 2004) with 92–96% accuracy, the latter achieved after incorporation of a neural network method (Hahn et al. 2004). However, different calculations were required for detection dependent on maturity.

Hahn (2002) detected spores of *Fusarium oxysporum* and *Rhizopus stolonifer* (fungi that cause fruit rots) with NIR following artificial inoculation with ~500 spores in a 50-µL droplet.

Another microsensor method was tested to distinguish the humidity of air exiting the peduncle scar of infected compared with healthy tomato fruit (Hahn 2006). Tomatoes have a thick cuticle with minimal lenticels and most gas and water vapour exchange is through the peduncle scar. When fruit are infected by fungi they become drier, resulting in reduced humidity. Fans placed over the peduncle in combination with compressing the fruit was used to sample humidity. This method was not affected by maturity, and could be used on both green and red tomatoes. However, it required a stand, positioning of the peduncle, and compression, and each sample took 30 s for compression and 4 s for sampling. It is unlikely to be used on-line, but could be used in place of other detection methods for quality surveys. Conventional methods require 1 day for processing (Hahn 2006). However, the method did not work well for soft or damaged tomatoes, which did not survive the compression step.

Early blight (caused by the fungus *Alternaria* spp.) symptoms on fruit were detected by machine vision (Arjenaki et al. 2013).

Potatoes

The development of a commercial system for on-line detection of potato scab (*Phoma exigua*), gangrene (*Streptomyces scabies)*, and soft rot (*Erwinia carotovora*) was reported in a conference paper in 1998 (Muir et al. 1998). The final operating speed was described as being between 2–10 potatoes per second (3–8 t/h).

Dry rot, gangrene and/or scab can be detected by NIR diffuse reflectance (Muir et al. 1982), NIR hyperspectral analysis (Dacal-Nieto et al. 2011) or RGB camera (Samanta et al. 2012). *Rhizoctonia* can be detected by CCD colour camera (Noordam et al. 2000).

MRI was shown to be able to detect non-visible spraing symptoms for the first time in 2004 (Thybo et al. 2004). Spraing disease is caused by two viruses, *Tobacco rattle virus* (TRV) or *Potato mop top virus* (PMTV).

There are a number of commercially available sorters that can detect rots, even in potatoes covered with soil (see for example Tomra (Norway) or Key Technology/Herbert Solutions (USA)).

Leafy vegetables

Spinach quality problems during storage can be detected by measuring chlorophyll fluorescence (Fv/Fm ratios). Pesticides applied before harvest were also detected (Keutgen et al. 2012).

Mangoes

A non-destructive X-ray scanning technique was used to detect postharvest mango rots caused by *Aspergillus niger, Rhizopus* and *Colletotrichum* spp. (Dhondiram and Ashok 2017). Rots were detected 4–5 days after inoculations. However, symptoms were also visible to the naked eye. No other reports of non-destructive detection of mango diseases that could be used in-line were found.

Onions

Portable field asymmetric ion mobility spectrometry (FAIMS) was shown to be able to detect onion sour skin caused by the bacterium *Burkholderia cepacia*, as early as 3 days after inoculation (Rajeev et al. 2017). It could also be detected with NIR hyperspectral imaging (Wang et al. 2012), and was recommended for application to detection on packing lines. That work has been recently extended by others, in the development of a dual laser beam NIR system with good potential for in-line application (Sun et al. 2020). X-ray systems were able to detect voids inside onions due to disease such as the bacterium *Pantoea ananatis* with an accuracy of greater than 93% (Tollner et al. 2005). Defective onions were not able to be detected by visual inspection.

Carrots

Body reflectance was able to identify dry rot, soft rot and black crown disease of carrots with radiation wavelengths between 535 and 722 nm. However, cavity spots could not be distinguished from healthy tissue (Howarth et al. 1990).

Pathogen Detection Summary

Many of the described technologies above have only been demonstrated to be effective in laboratory studies for pathogen detection. Still some are used commercially for in-line grading and sorting including machine vision systems detecting external symptoms (e.g. clear and brown rots on citrus, carrot rots, nut moulds) and NIR systems detecting internal defects (e.g. mouldy-core in apples, potato rot diseases and onion rots). No commercial machines for detecting defects in leafy vegetables could be located. Table 12 summarises the potential of these technologies for detecting plant pathogens of importance to Australian horticulture.

Table 12: Summary of research conducted on detecting plant pathogens of importance to Australian horticulture using the technologies considered in this report. Pathogen or symptom detectability here refers to any scientific supporting evidence irrespective of circumstance, whether in the laboratory or the field, and does not infer commercial feasibility

Pathogen	Common name	Organism	Industry	Pathogen detectable?	Symptoms detectable?	Technologies researched	Comments	References
Eutypa lata	Grapevine dieback	fungus	cherry	no	no		could be in trash, which could be removed by sorting using machine vision**	
Greeneria uvicola	Bitter rot	fungus	cherry	no	no evidence*			
Monilinia fructicola	Brown rot	fungus	cherry	no	yes – in apples	Near-infrared spectroscopy		Aneshansley et al. 1997
Monilinia laxa	Brown rot	fungus	cherry	no	yes – symptoms similar to *M. fructicola*	Near-infrared spectroscopy		Aneshansley et al. 1997
Phytophthora megasperma	Phytophthora root rot	fungus	cherry	no	no		could be in trash, which could be removed by sorting using machine vision	
Podosphaera clandestina var. *clandestina*	Powdery mildew	fungus	cherry	no	no evidence			
Prunus necrotic ringspot virus	Ring spot	virus	cherry	no	no		could be in trash, which could be removed by sorting using machine vision	
Pseudomonas syringae	Twig blight/crown rot	bacterium	cherry	no	no		could be in trash, which could be removed by sorting using machine vision	
Pseudomonas syringae pv. *morsprunorum*	Bacterial canker	bacterium	cherry	no	no		could be in trash, which could be removed by sorting using machine vision	

Pathogen	Common name	Organism	Industry	Pathogen detectable?	Symptoms detectable?	Technologies researched	Comments	References
Pseudomonas viridiflava	Bacterial leaf blight	bacterium	cherry	no	no		could be in trash, which could be removed by sorting using machine vision	
Stigmina carpophila	Shot hole	fungus	cherry	no	no		could be in trash, which could be removed by sorting using machine vision	
Botryosphaeria ribis	Branch canker	fungus	citrus	no	no		could be in trash, which could be removed by sorting using machine vision	
Gloeodes pomigena	Sooty blotch, fly speck	fungus	citrus	no	no evidence			
Guignardia citricarpa	Citrus black spot	fungus	citrus	no	no evidence			
Mycosphaerella citri	Greasy spot	fungus	citrus	no	no evidence			
Phytophthora citricola	Collar rot	fungus	citrus	no	no		could be in trash, which could be removed by sorting using machine vision	
Phytophthora hibernalis	Brown rot	fungus	citrus	no	no evidence			
Phytophthora syringae	Citrus brown rot	fungus	citrus	no	no evidence			
Pseudomonas syringae pv. *syringae*	Bacterial canker	bacterium	citrus	no	no		could be in trash, which could be removed by sorting using machine vision	
Septoria citri	Septoria spot	fungus	citrus	no	no evidence			
Sphaceloma fawcetti var. *scabiosa, Elsinoë australis*	Citrus scab	fungus	citrus	no	no evidence			
Xanthomonas citri subsp. *citri*	Citrus canker	bacterium	citrus	no	yes	hyperspectral imaging		Qin et al. 2009 Qin et al. 2012
Venturia inaequalis	Apple scab/black spot	fungus	apple	no	yes/no***	Near-infrared	latent infections cannot be detected	Mehl et al. 2004

Pathogen	Common name	Organism	Industry	Pathogen detectable?	Symptoms detectable?	Technologies researched	Comments	References
Chaetothyrina tenuissima	Stem sooty blotch	fungus	mango	no	no evidence		could be in trash, which could be removed by sorting using machine vision	
Elsinoe mangiferae	Scab	fungus	mango	no	no evidence			
Neoscytalidium novaehollandiae	Dieback	fungus	mango	no	no		could be in trash, which could be removed by sorting using machine vision	
Oidium mangiferae	Powdery mildew	fungus	mango	no	no evidence			
Pestalotiopsis theae	Blight	fungus	mango	no	no evidence		could be in trash, which could be removed by sorting using machine vision	
Pestalotiopsis virgatula	Leaf spot	fungus	mango	no	no			
Fruit/tuber rots								
Cytosphaera mangiferae	Stem-end rot	fungus	mango	no	no		latent infections cannot be detected	
Dothiorella dominicana/'long'/*mangiferae*/	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Fusicoccum mangiferae	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Lasiodiplodia pseudotheobromae	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Nattrassia mangiferae	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Phomopsis maniferae	Stem-end rot	fungus	mango	no	no		latent infections cannot be detected	
Colletotrichum gloeosporioides	Anthracnose/fruit rot	fungus	mango	no	yes/no***	X-ray	latent infections cannot be detected	Dhondiram and Ashok 2017
Neofusicoccum mangiferae	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Pestalotiopsis mangifolia	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Schizoparme straminea	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	

Pathogen	Common name	Organism	Industry	Pathogen detectable?	Symptoms detectable?	Technologies researched	Comments	References
Stemphylium vesicarium	Fruit rot	fungus	mango	no	no		latent infections cannot be detected	
Xanthomonas campestris pv. *mangiferaeindica*	Black spot	bacterium	mango	no	no evidence			
Potato spindle tuber viroid	Malformed tubers	viroid	potato	no	no evidence			
Potato cyst nematode	Yield reduction, cysts on roots	nematode	potato	no	no		could be in soil, which could be removed by washing**	

*no evidence – symptoms should be able to be detected and distinguished from other diseases based on results for apple diseases, but no research has been conducted
**these diseases do not affect fruit, but rather leaves, roots, twigs or branches
***these diseases have symptoms that can be detected at harvest, and latent infections, which may express (show symptoms) after several weeks in the coolstore.

Output 3. What do industry stakeholders think?

Survey and Industry Representative Interviews

Stakeholder consultation in this project was approached as a survey across citrus, vegetables, almonds, stone fruit and macadamias. Unfortunately, response to the survey was low (47 people accessing the survey) with only a limited number fully completing the questions (27 answering most of the questions). After interviews with industry representatives, we were told that many growers and packers felt “over surveyed”. Therefore, the rate of participation was below what was expected. Although limited observations can be made of the data, there are no statistical inferences made.

A total of 27 people answered a large number of the 22 questions. Those who only opened the link but did not answer anything past the first question, which was a simple ‘I consent…’ question were deleted from the pool.

Within the 27 respondents pool, not all answered the full suite of questions. Therefore not all questions have an *n* of 27. In the results summary below, the number of respondents for each question is shown as n in the graph. All answers are presented in the Appendix 1.

In summary, the most effective tool in gaining insights into the use of scanning technology was one-on-one interviews with industry leaders and packhouse managers. Industry representatives from peak bodies were targeted for interviews and some interviewees came as suggestions from those same peak bodies. The interview team consisted of F. Doerflinger, N. Cunningham, A Granger and K. Fiedler (all co-authors of this report).

A clear outcome from all interviews was the need for reduced labour costs in packhouses. If technologies could be deployed to replace people sorting and manual handling it would greatly reduce costs associated with those tasks. In addition, if technologies could detect internal problems of quarantine concern, this would remove or decrease the need to destructively sample produce for export protocol markets. Less destructive sampling could also open markets for smaller growers where the sampling regime has clearly prohibited their participation. Providing alternative solutions to destructive sampling through deeper sensing/scanning and improved means of removing fruit where needed, could not only open up export for more within horticultural industries but could also open up new export countries.

Some examples of destructive and excessive monitoring requirements for market access are given here. The mango industry has to destructively sample a large number of fruit (~4000 fruit per grower) to export into the Asian market and additional fruit at similar numbers (~4000 fruit) to enter into Western Australia. The number of fruit sampled varies depending on the number of trees, but the sheer volume of cut fruit to detect for mango seed weevil is prohibitive for many smaller growers. A tomato grower in South Australia has opted to not export to the USA because of the high costs associated with having to meet certain export protocols of trapping, monitoring and capturing potential pests in and around the greenhouses (extensive parameter exclusion zones).

Other industries such as leafy green vegetables do not export into the international market because of the perishable nature of their produce and the short time frames needed for transport to maintain produce quality. Hard vegetables such as carrots and potatoes are the exception, and a high percentage of Australian root vegetables are exported to international markets.

Interviews with industry representatives most frequently revealed the view that detecting pests and diseases in the packhouse was already 'too late'. Many in industry felt that detection of pests and disease was better suited to field measures, and that if control was effective in the field, affected fruit and vegetables would never make it to the packing shed. Produce that then makes it to the packhouse would ideally be sorted and managed in a way that information on why it did not reach quality standards is recorded and can be relayed back to the grower. Being able to classify the quality problems and relaying that back to the grower for each issue that arose because of rejection would enable improved management in the field for following seasons.

Consolidated interview summaries can be seen in Appendix 2.

In-depth interview summaries

In-depth interviews on Zoom or via telephone have been conducted covering nine industries, five states and territories, and with people who have a diverse range of industry expertise. The interviews were conducted with industry representatives and packhouse operators. The focus was primarily on industries with a larger export potential and those un-represented in the survey.

Each interview was conducted by asking approximately five questions – the applicability of each question varied from industry to industry. Below is a brief summary of responses to the questions. Interview summaries can be found in the appendices.

Question 1: What equipment for sorting are you using currently on your line, especially for blemishes, pests and diseases?

In most cases the application of scanning technologies in packing facilities is used to detect size, shape, weight (indirectly) and irregularities of any kind. Sorting is done to either industry or customer/export specifications. Some of the industries such as almonds have no Australian standard and therefore pack to specifications set by the US Department of Agriculture. Depending on the export market or the desired domestic market, adjustments in the scanner detection is done to minimise 'losses'. Losses are relative in many of the industries that have alternatives uses for the rejected materials. But the difference in per tonne price can be significant for premium, or first grade, compared with any other grade. Therefore, reducing the amount of product that is falsely classified as a lower grade is very important for many of the industries.

Specific technology to detect pests or diseases has not to this point be deployed as far as the interviews revealed, although what they are grading for is a result of pests and diseases. Many of the interviewees pointed out that the industry expects most of the disease and pest issues to be usually dealt with in the field and that during harvest, produce with obvious signs of damage will not be transported to the packhouse.

Question 2: Why did you choose the kind of technology/equipment you are using? (specific to pests, diseases and blemishes)

Most of the facilities, as mentioned above, are not sorting specifically for pests and diseases and so equipment is not specifically calibrated for that purpose. As mentioned before, damage from pests and diseases are picked up as 'blemishes' where fruit/vegetables are not matching specifications. In citrus, wind and frost damage are removed from the packing line as is scurfing (from thrips) and other damage that may be insect related. Other industries expressed the desire to be able to detect insect bore holes or scratch marks on the fruit indicating pest presence inside the fruit. Also, the detection of possible precursors that could indicate the possibility of a disease developing would be desirable. Some diseases show up as a problem only after they have reached the market or the consumer.

Industry requires that any sensing and scanning technology be adaptable in order to detect different problems at different times of the year and between seasons. Pests or diseases prominent in one season may disappear or have minimal impact on produce in other seasons. The adaptability and flexibility of machinery, both hardware and software would be a bonus for industries seeking to expand their markets and remain providers of quality produce. Ability to 'learn' and improve would further increase the usability of equipment and many industries are investigating the use of artificial intelligence to improve delivery of market specifications.

The majority of pests and diseases can be dealt with in the field. It became clear during the interviews that many in the industry felt that once the produce had reached the packhouse, it was considered 'too late' to diagnose and deal with the issue. As a result of this, many industries are employing infield technologies to improve detection, manipulation and assessment of pest and disease problems, including providing pre-export clearances 'orchard free'. However, solutions to problems infield or in-glasshouse can be built into a systems approach and the packhouse still plays a valuable role. An anonymised but central platform that collates the pest/disease detections, scoutings and outbreaks in crops could help manage and prevent major outbreaks and prepare regions for incursions – packhouses would then play a vital part in further filtering out potential pests and diseases that are not picked up in the field or glasshouse. This systems approach helps the industry move towards claiming 'pest and disease free' status in current and potential export markets.

Question 3: What kind of technologies would you invest in if it was available and money was not an obstacle? And why?

Industries that have to manually and destructively sample a large number of fruit e.g. mangoes, are eager to invest in technology that could reliably and non-invasively detect internal problems such as mango seed weevil. Mango seed weevil lays eggs on the surface and the larvae then burrow deep within the fruit, often well below current technologies detection level. However, detection of egg laying scratch marks, tiny bore holes or similarly 'impossible' to detect signs of pest presence on the surface of the fruit or vegetables could reduce labour costs as well as the amount of produce destroyed in the sampling process.

Export market access into current or potential markets can be prohibitive to some growers if the sampling strategies required outnumber the fruit exported, or the destructive sampling needed to meet export protocols causes severe reduction in the volume of exportable product. Access to scanning technologies that reduce or eliminate these destructive sampling protocols could boost the potential of exports for smaller producers.

Scanning requirements for nut crops, in this case almonds as well as macadamia nuts, are distinctly different from other crop producers, due in part to the need to separate non-kernel material from kernels. Imperfections in nut crops are usually harder to detect so more precise machinery and software is needed. Developments in scanning technology can detect very small defects in the nut kernel and, compared with other horticultural industries, both almond and macadamias had the most advanced mechanisation process with limited manual handling.

Question 4: What prominent pest/disease are you dealing with in your product that cannot be detected with any of the available technology?

Depending on the commodity the answer to this question varied considerably. The most prominent pest problems of concern also depended on market requirements. Fuller's rose weevil – although unlikely to cause damage to citrus, is a major pest of quarantine concern and predominantly because the insect lays its eggs under the calyx of citrus fruit and the resulting egg mass is difficult to dislodge. Mango seed weevil is of great concern to the mango industry as the pest burrows deep within the fruit and can only be found through destructively sampling. Fruit fly too has been a pest of concern across multiple horticultural industries.

A systems approach to handling these particular pests already exists. Citrus and mango growers exclude orchards that are known to have high infestation levels of Fuller's rose weevil or mango seed weevil. Fruit fly is often dealt with through an area-wide management approach with zones excluding produce from known outbreak areas. Alternatively, fruit is treated with insecticide (dimethoate) or has a strict temperature reliant protocol imposed as part of export requirements. The packhouse plays a role in this by either segregating out fruit from areas known to have pests and disease present and re-routing it to non-protocol markets or removing it completely.

The almond industry successfully employs sensing and scanning technology to detect drill holes from Carpophilus beetle and carob beetle. Although the technology is set up primarily to detect the damage rather than the presence of the actual insects, it is far in advance of other horticultural industries.

Disease issues are slightly more complicated. They can be filtered out in the shed, or before the produce reaches the shed, but some viruses and diseases are not obvious until after the fruit has been through the packhouse. Resin canal disease in mangoes is one example of problems not being seen until well after the fruit has left the shed. If there were means of detecting pre-cursors to this disease, and using scanning/sensing technology, it would be a great advantage to growers and packers.

As mentioned previously, it is not always the same problem every season. Depending on the conditions, some pests or diseases can be aggravated or improved. Therefore, technology needs to be flexible in its use to be useful each season.

Question 5: Where do you see the industry heading in the future in regards to sensing technologies for packing and sorting lines?

Many of the interviewees expressed interest in a packinghouse system that was fully automated and removing human error from visual inspections and the fatigue of destructive sampling of large amounts of fruit in a short period. Manual labour can be intensive and therefore expensive. Depending on the industry, inspections of ‘discarded’ produce is an additional step in the sorting process. Many interviewees spoke of having to re-run produce over the sorting line if the amount of fruit didn’t meet requirements and costing additional time and resources to the process.

The cost of labour in Australia compared with other export countries makes it hard to gain competitive advantage. Many across the various industries felt that the quality standards and packout needed to be high in order to justify the higher cost of production and see a good return on investment.

To guarantee higher quality standards, technologies that can detect internal quality such as total soluble solids (TSS) and titratable acidity (TA), as well as crunchiness and bitterness balance could provide a competitive advantage for Australian horticultural producers and allow them to meet current and new export market preferences.

Interviews with manufacturers of scanning equipment

Further to engaging with packhouses and industry representatives, manufacturers were also interviewed about what they are providing commercially in scanning technology. A summary of the interview questions from the four companies interviewed can be seen in Table 13.

All of the companies interviewed (Maf-Roda, Compac, Aweta and GPGraders) said that when packers make enquiries about scanning technology for packing lines it is usually because they are about to install new or update existing equipment. There is interest in whether the scanners can detect pests or disease but the majority of clients are looking for general blemish/defect capabilities. It is expected that if pests and diseases are present that it manifests in some way that is already being picked up by the camera and sorters. All felt that buyer specifications drove investment by individual packers. An example of this is the recent introduction by Woolworths and Coles that all apples provided to the domestic market be scanned for internal browning. This ensures an end of supply chain quality that is acceptable to consumers.

All companies have provided equipment to packing sheds with minimum capability to detect damage that is caused by pests and disease. All provide multichannel sorting with NIR spectroscopy capability as well as visual assessment cameras. The majority of equipment is for commercial sorting of produce into grades. Some equipment is specific to testing Brix levels for ripeness.

All the companies interviewed felt that software innovation was the area most likely to be developed in the next few years. This involves mainly software 'training' and artificial intelligence to identify defects. However, this would have to be specific to the commodity and possibly the pest or disease in question. Several companies felt that this would also be very market driven as export protocols can change. All expressed an interest in development of equipment that could penetrate deeper into fruit, for detecting internal pests such as fruit fly and mango seed weevil; however, the technology would require significant capital to develop before a cost-effective commercial solution was available.

Feedback to growers has been one way of alleviating problems by circumventing the issue before the fruit or vegetable reaches the packhouse. All scanning and sorting machines can grade out produce on quality and is only limited by the number of channels they can run and the size of the packhouse in question. One manufacturer felt that although the current scanning technology provided a vast array of information about the produce going through the lines, much of the information may not be needed depending on the level of market specifications in question. Many clients of scanning technology equipment are often small companies or 'mum and dad' operations who may not require the depth of information that some of the scanning equipment can provide. It may be a matter of catering both to the client and markets they seek to enter.

In common with packers and industry representatives, all manufacturers spoke of the desire of clients to reduce the level of manual handling and labour and see the use of scanning technologies as a means to increase reliability of sorting methods and reducing costs.

Table 13: Questions and summary of answers from scanning technology manufacturers.

Question	Company 1	Company 2	Company 3	Company 4
Interest in sorting for pest and disease	Some interest, especially with upgrades			
Delivered in pest and disease space	Yes, but secondary to blemish/general defects and moulds			
Key direction of scanning technology	Improved hardware (cameras) UV and spectra analysis	Increased number of graders for improved scanning software to manage produce consistency	Improved hardware and software development	Artificial Intelligence Improved hardware (cameras) UV and spectra analysis
Can you provide feedback to grower?	Yes			

Packhouses

A range of horticultural commodities require the use of packhouses to clean, sanitise and treat the produce to a standard that is acceptable to markets. This includes export markets, wholesalers and ultimately consumers.

The majority of packhouses follow a logical pathway, and although many industries have individualised processes, an efficient system will follow basic principles.

The size/length of the line will depend primarily on building size and limitations to costs. Other considerations include access to electricity (a bigger issue in developing countries), plumbing, and cost effectiveness. Removing non-marketable fruit/vegetable material earlier in the process will reduce the amount of produce in the remainder of the line, and may increase the accuracy of automated grading technologies.

A general packhouse set up may have the following systems in place (this example is from citrus and does not include cold room pre-sorting or pre-/post-degreening sorting); see Table 14.

Table 14: An example of a general packhouse set up (citrus).

General packhouse set up (example citrus)	Packhouse equipment needed
	(Manual, in-line technology scanning, mechanical)
Pre-dump sorting	
Dump	
Elimination	Manual/scanning
Pre-sizing – over/under size	Manual/scanning/mechanical
Water spray	
Wash (sanitiser)	
Rinse	
Water removal	
Pre-grade	Manual/scanning
Fungicide application	
Wax application	
Heated air drying	
Final grading – non-packable fruit (fruit for juicing/repack for domestic/interstate markets)	Manual/scanning
Size (mostly done in final grading)	Manual/scanning/mechanical
Label	Manual/automated

Sorting/grading can either be done manually or through mechanical/scanning technology. The most common technical scanning method is the use of colour vision machines. This scanning equipment has the capacity to weigh, assess colour (for uniformity), diameter (checking the regularity of shape of the fruit), and with some versions of colour vision machines assess sugar content (with a larger number of sensors). Scanning technologies can be used on smaller fruits such as cherries to larger fruits including citrus, pome fruit and pineapples. There are also technologies available to scan irregularly shaped vegetables such as carrots and aubergines.

Scanning technologies have advantages over manual means of grading and sorting – with packout, fruit observations done manually are prone to operator error or through inability to put through fruit at a reasonable rate (operator experience will often be a factor).

With mechanical and or scanning technologies the line can increase throughput at any given time and there is less likely to be operator error. Well-trained operators are still required to ensure equipment is in full working order and for regular maintenance requirements.

Output 4. Can we reimagine the statistical methodology?

CLASSIFICATION METHODS

Current practice to provide assurance that a consignment pest and disease meets standards is based on the international sampling standard (ISPM 31). It involves taking a subsample of the consignment for visual inspection with decision of acceptability dictated by the number of positive samples. The size of the subsample is chosen based on a desired level of confidence that the pest or disease will be picked up for a given level of infestation. A common example referred to in ISPM 31 is given as *"At a 95% confidence level, not more than 0.5% of the units in the consignment are infested"* (MAF Biosecurity New Zealand 2008).

The sample size required to achieve this confidence is often modelled as a binomial distribution and assuming a given acceptance level, for example 0 infested units allowed in the subsample.

Let X be the number of infested units in the subsample then $X \sim B(n,p)$ where n is the subsample size and p is the proportion of infested units in the whole lot. The sample size required can then be found by setting $p =$detection level (0.005 in the above statement), and finding the minimum n such that $Pr(X > 0) = 95\%$. This is equivalent to solving for n such that $Pr(X = 0) = 5\%$. The commonly used 600-unit equates to a 95% confidence in picking up an infestation level of 0.5%.

This calculation does assume that if any samples are included in the subsample then the visual inspection will always pick them up. Relaxing this assumption requires adjusting the P parameter, for example if the visual inspection correctly classifies an infested unit 90% of the time then in the above example we would set P=0.005x0.9=0.0045. This results in a sample of 665 units required to achieve 95% confidence that a lot with an infestation level 0.5% will fail inspection. The tables below, as presented in ISPM 31, demonstrate the relationships between sample detection level and confidence level with the required sample size.

Table 15. Detecting a 5% infestation level in a large lot (as defined by the lot size being at least 20 times larger than the sample size)

Confidence	Sample size
90%	45
95%	59
99%	90
99.9%	135

Table 16. Sampling a large lot with 95% confidence

Detection level	Sample size
0.10%	2995
0.50%	598
1%	299

Detection level	Sample size
2%	149
5%	59
10%	29

Additionally, the calculations ignore the fact that the consignment will have a finite number of units from which to sample. When the total number of units is large, the estimates will provide a good approximation. When the sample size is small, the hyper-geometric distribution can be used in place of the binomial. Defining the number of infested units included in the visual inspection sample as X, then $X \sim Hypergeometric(N, K, n)$, where N and n are the population and sample sizes, respectively. K is the total number of infested units in the lot. For a lot size of 1000 with 5 infested units (0.5%) a sample of 450 gives a 95% confidence of detection.

Grading technologies have an advantage over the visual inspection in terms of the number of fruit that can be feasibly sampled. This ranges from the grading all of the units in the lot to taking a large sample. The possible disadvantages are related to the performance of the technology to correctly classify units into clean and infested categories. Two important measures of this performance are sensitivity and specificity. Sensitivity is the probability that the grading will correctly detect an infested fruit. Specificity is the probability that the grader will correctly classify a clean unit. It is desirable to have both as high as possible but can vary by technology, algorithm used for prediction, and also the severity of infestation. For example, a consignment of fruit with mild disease symptoms may result in a lower sensitivity as a larger proportion of infested units are incorrectly classified as clean.

It should also be noted that a visual inspection may not have 100% sensitivity and specificity, although it is often assumed that these will be higher than for automated grading.

The assurance provided by automated grading when compared with visual inspection is influenced by these two measures. Lower sensitivity is often less of an issue as the increased sample size for the automated grading will offset this drawback and it will outperform a smaller sample visual inspection.

Specificity, however, could pose a significant issue if not 100%. This level is generally unrealistic and so caution should be used to reject lots based solely on a small number of units classified by the grader as infested. Specificity less than 100% means that the inspection is at risk of false positives and is amplified by the high number of units graded. Therefore, a lot should not be declared infested solely on failing a grader scan. An additional subsample of the units rejected by the grader should then be taken for visual inspection. In general, this subsample would be lower than the 600-fruit sample needed if the decision was based solely on the visual inspection. This is because the infestation level should be higher in the rejected units than the population, thus the visual inspection sample is more likely to include infested units.

If the full lot is graded and ignoring the finite population then we can use the standard calculations of sample size, except that the expected infestation level of the rejected unit from the grader is used in place of the whole lot infestation level. For example, a grader with 90% specificity and 80% sensitivity grading units with a 0.5% incidence would expect its rejects to have:

$$\frac{true\ positives}{true\ positives + false\ positives} = \frac{0.8 \times 0.005}{0.8 \times 0.005 + (1 - 0.9) \times (1 - 0.005)} = 0.039$$

This would require only a sample of 76 units to achieve 95% confidence.

Another scenario would be to take a subsample rather than the full lot for grading. The calculation of the confidence under varying levels of sensitivity and specificity is more complicated to derive and instead can be approximated through simulation.

The process is outlined below including accounting for the finite population.

1. Define the number of units in the lot (N), number of infested units in the lot (K), the number of units to be randomly sampled for grading (m), the number of rejected units to be visually inspected (n), sensitivity, and specificity.

2. Simulate the number of infested fruit sampled (k) to go over the grader by drawing a sample from the hypergeometric distribution $k \sim Hypergeometric(N, K, m)$

3. Simulate the number of true positives (tp) by drawing a sample from a binomial distribution $tp \sim B(k, sensitivity)$

4. Simulate the number of false positives (fp) by drawing a sample from binomial distribution $fp \sim B(m - k, 1 - specificity)$

5. Calculate the probability of the lot failing inspection $1 - Pr(X = 0)$ assuming $X \sim Hypergeometric(tp + fp, tp, n)$. Note if $n < tp + fp$ then there are less rejected units than units to be sampled. In this case use $n = tp + fp$.

6. Repeat a large number of times. The mean of the calculated probabilities approximates the probability the lot fails the inspection given the infestation level.

7. For comparison, calculate the probability the lots fails using the standard visual inspection 600-fruit sample.

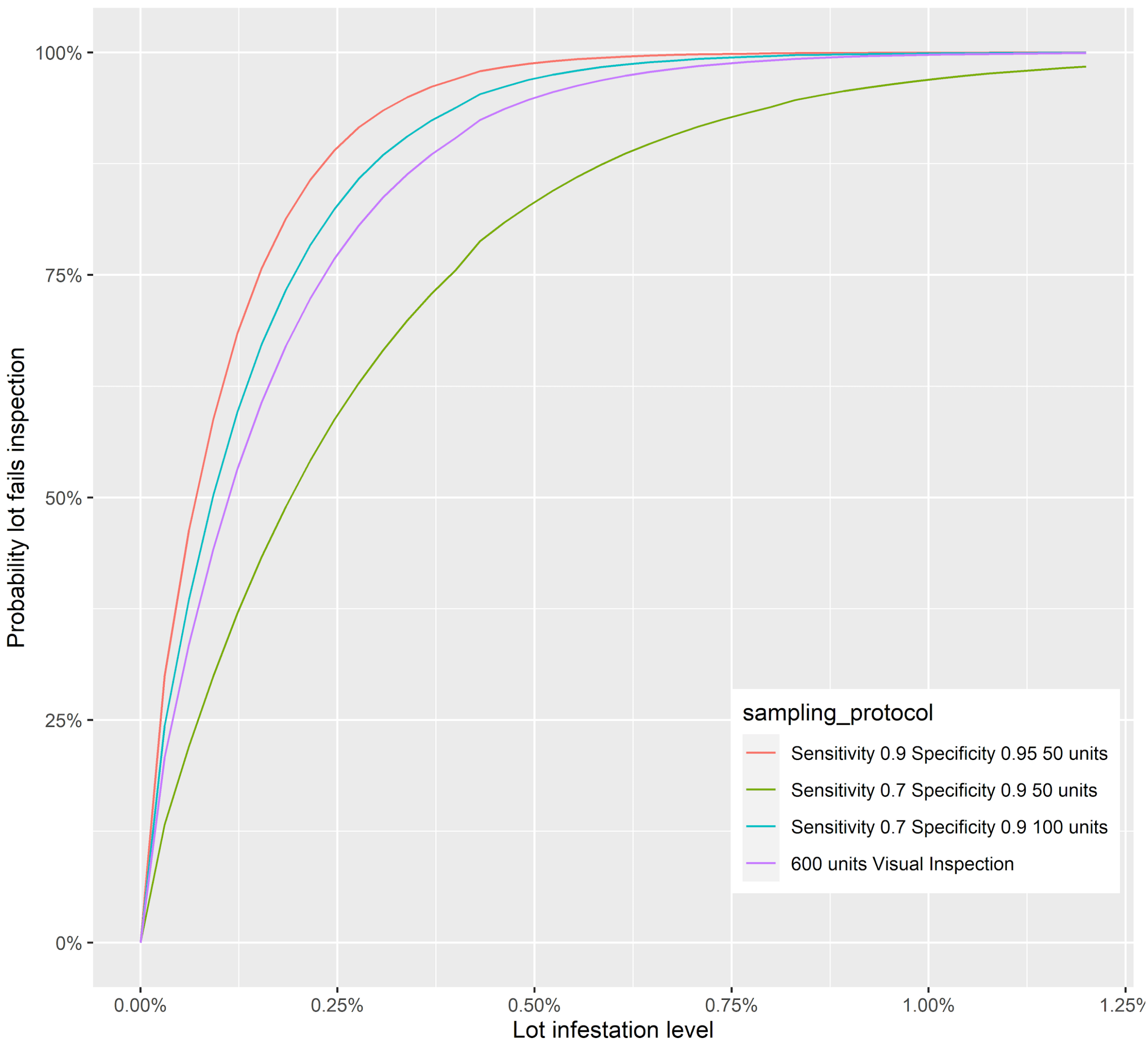

Figure 11: The probability a lot fails inspection under various sampling protocols.

Figure 11 shows the probability a lot fails inspection under various sampling protocols. The standard 600-fruit visual inspection curves with and without accounting for the finite population are given as a reference. The data are based on a lot of 10,000 units with the varying infestation levels. The simulation involved a 1000 unit sampling being graded with a smaller sample, 50- or 100-unit sub-sample taken for visual inspection. With reasonably high sensitivity and specificity, the probability an infested lots fails inspection performs better with only 50 units visually inspected versus the unscreened 600 unit samples. Reducing the sensitivity and specificity does make this perform worse; however, increasing the visual inspection of the screened units to 100 improves performance over the standard protocol.

Table 17 shows the effect of the sensitivity and specificity on the required visual inspection sample size needed for 95% confidence in detecting an infestation of 0.5%. Lowering specificity has a greater impact than sensitivity with more samples needed to achieve the same confidence. Lowering specificity dilutes the screening rejects by including more clean units, whereas lowering sensitivity reduces the number of infested units being rejected.

Table 17. The effect of the sensitivity and specificity on the required visual inspection sample size needed for 95% confidence in detecting an infestation of 0.5%.

Screening	Screening sample size	Sensitivity	Specificity	Visual Inspection Sample size
No	0	-	-	600
Yes	1000	0.95	0.95	32
Yes	1000	0.9	0.95	34
Yes	1000	0.8	0.95	38
Yes	1000	0.7	0.95	44
Yes	1000	0.95	0.9	63
Yes	1000	0.9	0.9	66
Yes	1000	0.8	0.9	74
Yes	1000	0.7	0.9	85
Yes	1000	0.95	0.8	124
Yes	1000	0.9	0.8	131
Yes	1000	0.8	0.8	147
Yes	1000	0.7	0.8	167
Yes	1000	0.95	0.7	184
Yes	1000	0.9	0.7	195
Yes	1000	0.8	0.7	219
Yes	1000	0.7	0.7	250

It can be seen that the automated grading improves the probability of detection units in a lot over the conventional visual inspection procedure even with moderate sensitivity and specificity.

Outcomes

The requested outcomes of this study are discussed below:

1. 'Increased understanding of the packing line options available'

Australian horticultural industries have widely adopted scanning technologies for in-line quality grading although almost exclusively for appearance and taste parameters rather than for the specific detection of pests and diseases of market access concern. The level of adoption and use varies by industry and crop, largely by size with, for example, the large citrus and almond industries typically having installations with the latest in-line grading systems commercially available. The report has reviewed a very wide range of possible technologies, qualifying each with advantages and disadvantages for pest and disease detection, plus their likely prospects for commercialisation.

The main technology options available are those of machine vision and NIR spectroscopy, both commercial and well used where proven to have value. There are inherent limitations with each, perhaps the major one for pest and disease symptoms being the high minimum detectable size, which is in the order of 1 mm or more for an external defect and possibly only as low as 10% by volume for an internal defect. A large list of manufacturing companies with current technology offerings in the topic space has been given.

2. 'Increased awareness and understanding of the pest and disease threats to fruit and vegetable exports'

From the industry survey and consultations it is clear, not surprisingly, that there is high awareness of the pest and disease threats to the Australian horticulture industry. Large sections of the industry are export orientated and market access issues are high on their agendas. Threats vary by crop, region and season, and a systems approach is generally taken for any threat, starting in the orchard or field. Whilst scanning technologies in a packhouse are part of the system, it is generally viewed as a step that is nearly 'too late'. Hence the emphasis for the industry is before the packhouse, in the field or orchard. At-line inspections at packing are a necessity, however, and anything that can improve the detection efficiency would be of great value, especially if it can do so with lower labour costs and/or reduce later phytosanitary audit requirements.

3. 'Improved detection and prevention of pests and diseases of concern'

This report allows an appreciation of the opportunities for improved detection of pests and diseases by using scanning technologies. Primary to this has been computer simulation study of alternative statistical methodologies that take advantage of on-line or at-line scanning efficiencies to deliver improved detection accuracies at reduced labour costs. Much hinges on knowledge of the achievable sensitivities (true positive detection rate) and specificities (true negative detection rate) for any scanning technology.

The possibilities were also raised of improved at-line detection efficiency using likely future technologies such as X-ray CT, MRI and volatile sensing methods. None of these three technologies is yet suitable for at-line inspections, being too slow and/or expensive, but there is some promise for the future following recent scientific developments and research funding investments both private and government.

4. 'Increased understanding between industries and grading equipment manufacturers about potential R&D investment areas'

The equipment manufacturers interviewed all displayed a thorough understanding of the industry needs in relation to scanning technologies. It was clearly understood that market demand for improved quality, for instance from supermarkets or export entities, largely drove investment by the packhouses. They also echoed the desire of industry to reduce labour was driving investment, seeing the use of improved scanning technology as a means to increase reliability of sorting operations and reduce the costs. There was understanding about the value of intelligence captured by technologies in the packhouse, beyond the simple level of market specifications, as valuable feedback to the growers as part of the systems approach. The manufacturers see investment in software innovation as the most likely route to near future developments. There was a recognition that development of improved hardware, for instance with NIR spectroscopy methods capable of more searching and deeper detections, will require significant investment.

Recommendations

It has been clear in this study that investment in scanning technologies is currently market driven, for example by exporter specifications for a particular commodity. The main result of this is that any investment in R&D development around scanning technologies will likely have to be commodity based and particular to the associated market access concerns. Some exporting commodity industries, such as the almond industry, are already well advanced in the use of scanning technologies. Many others, such as the citrus industry, are on a strong path to rapidly developing their use of such technologies. Then there are smaller or emergent industries, such as the mango industry that, although on a rapid growth curve, have little or no current in-line scanning technologies.

The benefits of new or improved scanning technologies for pests and diseases are clear, mainly in reducing the high costs, errors and failures that accompany manual inspections. There is reduced chance of operator error, consequently reduced need for further audits and reduced labour costs overall. An in-line scanning technology can operate with much higher consistency and, if advanced enough, can detect more than what the human eye can see, resulting in greater detective power and confidence in the grading and sorting results.

While the focus of the study has been in-line technology, a particular opportunity, of possibly high return on R&D investment, would be to examine smart ways to improve the accuracy and efficiency of the at-line inspections undertaken at packing. These inspections are variously necessary to confirm grading operations and are similar in practice to the regulated or mandated audit inspections required later for export consignments. The higher accuracy and consistency with which they can be performed then the greater the confidence in the overall grading processes. The evidence is in, from the statistical modelling, that even only moderately accurate non-destructive scanning of additional samples, supplementary to the normal level of destructive at-line inspections, could simultaneously greatly improve accuracy while reducing the overall amount of destructive sampling required. A salient point to recognise is that the supplementary inspections would involve large numbers of sample pieces randomly selected and dropped from the grading line for inspection, most of which would be returned undamaged back to the grading line. True representative sampling becomes easier to achieve and more accurate scanning inspections are possible as well since there is more time available in the at-line circumstance.

Investment to advance the state of scanning technologies could come in several forms and could form part of a partnership between researchers and manufacturers.

- Research on improved scanning technology for detecting pests and disease of significance (commodity by commodity).
- Examination of opportunities for smarter at-line inspection processes leading to improved accuracy and confidence in grading and sorting operations (e.g. supplementary non-destructive inspections).
- Research on outcomes of improved technology to engender confidence in technology for detecting pests and diseases.
- Investigation of new technologies for pest and disease detection (MRI, X-Ray CT).
- Extension and commercialisation of technologies to facilitate adoption by horticultural industries.
- Improved software capabilities and artificial intelligence capabilities of scanning technology.

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Intellectual property, commercialisation and confidentiality

No project IP, project outputs, commercialisation or confidentiality issues to report

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Appendices

APPENDIX 1: Survey questions asked via SurveyMonkey

Q1. I agree to take this survey and understand the limitations

Q2. State/Territory in which you are located:

Q3. Which horticulture levy do you associate with? Please choose one from the dropdown list

Q4. What is the major crop(s) you pack in your facility: Please choose from the drop-down menu

Q5. Do you use a sorting line(s)?

Q6. Why do you use a sorting/packing line? The main purpose(s) of sorting is: Tick all which apply

Q7. What is the average age of the sorting equipment you have? If you have more than one, please specify below.

Q8. Specific to electronic scanning technologies on your line, how old is that equipment?

Q9. If you would like to specify what detection technology you use, please do so here.

Q10. Do you use the sorting line for all of the produce, or for export (interstate or international) only? Tick all which apply

Q11. Are you using non-destructive sorting techniques in the packhouse?

Q12. If yes in Question 6. What visual/imaging/non-destructive assessment technologies do you use on your packing/sorting line? Tick all which apply

Q13. If you answered NO in Question 6. Why have you opted not to use non-destructive technologies in your packhouse?

Q14. If money were no obstacle, what (sensing) technology would you first invest in for your packing/sorting lines?

Q15. Is there a formal and written industry export standard for pests and diseases for your major export commodity?

Q16. To whom are the QC/QA results reported? Tick all which apply

Q17. When is your QC/QA inspection(s) done? Tick all that apply

Q18. How much of a problem is pest/diseases to your export business (interstate or international)?

Q19. For your main commodity, what are the primary pests/diseases/blemishes you are worried about?

Q20. For pests which are an impediment to export, which life stage(s) are you most worried about? Click all that apply

Q21. What disease symptoms cause you the most problems for your export business? Click all that apply

Q22. What are the two greatest problems you encounter with the pest and disease detection technology you use in your packing facility? (mechanical, people etc.)

Survey results

Survey participation was low, and a lot of the industries tell us this was due to a feeling of being 'over surveyed' in the past, considering this, the survey is used more as an indicator and direction tool, rather than to make conclusions for any specific industry.

The survey has been answered by ~27 participants, some 20 others have opened the link and looked at the survey but not answered any questions. Each graph and statement made about any of the survey questions has the number (n) of respondents displayed.

Overall the participation was relatively even throughout the whole of Australia (Figure A1 (A)) with answers from every state. The representation of different levy associations was less well spread out with mostly citrus packers answering to the survey request (Figure A1 (B)), followed by vegetables and cherries as the second-highest participation.

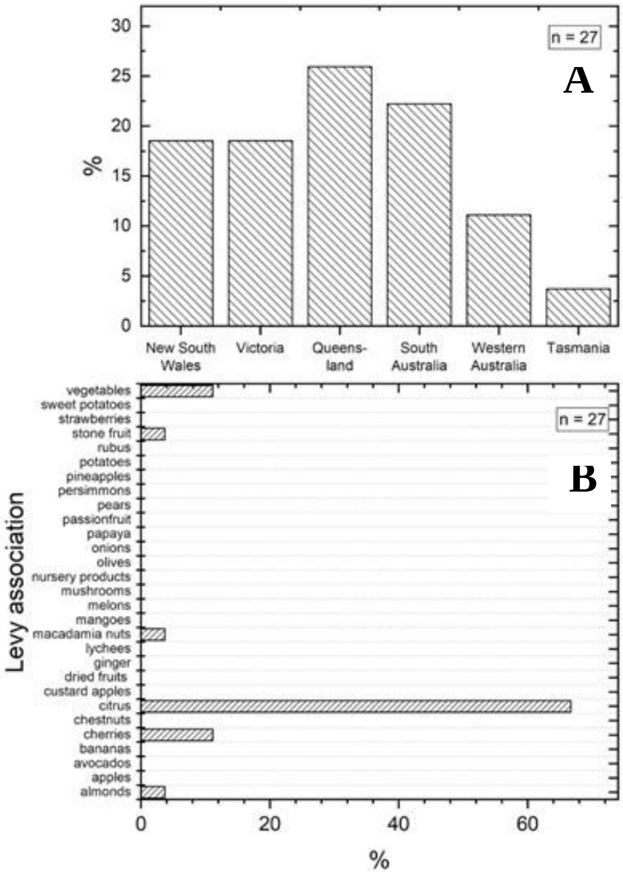

Figure A1: Percentage of respondents from around Australia (A) and which commodity (Levy) they associate with (B)

Of those who answered the questions, 95% use a packing/sorting line in their packing facility (Figure A2 A), and most of them use a form of non-destructive measurement.

For most of the industries connected to the survey answers a formal written export standard is available for their commodity for at least some country (Figure A2 C). The country for which a formal standard is available was not asked. Export standards are a driving force to have non-destructive assessment tools on the packing line and in the packing shed.

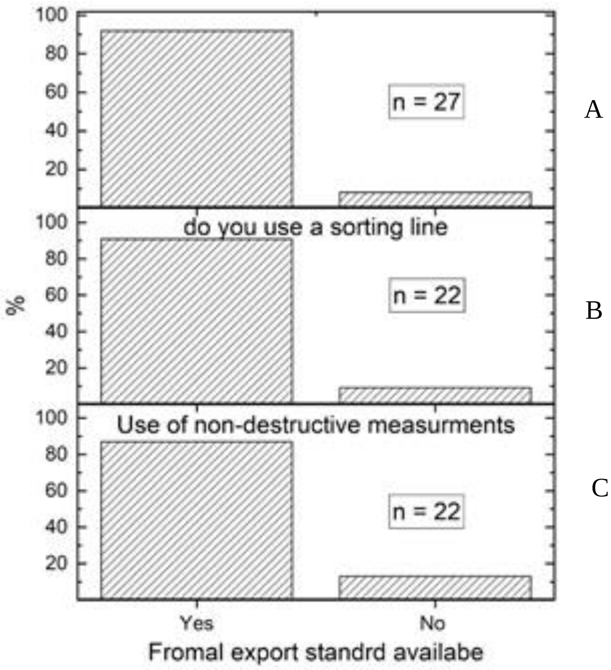

Figure A2: Percentage of respondents who are using A) a sorting line, B) have ways of non-destructive assessment (Use of non-destructive measurements) and C) have a formal export standard for their commodity (Formal export standard available)

Packing lines and the non-destructive detection equipment (scanner technologies) are in most of the cases between 0 and 5 years for the whole lines and 3 and 5 years for the scanning technologies (Figure A3, A and B) and most of the respondents use manual and camera-driven visual inspection, only a small percentage of those who answered the question uses NIR (~20%) (Figure A3 C). Of the five respondents who use NIR 3 are citrus packers and two pack cherries.

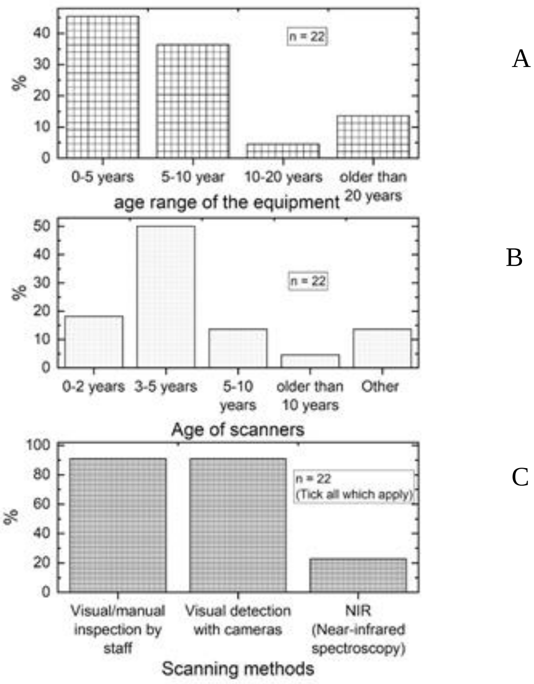

Figure A3: Percentage of respondents whose packing lines are aged at a certain range bracket (A), percentage of respondents whose packing line scanning equipment is of a certain age bracket (B) and the scanning methods used on their packing line (C)

Table A1 Question 9 allowed a follow on from Question 8 – the age of the scanning technologies and Question 9 provided the opportunity to name the equipment used. (n=9)

System named	**Industry association named**
Maf-Roda	citrus
GP Graders Airjet Software	cherries
Unitec Vision 3	cherries
Compac Spectrim	citrus
Compac InVision 9000C	citrus
Global Scan	citrus
Colour scanning	citrus
EDP	citrus

Another question gave the opportunity to say which scanning technology would be purchased or deployed if money was no obstacle and it was readily available in Australia.

Table A2 Answers given to Question 14: If money were no obstacle, what (sensing) technology would you first invest in for your packing/sorting lines? (n=15)

Desired technology	Industry association named
Spectroscopy	citrus
Onion and potato internal defects	vegetables
I would just upgrade my cameras to current 4K cameras from HD. However, the software is still being developed to optimise this.	cherries
Brix/acid inline scanner	citrus
3-D sorting	citrus
Brix /Acid	citrus
Pests	citrus
Optical sorting	vegetables
More NIR	citrus
Greater defects	stone fruit
NIR	citrus
NIR	citrus

Brix	citrus
maf	citrus
Hyperspectral such as NIR	macadamia nuts

The questions around quality assessment and control (QA and QC) were geared towards understating how the data collected from non-destructive scanning might be used. How much manual labour is needed to fulfil the QA system requirements and when in the packing process, QA is applied (Figure A4). The answers of the respondents indicate that the QA outputs are mainly shred with the consumers directly.

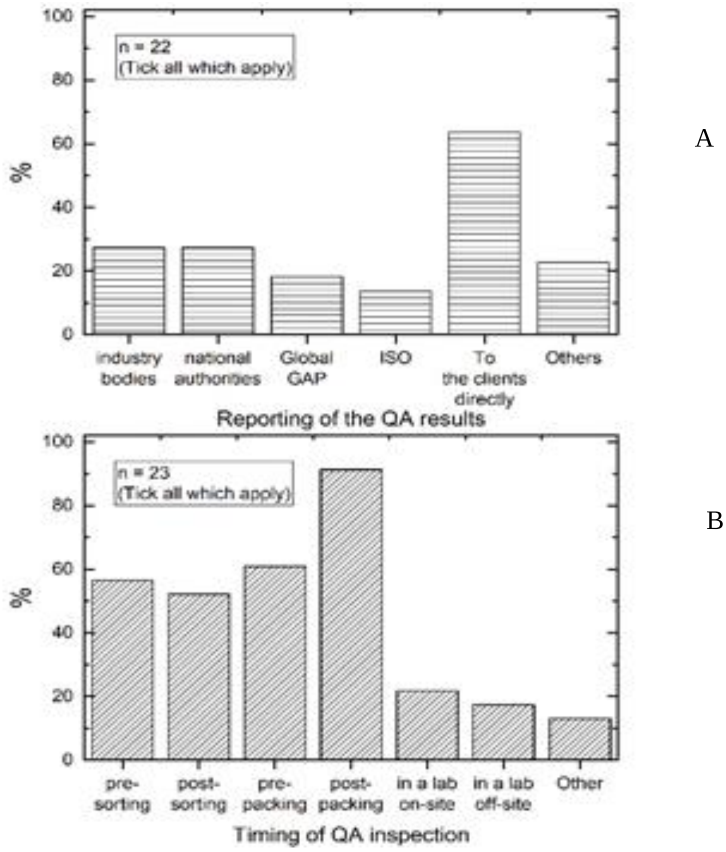

Figure A4: Percentage of respondents who said their QA results go to which of the following institutions [(A) industry body, national authorities, Global GAB, ISO, to the clients directly and other options] and when the QA is performed in the packing shed (B)

The two prime pain points (Question: What are the two greatest problems you encounter with the pest and disease detection technology you use in your packing facility (mechanical, people etc.))? As became clear from the phone/Zoom conversation with representatives from different commodity groups, labour and labour cost are some of the greatest pain points for packing facilities. Training is time consuming. Looking at a large number of fruit destructively (cutting etc.) is exhausting and even non-destructive visual inspection causes fatigue and most likely decline in detection over time. Having to rely on human inspection or humans in the packhouse has been named as a problem. In the phone and Zoom conversations, also employment costs and the challenges of finding adequate numbers of employees and qualified people was a problem.

Table A3 Comments of participants on the question about the two biggest issues they encounter for detecting pest and diseases in the packhouse and on the packing line. Showing the answers and the associated industry each responded associated with

Issue 1	Issue 2	Industry association named
Consistent human sorters	Training sorters that every day is different	Citrus
Cost	Service	Vegetables
Mechanical – not getting a good result of rejection	Trained people	Almonds
It is run by myself. Outside of me, it is very difficult to find suitably trained staff to run the grader and the parameters of the grading program effectively.	General staff availability	Cherries
Human eyes are subjective	Trustworthiness and accuracy of machine detection	Citrus
Internal damage hard to detect		Citrus
People	Time for the postharvest oil to work	Vegetables
They are not effective enough. Only finding 90% of foreign objects, and manual sorting is still required. Focus moved to improving quality in the paddock.		Citrus
Detecting internal issues	Shadows from lighting	Stone Fruit
People - language barrier, training		Citrus
Rely on People to detect	Technology is not quite there yet to detect mechanically	Citrus
The oil/pressure wash not eradicating the mealybug effectively	The eggs being hidden under the calyx	Citrus
Getting a clear image on Mandarins (Imperials)	People - training sorting staff	Citrus
Training people use of equipment	Getting people into the industry	Citrus
Identification	Recourses	Citrus
It is detection of internal quality parameters such as brown centres, after roast darkening	We are also keen to be able to assess shelf life through no destructive testing	Macadamia Nuts

To estimate why each industry uses sorting equipment in the packing shed, Question 6 asked why the sorting line is used. The question had seven answer options (Figure A5). Most of the respondents needed to sort for size and shape, colour and defects as the three main criteria 82–91% wanted to sort for. Never-the-less, almost half of the respondents also wanted to sort for either pests, diseases, industry-standard requirements or others. A good indication that a minimum requirement for technologies is the ability to classify the fresh produce by size and colour and possibly by weight (through size and shape).

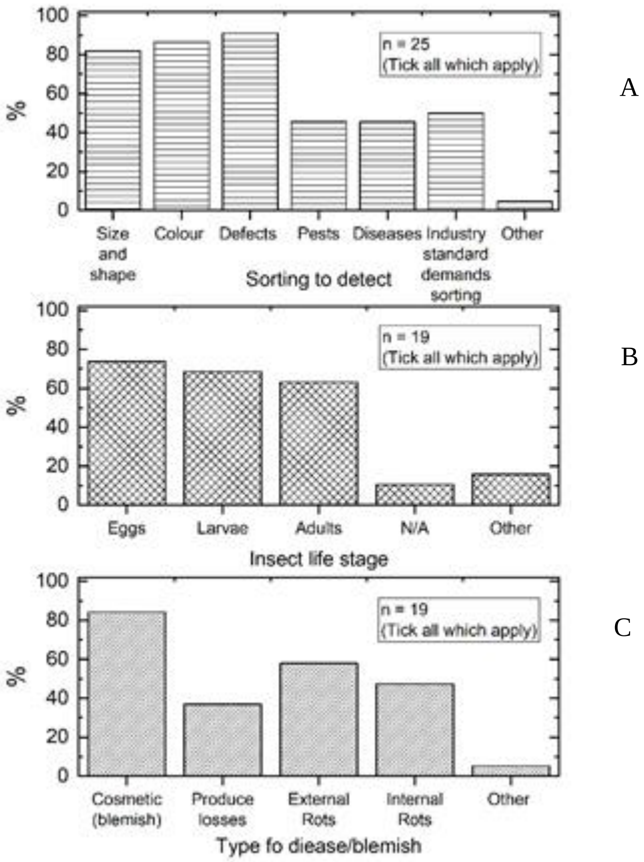

Figure A5 Percentage of respondents using their packing line technology to sort for specific criteria (A), the life stage of an insect that needs to be detected on the product (B) and which disease or blemish issues should be detected (C)

Detection of diseases and pests on the produce is also of importance for half of those who answered the survey (n=10 for pests and disease detection; Figure A5 B and C). Which stage of the pest development and which diseases/blemishes need to be detected by the scanning technologies? As per the survey for pests any stage should be detectable if it was up to the survey respondents, 63 to 73% want to detect eggs, larvae and adults in line.

When asked in the survey, which are the primary pests and diseases causing issues for your produce, the answers in Table A4 were provided. Several different pests, diseases and blemishes have been named as problems for different industries. But the survey indicates that fruit fly (answered 7 times) and Fuller's rose weevil (6 times) are an issue for several citrus packers. Other pests as a problem in the packing facility is the mealybug (5 times named) and scale insects (4 times). Black spot is the disease name most often (3 times) cited as a problem.

Table A4 Answers of respondents to the question of naming up to six of the greatest pest and disease issues they experience on their main crop(s) (Q19: For your main commodity, what are the primary pests/diseases/blemishes you are worried about?)

1	2	3	4	5	6	Industry association named
Emperor brown						citrus
Potato defects	Onion defects					vegetables
Indian meal moth	Carob moth	Carpophilus beetle	Moisture-related issues (mould, stain, aflatoxin, high moisture)			almonds
Brown rot	Botrytis grey mould	Earwig				cherries
Wind	Scale	Mediterranean fruit fly	Rots			citrus
Fruit fly	Black spot	Rough skin				citrus
Earwigs	Thrip					cherries
Light brown apple moth	Fullers rose weevil	Decay	Wind blemish			citrus
Different pests for different markets?	Fullers rose weevil	Mealybug	Scale	Phytophthora		citrus
Black spot	Red scale	Emperor brown spot	Anthracnose	Oleocellosis	Fruit fly	citrus
Fruit fly	Carpophilous bug	Thrip marking	Split stone	Soft fruit		stone fruit
Light brown apple moth	Mealybug	Fullers rose weevil	Fruit fly	Sooty mould	Sour rot	citrus

1	2	3	4	5	6	Industry association named
Fuller's rose weevil	Mealybug					citrus
Queensland fruit fly	Black spot	Melon thrip				citrus
Fruit fly	Scales	Mealybug	Fullers rose weevil			citrus
Fullers rose weevil	Queensland fruit fly	Thrips	Mealybug	Snails	Phytophthora	citrus
The drying, shelling and roasting process satisfies all phyto requirements for macadamia exports. Any damage to the kernel can lead to the kernel being classed as commercial rather than premium.						macadamia nuts

APPENDIX 2: Excerpts/transcripts from Industry representative interviews

These interviews have been consolidated and are not the full transcript.

Interview with, Biosecurity Adviser for Citrus Australia

Background:

The Australian citrus industry exports over $500 million worth of citrus. The key markets are China, Japan, USA, and Thailand. A lot of grey trade into China happens through Hong Kong as well. The KCT protocols meet the protocol standards for exports to Korea, China and Thailand to show the absence of pests like Fuller's Rose Weevil, Red Scale, light brown apple moth.

To verify absence, packhouse staff conduct a 600-piece inspection; they look at the outside of the fruit and under the buttons. It is entirely a visual inspection and no technology in the packhouse is used for the protocol requirements. Fuller's Rose Weevil eggs may be under buttons and it is the opinion of the industry that the cameras aren't going to see under the buttons anyway.

The largest packhouses and distribution companies out of Australia for citrus are Mildura Fruit Company and Costas.

What kind of equipment or sorting equipment Are you aware of that's being used in packing sheds, especially for blemishes, pests and diseases? Across industry, what's your knowledge of that?

Most of the bigger packhouses now have a blemish sorter with multiple cameras that also measures weight, sizing, and fruit diameters. Some facilities even have the equipment to measure soluble solids. These sorters are calibrated for defects and usually don't pick up things like sooty mould and red scale. Sometimes the machine will kick out fruit if the pest damage or infestation is severe enough, but manual inspections are still used primarily for pest and disease detection.

High pressure washers are used in-line to remove red scale before imaging fruit.

What is the primary reason packers have imaging technology in the packhouse?

Blemish and defect detection for now, but the technology isn't calibrated specifically for pests.

Are there industry standards in place for pests?

Citrus Australia (CA) manages the KTC protocol, which includes all of the pest records. Field scouting records by certified scouts, and packhouse QA data is all submitted to CA and there is a large database.

What are the biggest pests of concern for your most critical markets? (Chine, Korea, Thailand)

Fuller's Rose Weevil, red scale, thrips, light brown apple moth

Do you think the citrus industry is interested in investing in scanning technology for market access pests? And if money wasn't an obstacle, would they be more interested in for the packing shed?

I think they would say that it's too late by the time the pest is in the fruit at the packhouse, but then if it is able to reduce their export inspection costs and ease the 600 piece inspection then there may be interest. We are more interested in remote sensing of pests in the field before it becomes a problem for fruit.

What is the number one pest that you think is an issue going into citrus packing sheds?

Light brown apple moth and Fuller's Rose weevil going into those protocol markets. If the scanning system was able to assist in reducing the 600 pieces per consignment there would be more interest. The Nutrano shed in South Australia does approximately 50,000 bins and they have two full time staff on QA doing only inspections and that gets expensive.

Where do you see the interest heading in regards to packhouse sensing technology?

The industry is more interested in reducing pest pressures in the field primarily, so the packhouse is just meant still for defects. In the packhouse our current (and future) concern is testing for MRLs because many countries are reducing or eliminating chemistries. Because they are losing chemistries, there will eventually be more interest in how to verify the absence of pests in fruit.

Interview with Vegetables WA

Background

Of the vegetables produced in Western Australia, carrots and potatoes are the biggest that have any postharvest packhouses. Potatoes are a very large industry, but many do not use imaging technology because 1) it is expensive, and 2) because a significant amount goes directly to processing.

What kind of equipment or sorting equipment Are you aware of that's being used in packing sheds, especially for blemishes, pests and diseases? Across industry, what's your knowledge of that?

Carrot and potato producers mainly use this technology because those vegetables are more durable and go through large volumes. There is some work in baby leafy greens production but is primarily manual sorting with workers conducting visual inspections for pests and diseases.

For potato and carrot sheds with scanning technology, what are they looking for? Pests and diseases?

The imaging is used to sort out imperfections, size, and blemishes rather than pests or diseases. This sometimes eliminates pests and diseases that cause severe enough symptoms, but it is based on the defects and not specifically targeting pests. The workers with the leafy greens industry are sorting for bugs, caterpillars, and diseased leaves. In Gingin they get a lot of leaf pitting and insect feeding damage.

Do you think that the leafy vegetable growers/packers would be amenable to using scanning technology at some point in the future?

It is important to the growers to reduce labour costs but to also have a machine that is not too expensive. Vegetable producers have said that if they could fully automate they definitely would. One potato producer (in WA) has a fully automated packhouse but it was very expensive, with customized components.

Any more prominent pests and diseases your industry might be looking for that they might not be able to detect at the moment?

TPP (Tomato potato psyllid) is a significant problem with vegetables in Western Australia that need to be inspected for. With the pests that WA growers regularly deal with, scanning technology that can pick up produce that have marks, boreholes, feeding damage, or actual insects is what producers would be looking for.

Is there opportunity for something that could detect disease in these vegetables?

Yes, if it is proved to pick up the actual pest or pest or disease symptoms.

Where are the WA vegetable export markets?

Dubai, Singapore, Southeast Asia, UAE (generally considered non-protocol markets).

What kind of sensing technology would the vegetable growers be interested in?

The ability to automate the detection process in the field for pests and diseases.

Interview with Tomato industry representatives

What are some major pests of concern for your industry?

Tomato Potato Psyllid carries zebra chip virus, which affects the potato industry, but the insect pest affects tomatoes as well. Currently, zebra chip virus does not exist in WA, but it is only a matter of time when it comes over from NZ or another country. There is a 2 week diagnostic period to determine if the psyllid has the virus, which is devastating for tomato growers.

Do you use any equipment for sorting in your facility? So any kind of technology?

There is an optical grader in the packhouse, but we need to update it. It is used primarily for color and size, and removes gross defects (cuts, etc.). It is not successful for picking up pests or diseases.

Do you have manual sorting for pests and disease detection?

Pest and disease detection is not a primary concern for us. There is regular scouting in our greenhouses, but not in the packhouse. If they are concerned about pests, it is more about the damage they cause onto the fruit. When there are caterpillars, the scouts and sorters are looking for fruit holes, and that damage is also picked up by the optical grader. It could come through as a gross defect or gross bruise on the tomato, but microscopic sized damage would not be able to detect it. In the greenhouse, we see the pest impacting the plant before it impacts the fruit.

Why did you choose that technology?

Size and color, and other specifications for customer requirements.

What kind of technology would you invest in if it was available in Australia and money wasn't an obstacle?

The tomato fruit are picked by hand, so any surface insect gets knocked off during harvest and is rarely seen in the packhouse. Whiteflies, sooty mold, and powdery mildew can all be problems, but they are managed very early on and don't make it to the packhouse. There is a significant amount of scouting and monitoring that happens for export tomatoes. The USA protocol requires trapping within an 8km radius of greenhouses. Manual scouting and monitoring of traps is still the requirement. There is no way to automate any of the pest monitoring activities for the export programs. The pests they are referring to were probably cut worm and Russian Wheat Aphid. Because the monitoring takes so much time and man-hours, it would be great to automate fruit scanning in the greenhouse setting. It could probably be in packhouses too.

For your export protocols, do you have any of these protocols where you have to conduct destructive sampling for phytosanitary inspections?

No, it is not currently required for any protocols. It will probably happen in the future though. Methyl bromide fumigation is required, but it would be great if there was a technology that could guarantee there were absolutely no pest and disease.

What are the prominent pests and diseases you're dealing with? Ones that you cannot detect at the moment with any technology.

Psyllids and thrips, which are monitored regularly in greenhouses.

Where do you see the industry heading in sensing technologies geared towards sorting and packing lines? Would 100% detection be what you want?

Maybe more into X-ray technology to see the smaller internal pest issues that you don't see until they mature (ex: insect egg laid in a tomato). It would be excellent if or if other imagining from a scanner can detect that, pull from the line, and reject. Or that we can hold the tomato and see if anything becomes of the egg and see if there is any internal damage too. Also, scanning technology needs to be more cost effective. X-rays is where the industry is going. The cameras are already good, but the AI and computer training to detect pests is what needs to be improved.

Interview with Almond industry representative

Are you using any scanning equipment in the shed? And if you are, what are you using it for blemishes or pest and diseases?

When almonds arrive at the processing shed there is a receival inspection, which is visual and manually done. And we have a technology now called QCIFY. The technology uses image recognition and artificial intelligence. It identifies edges of the nut and classifies a defect based on USDA categories. We follow USDA specification, because the Almond Board of Australia doesn't have standards, like California. The QCIFY technology is something used for assessment so that it can simulate what humans can do and preserve the system for further assessment. Then, the almonds are fumigated, after fumigation it passes through the hulling and shelling line. The colour sorter from Tomra targets external defects. Anything external that doesn't look good is rejected. There is also a colour sorter by Satake EVO. And a Tomra Helius which is a laser sorter. When we pack for customers, it again goes through another three colour sorters Satake, Tomra Helius then a Genius sorter which is a monochrome sorter and can target white and black colours effects like mould. Every colour sorter has different capabilities and can target different defects. And once the product is cleaned up, it goes into a finishing room where we do a final assessment. And that data is available for the customers to see their specification.

Generally the pack-out rate (amount that is not 'grade A' quality) is roughly 90%. They are always trying to improve this rate though. The market keeps changing, and consumer demands keep changing, based on that, we need to keep going and get the latest technology. We are looking at new technologies in the coming year. The Australian systems are more mechanized than the US and other countries because of the high cost of labor.

What pests and diseases are you mainly looking for?

Insect damage is a problem, and also Carpophilus beetle and carob beetle. Hull rot and limb dieback are the disease problems, but those are field-based.

What sort of technology or sensing and scanning technology you're looking at for future use?

Tomra has a new technology called BSI plus. That's the high end in the market at the moment. And Satake is also looking at X-ray sorters, that's not commercialised yet. Both companies are doing research to detect pinholes. The only way we will invest in new technology is if there is a significant economic benefit from what we currently have.

What is your main export market?

We export across the globe, it is mainly India and China. But the kernels go to Europe, America, Asia, and China. There is also a big domestic market.

Interview with Citrus industry representative

SUMMARY KEYWORDS

Pests, fruit, citrus, export, technology, industry, protocols, programme, guess, packers, albedo, packaging, bag, lemons, chilling, people, plastic, packing, shed

What is being currently used by sheds in WA for blemishes or pests and diseases?

Exporting WA citrus sheds have MAF sorters. There are five or six sheds of larger scale. They have the cameras for defects, but no NIR that measures brix, which is becoming common with East Coast packers. One of the packers is dealing with Fuller's Rose Weevil, but it is not getting picked up by the imaging technology. The packers don't have cameras that are programmed specifically to pick up mealybug or other pests, they are primarily used for albedo and wind damage, some rind disorders.

What kind of activities are they interested in investing if it was available, and money really wasn't an obstacle for them?

All labour reducing technology. There are not many rejections due to pests, so it is not a driver for new technology, but reduced labor is. Labor costs are high. Pests are a very sporadic thing, and frost. I haven't heard of anybody from WA suffering from a pest contamination issue. Chilling injury and frost damage can be an issue sometimes, so an algorithm to identify the precursors for chilling injury from storage would be helpful. It also would be helpful to get a more precise readout of the rejects the packers are getting (ex: % chill injury, % wind damage, etc.). This would allow farm managers to change practices to reduce loss. This technology exists, and instead could be a refinement of the programming side of the systems.

There are also some mandarin cultivars that are nobby (ex: Gold Nugget) that are difficult because the texture causes shading and makes defect sorting challenging.

Is there any pest or disease that can't be detected by current technology that you would find useful?

Fruit fly is a problem and being able to detect eggs inside the fruit would be a benefit. It would also be helpful to detect Fuller's Rose Weevil eggs under the calyx and mealybugs in the navel.

It would be interesting to be able to detect Fuller's Rose Weevil that lays eggs under the calyx and also to detect mealy bugs in the navel. Citrus gets pests inside the fruit, so that is something that needs to be detected.

Do citrus exporters require destructive sampling during inspection?

Yes, 600 piece inspection for Japan, Korea, China, and Thailand (KCT),

As far as the industry in the future – do they see possible new sensing technologies becoming more a part of the packing process than it is currently?

Yes Like most things, there's no shortage of interest. When the industry was asked, the willingness to change was 90%, the knowledge to change it was 87%, the skills to change was 80%, but the resources to change was 30%.

With interstate trade, there are recent issues with insects like thrips and psyllids, which carry viruses. One of the questions we've been asked is how we're going to extend some of these results.

Interview with Melon industry representative

Background:

Melon was one of the first industries that used near infrared. University of Central Queensland did a lot of work on that 20 years ago. Rock melons were one of the fruits that they worked on and used it to determine sweetness. But the industry went away from it. The biggest melon grower is in Perth and is also the largest exporter. He just installed a new NIR system in his packhouse. He's the only one using it. It is primarily used to determine the sugar content of rockmelon. Another grower in South Perth recently installed a Metro system.

What equipment is being used currently in packing shed lines, especially for blemishes, pests and diseases?

Watermelons don't go through packing lines. One grower washes them as they get packed in the field and sometimes repacked in a shed. Rockmelon and honeydew melon go through packing lines so they have a sanitization process and a fungicide process. There is no scanning technology for the melon growers.

If there was a technology out there and money wasn't an obstacle, what would be something growers in your industry might want to detect if they could?

Shape and blemish detection are currently done manually. Watermelon grading is done by eye in the paddock, for other melons it's done in the shed. A scanning colour vision system that could look for some of what we look for by eye would be useful so we can reduce workers, which is always an issue within the industry. Melons have very few packing sheds, so it would be sensible to invest in that kind of technology for the few packers. Plant viruses are particularly bad in melons, so detection of virus symptoms would be helpful. Australian melon growers lost access to New Zealand December 2020 because of cucumber green mottle mosaic virus (CGMMV). Currently the only detection for CHMMV is through PCR, which can be detected at very low levels, well before any symptoms develop.

Is there any technology out there that might be picked up by the melon industry in the future?

It has not been discussed within the industry, nor have we seen anything of interest elsewhere. The industry is always looking for new technology and advancements, but it is just not there. Something for rockmelon and honeydew that detects color, shape, and abnormal shape would be an improvement.

Do you have any export markets or is it mostly domestic?

Australian Melon Association is a big exporting industry, and probably similar in size to stonefruit. Biggest markets are Singapore, Hong Kong, Malaysia, and increasingly Japan, usually New Zealand. About 25% goes to New Zealand. And after SE Asian, New Zealand, and the Middle East we have Dubai, Kuwait, Bahrain, Saudi Arabia (non-protocol markets).

What are the major melon pests?

Silverleaf whitefly, aphids but only because they transmit viruses. Some fungi are a problem. Zucchini yellow mosaic virus (ZYMV) is also present. Fruit fly is not a management problem, but it is for market access.

Interview with Australian Mangoes

What equipment is being used currently in packing shed lines, especially for blemishes, pests and diseases?

For export protocol markets, they do crop monitoring in the orchard. There's not that much happening in the packing shed. What's happening in the packing shed is really just a grading process. They're not using visual imaging or even IR to do any grading for pests. I don't think in the Northern Territory anyone would be using this sort of technology to look for bugs. Obviously, when you grade there's a manual check and if the fruit has blemishes, they'll be set aside. Sometimes if they have blemishes, it is related to pests or diseases.

Anything that is very obviously damaged by insects, boring into the flesh and the seed and if there's frass, most of that fruit wouldn't make it into the packhouse, let alone on to the packing line to be visible to any grading cameras. A lot of them will just leave it in the orchard on the ground.

There's one or two growers that have—they say that there is near infrared technology to measure dry matter on the packing line. But how accurate that is I don't think it would be at this stage because it's moving so fast. But definitely there are people using visual camera graders. And for quality purposes.

Do you have any export markets or is it mostly domestic?

Export is a key priority. China, Korea and Thailand are the biggest markets. However the current protocols for those markets need updating. Protocols means that we have to destroy a lot of fruit. And also, with vapour heat treatment for fruit fly there's a little bit of loss in terms of quality. Because it's vapour heat.

What's your biggest pest and/or disease problem?

Resin canal disorder RCD caused by certain bacteria can take up to five to seven days to start showing up on the fruit. And when on the packing line, growers might not even see it until it reaches the export destination. It's not currently a market access issue but growers are concerned and would be interested to be able to detect it before it leaves their packing shed because once it's in the market, it's hard for them to confirm its presence.

Mango seed weevil is a big one. It's big for China and also domestically it's an issue for WA. Destructive sampling for seed weevil can be up to 4000 + fruit.

Is there any technology out there that might be picked up by the mango industry in the future?

Anything that would remove destructive sampling as sampling 4000 fruits + is prohibitive for some smaller growers who could otherwise send fruit to export. Perhaps even X-ray technology that could go deep into the fruit. Monitoring for disease might be trickier as it's mostly done in the orchard at the moment.

Anything that reduces the labour requirements on a packing line. So for example, one thing that would be obvious for cameras is old insect damage that has developed like scabs on the outside, particularly, from thrips damage that ends up with that scab on the outside, and also, we get this pink wax scale that makes little pink dots on the on the fruit so that's quite obvious. Also sunburn.

Interview with Almond industry representative (2)

What scanning equipment are you aware of being used currently by the industry?

We have probably the most sought after stock/sort after sorting equipment - the Nimbus BSI sorting machine, made by American company TOMRA. It's a laser and also a biometric scanning device. They call it a biometric signature identification and can look for fluorescence around insect damage. The majority of packers would have one or be looking to get one. And they're really good for mould and.

What are some of the pests and diseases you're looking for?

One of the biggest problems for the industry are carpophilus beetles that drill holes in the kernel and many markets don't like the drill hole. The BSI cameras can pick up the fluorescence around the hole and kick the almond out. We're very fortunate we don't have a real issue with that at all. We've been very lucky and our growers have dealt with the problem but it's definitely been a bigger problem for the industry. Carob moth can also be a problem that leave a drill hole. Other moths that can be an issue is Indian meal moth—especially in storage.

The technology you're using, is it primarily for pests or are diseases more of concern?

It's a combination really of what we call serious damage which would be insect and mould. It is really seasonal. In one year for example, the insect damage isn't as noticeable as your mould level because you mould damage is through the roof and in a dry year like the last couple of seasons, insect damage becomes more noticeable because the mould isn't present.

Aspergillus can be a problem and lead to aflatoxins.

Are there any kinds of technologies that the industry is not using that they would like to use? If money wasn't an obstacle for them?

It's probably what the Tomra cameras can do where each individual nut is assessed. There are some technologies that are out there that help you classify nuts and ones that sort, but a combination of the two would be good. We have very little waste with current scanning systems.

What's your biggest export market?

We basically export everywhere, Europe, Asia, India.

Are mrls an issue chemical residues at all?

Our growers have a pretty stringent MRL program so we could just stay in the national registry scheme and we have quite regular meetings with growers when we talk about MRLs, offer suggestions and advice as to any country's particular requirements

Where do you see the industry heading in regards to sensing technologies for packing lines?

We're looking for the 'perfect sort'. That's what every processor wants. If you're processing perfectly, then you've just got so much more flexibility. If you have that perfect sort you remove the lower grade where the cost is a little bit less. You'll still have your sort to the lower grade where it goes into muesli bars and confectionery. But ideally you want most nuts to go into a higher grade product.

Interview with Vegetable industry representative

What equipment for sorting are you using currently on your line, especially for blemishes, pests and diseases?

Some vegetables get packed straight in the field – sorting just in the field and leave what is not usable e.g. lettuce. Most people do not have camera sorters. Some for colour such as for tomatoes use colour sorting with cameras such as Bell pepper sorters.

Need to get away from Methyl Bromide for fruit fly – even for interstate exports.

Jenny Eckman has a project to look at sorters and sorting out some technologies for sorting and detections.

Internal rots are a problem and can be detected with the cameras but focus is more on future technologies.

Carrot packing goes through some kind of automated system and visual inspection after harvest and production is year-round and delivery from Australia.

Why did you choose the kind of technology/equipment you are using? (specific to pest, diseases and blemishes)

Mostly the technology that is used is for colour sorting and there is very little technology used in the veg industry. Mostly interested in internal rot problems for capsicums and the need to detect fruit fly.

What pests and diseases are prominent?

Rutherglen Bug is a problem in lettuce (stops export).

Redback spiders in broccoli – packed in the field, cold-stored and packed in the shed [however there are only about 25 incidences per year; Australia wide] – visual inspections and posters in the packing sheds alleviate the problem {there is research out there to look at the time of year it becomes a problem}

Chain stores have zero tolerance for anything that deviates beyond their QC specifications. An education program for the consumers; no contaminants, no chemicals and no blemishes…. would be useful.

Where do you see the industry heading in the future in regards to sensing technologies for packing and sorting lines?

Competitive advantage in the world is not there at the moment – labour costs are the problem. Lean and green is no longer an advantage.

Mechanisation is the big one they are working on, some form of automation of IPM and detection in the field.

And difficulties around insect management (MRL residue issues).

Are any of the bigger growers investing in any kind of new technologies?

Young capsicum growers have set up a huge packing shed. They use the shed only for about 2 h a day due to the efficiency and size. Could pack for the whole sector. Export is an issue also due to small growers but if they all would pack together, they would be more competitive in the export market.

Currently there is too much competition between growers locally – drastic oversupply locally but the export space is so complex due to the high tariffs and biosecurity issues. Government support and initiative is needed to enable export

Soft vegetables are very perishable, and therefore export is hard; compared to say potatoes and onions (hard vegetables).

Export of broccoli for example used to be on ice and half their cost was ‘shipping water’ to Japan, and now they use ‘modified atmosphere packaging.’ Saves a lot of cost on shipping.

Short shipment times are a necessity to enable to get to markets and the Australian domestic market is almost like international export due to differences in states.

Interview Summerfruit Australia

What are you aware of that's being used in packingsheds as far as scanning technology or sensing technology? If it is being used, is it fairly widespread or is it limited to just a few packers?

Depends on what sort of pests and diseases. If an insect-based aspect, it's going to be a visual inspection of product rolling along the line. If picking is done properly and they happen to pick a piece of fruit that's got an obvious entry of an insect then you hope they throw it away. Similarly, if it's showing up and rotten, it's on the ground or into another bin and doesn't make it to the packing sheds.

From the point of view of fungus, bacteria and viruses if they're internal, it's going to be very hard unless you are doing an X ray type process which might show up some damage within the tissue. I think the other approach going forward is to look at analysing what the organism was giving off as a precursor, whether it be ethylene or something else, and perhaps there's a piece of equipment that analyses a piece of fruit in that same way and picks up those changes within the content of the fruit and can make decisions on the packing line.

Do summerfruit have programs aimed at particular pests and diseases to assure quality?

International protocols have lists of pests and diseases of concern. If we look at the China, Taiwan, Thailand protocol, the registration growers do or the exporters do includes a crop monitoring program. Most monitoring is insect based but there are things like Prunus necrotic ringspot virus (PNRSV)- a plant pathogenic virus causing ring spot diseases affecting species of the genus Prunus. It was found late last export season in shipments to China.

The product going into places like China and others is inspected now some of that is a random inspection. Why they were particularly looking for Prunus ringspot virus we don't know.

Do you know what kind of equipment the sheds are using at the moment?

The good packing sheds and the larger packing sheds have the best available packing line and equipment. Their lines use photographic images for external blemishes and damage. That doesn't necessarily cover internal aspects which is where I think future potential research might head. There is work being done in Victoria in relation to trying to develop sensors that test the ripening of the fruit.

Are there many pest issues with stone fruit that you're aware of compared to the virus and rots?

There is a range of pests and diseases. There is the Queensland fruit fly we don't have medfly. It's not an issue as they're not here in Australia but there are concerns with possible other exotic fruit flies. Obviously, since the previous ringspot virus is an issue as is brown rot in stone fruit is historically a problem. From an exotic point of view, there's a range of concerns xylaria is the top of the list for everybody to keep an eye open for and brown marmorated stink bug.

What is the number one pest for Australian stone fruit growers?

Queensland fruit fly is the number one test, which affects trade domestically and internationally that's really what most of the protocols are built around. If you look at the protocol list there are other pests and diseases there but a lot of the treatments are around treatment for Queensland fruit fly and to a lesser degree med fly

Do you think that as far as sensing technologies, that industry would be open to more research in that area?

Anything that makes life easier from the point of view of solving problems before they become problems. For example finding the maggot before they are sent overseas in produce. But like any of this equipment the grower will weigh up the economic costs versus the benefits of it. Yes, the technologies that have been developed across apple/cherry/stone fruit packing lines and all the work of GPGraders and others is leading the world in technology and most growers are committed to providing high quality fruit the more we can give them to help that the better

Is there any protocol for destructive fruit assessment for the stonefruit industry? Like the 600 piece assessment or something similar?

There's no defined quality assessments as such. Growers who supply the domestic market would be required to satisfy quality assurance that would flow on to the international market.

APPENDIX 3: Produce Grader Manufactures

- All listed companies, except Ellips (4), offer full turnkey solutions for grading and sorting.
- The target produce, for the grading equipment, was not often clear or specified - guesses made here from examples given and/or website pictures offered.
    - Company histories often indicate an initial specialty target, example olives, before extension to large range of other produce.
- The availability of scanning technologies is noted, mainly Machine Vision and/or NIRS.
    - The systems were OEM solutions except for two companies (Elifab, Elisam) using the Ellips hardware/software.
    - One company offers X-ray (Multiscan Technologies) and another offers Electron Beam (Shibuya Seiko).
- The sales reach for most appeared to be global (one exception, Futura) although it was often very hard to tell the strength of the reach.

1. Compac (part of the Tomra family of companies)

https://www.compacsort.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Medium to large sized produce (cherries to potatoes and similar).

Scanning Technologies: Machine vision and NIRS systems.

Sales Reach: Global.

Head office: Auckland, New Zealand.

2. BBC Technologies (part of the Tomra family of companies)

http://bbctechnologies.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to medium produce (berryfruit, cherries and similar).

Scanning Technologies: Machine vision.

Sales Reach: Global.

Head office: Hamilton, New Zealand.

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3. Aweta

https://www.aweta.com/en/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Medium to large sized produce (cherries to mangoes and similar).

Scanning Technologies: Machine Vision and NIRS systems.

Sales Reach: Global.

Head office: Pijnacker, Holland.

4. Ellips

https://ellips.com/

Manufacture Speciality: Grading/sensor hardware and control software.

Target Produce: Small to large sized produce (e.g. dates to potatoes).

Scanning Technologies: Machine Vision and NIRS systems.

Sales Reach: Global.

Head office: Eindhoven, Holland.

5. Elifab Solutions (member of Ellips group of companies)

https://www.elifab.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small fruit (berryfruit, cherries, cherry tomatoes).

Scanning Technologies: Machine vision, NIRS (use Ellips technologies).

Sales Reach: Global.

Head office: Murcia, Spain.

6. Fujita Fruit Graders

Maybe too new, not officially realised to the market yet – only have the following citation from last year to indicate their possible existence (an article in the industry newsletter Fresh Plaza)

https://www.freshplaza.com/article/9173157/next-april-we-will-finish-two-new-projects-in-china/

Speciality: Unknown.

Scanning Technologies: Unknown.

Sales Reach: Unknown.

Head office: Fujita (China) is solely owned by Fujita Corporation, a large Japanese construction company with HQ in Tokyo, Japan.

7. Elisam

https://www.elisamgrading.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized produce (dates to melons).

Scanning Technologies: Machine vision, NIRS (use Ellips technologies)

Sales Reach: Global.

Head office: Budrio di Longiano, Italy.

8. Futura

https://www.futura-grading.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized produce (dates to melons).

Scanning Technologies: Machine Vision.

Sales Reach: Europe, Asia, Africa.

Head office: Milano, Italy.

9. GP Graders

http://www.gpgraders.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to medium sized fruits (blueberries to apples).

Scanning Technologies: Machine Vision and NIRS (bespoke?).

Sales Reach: Global.

Head office: Victoria, Australia.

10. Greefa

https://www.greefa.com/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Medium to large sized produce (kiwifruit to mangoes).

Scanning Technologies: Machine Vision and NIRS.

Sales Reach: Global.

Head office: Tricht, Holland.

11. Maf Roda

https://www.maf-roda.com/en/page/grading.php

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized produce (nuts to melons).

Scanning Technologies: Machine Vision and NIRS.

Sales Reach: Global.

Head office: Montauban, France.

12. Reemoon

https://www.reemoon.com.cn/index.php

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to medium sized fruit (dates to citrus).

Scanning Technologies: Machine Vision and NIRS.

Sales Reach: Global.

Head office: Jiangxi, China.

13. Unitec (and/or UniSorting)

https://en.unitec-group.com/ (and https://www.unisorting.com/en/)

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized fruit (blueberries to melons).

Scanning Technologies: Machine Vision and NIRS.

Sales Reach: Global.

Head office: Lugo, Italy.

14. Multiscan Technologies

http://www.multiscan.eu/en/

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized produce (speciality in olives).

Scanning Technologies: Machine Vision and X-ray (food safety).

Sales Reach: Global.

Head office: Cocentaina, Spain.

15. Scami Iberica (part of the Sacmi Group)

http://www.sacmiiberica.com/en-US/Products/Process-controllers/Inspection-Systems/NIR-Systems.aspx?idC=61606&LN=en-US

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized produce.

Scanning Technologies: Machine Vision and NIRS.

Sales Reach: Global.

Head office: Imola, Italy.

16. Zetapack

https://www.zetapack.it/en/home.html

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to medium sized produce (berries to apples).

Scanning Technologies: Machine Vision.

Sales Reach: Global.

Head office: Cesena, Italy.

17. Shibuya Seiko

https://www.shibuya-sss.co.jp/sss_e/product/grading.html

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: Small to large sized produce (strawberry to melon).

Scanning Technologies: Machine Vision, NIRS, Electron Beam (for citrus skin separation, hollow heart in potatoes, onion diameter?).

Sales Reach: Global.

Head office: Hamamatsu, Japan.

18. Quadra Agricultural Solutions

https://www.quadramachinery.com/pages/sorting-machines.html

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: round produce, probably medium size (e.g. apples).

Scanning Technologies: Machine Vision.

Sales Reach: Global.

Head office: Zouk Mosbeh, Lebanon // Limassol, Cyprus.

19. SATAKE

https://www.satake.com.au/optical-sorting/

Manufacture Speciality: optical sorting equipment.

Target Produce: nuts, beans, cereals.

Scanning Technologies: Machine Vision.

Sales Reach: Oceania.

Head office: ZPerth, Australia (Global HQ: Tokyo, Japan)

20. Tomra Food (formally Best Sorting, Belgium; Odenberg, Ireland)

https://www.tomra.com/en/sorting/food/sorting-equipment

Manufacture Speciality: Full turnkey grading and sorting solutions.

Target Produce: nuts, grains, small fruit and vegetables

Scanning Technologies: machine vision, laser and X-ray systems.

Sales Reach: Global.

Head office: Leuven, Belgium.

21. Key Technology (including Herbert Solutions)

https://www.key.net/en/our-products/sorting/

Manufacture Speciality: Produce handling equipment including optical sorters.

Target Produce: Nuts, grains, small to medium fruits and vegetables

Scanning Technologies: Machine vision and X-ray systems.

Sales Reach: Global.

Head office: Walla Walla, USA.

22. VISAR Sorting

http://www.visar-sorting.com/

Manufacture Speciality: Optical sorters.

Target Produce: Potatoes and carrots

Scanning Technologies: Machine vision.

Sales Reach: Global.

Head office: Oppens, Switzerland.

23. Select GmbH

https://select.gmbh/sorting/?lang=en

Manufacture Speciality: Optical sorters.

Target Produce: Potatoes and vegetables

Scanning Technologies: Machine vision.

Sales Reach: Global.

Head office: Hartmannsdorf, Germany

24. Optimum Sorting

https://www.optimum-sorting.com/en/home/

Manufacture Speciality: Optical sorters.

Target Produce: Potatoes, nuts, vegetables

Scanning Technologies: Machine vision, laser scanning.

Sales Reach: Global.

Head office: Hasselt, Belgium