Final report

Assessment of GRAIN EDGE® technology to meet Australian government quarantine requirements for imported grain

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Prepared by:	Paul Meibusch and Dr Jorge Mayer Colere Group
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Meat & Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

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Abstract

Increasing drought frequency and intensity, uncertain domestic production, and increasing grain price volatility are significantly impacting the profitability of the feedlot sector. Australia's tight quarantine laws prevent the importation of grain into Australia unless the seed has been devitalised and the insect and pathogen-free status can be guaranteed. The cost and complexity of devitalisation and sterilisation for bulk grain importation represent an often-unsurmountable hurdle for large grain users, such as feedlots. Grain shortages usually coincide with spikes in prices, thus putting at risk the viability of their businesses.

A 2019 MLA-commissioned review of grain devitalisation methods (MLA, 2019) identified the use of infrared irradiation as a possible treatment to sterilise and devitalise grain, especially for quarantine purposes. The ***irtech*** GRAIN EDGE® technology can potentially provide a cost-effective, rapid single-pass devitalisation and sterilisation treatment that meets DAWE quarantine requirements for grain entering Australia.

The study reported here determines the suitability of the ***irtech*** GRAIN EDGE® technology to meet Australian government quarantine requirements for bulk grain imports, including a range of whole grains. Fundamental data was produced that can be used to support applications by lot feeders to import bulk grain and maintain productivity during future periods of domestic low supply and high prices. The ***irtech*** GRAIN EDGE® technology was effective at devitalising barley, maize and sorghum samples sourced for the pilot trial. For wheat, at low incoming moisture levels (≤ 10 %) some germination was evident, whilst complete devitalisation occurred at higher moisture levels. For all grains, transfer rate through the ***irtech*** GRAIN EDGE® technology was between 270 and 750 kg/hr during the project. Further commercial scaling and research with low moisture grains is therefore required to demonstrate efficacy of the technology in the future.

Executive summary

Background

The intensive livestock and feedlot industries require cost-effective, officially certified alternatives to treat imported bulk grain to quarantine standards in times of grain shortages.

The company ***irtech*** Pty Ltd has created a proprietary technology based on infrared irradiation of grains and other agricultural products. The technology, commercialised under the registered tradename GRAIN EDGE®, offers a technical solution to the treatment of grain in a conveyor belt and auger setup combination with high-throughput capability.

The purpose of the research conducted under this project was to validate ***irtech***'s GRAIN EDGE® technology as a treatment for bulk grain imports while fulfilling Australian biosecurity regulatory quarantine requirements. These requirements foresee grain being subjected to a minimum temperature and duration of 90°C for 60 seconds to achieve both devitalisation and sterilisation of the seed.

A further purpose of the research was to establish the scalability of the technology under realistic feedlot conditions while offering a cost-competitive to the industry when compared to alternative options.

The results of this research will be used to inform the intensive livestock and feedlot industries about the utility, cost effectiveness and scalability of the ***irtech*** GRAIN EDGE® technology in the importation of bulk grain and provide information relevant to the filling out of importation permits.

Objectives

1. Obtain an independent evaluation of the effect of ***irtech***'s GRAIN EDGE® selective infrared light source penetration technology on grain devitalisation (preventing the germination of the grain and weed seeds) and sterilisation (insect pests, plant and animal pathogens) in maize, wheat, barley and sorghum grain.
2. Generate modelled costs of treatment ($/tonne) and processing rate (tonnes/hour) for ***irtech*** port facilities of different sizes.
3. If the outcome of the first two objectives is acceptable to DAWE and the industry, provide Australian grain importers who want to use selective infrared light source penetration—as deployed using GRAIN EDGE® technology— for imported grain treatment with the necessary resources to support a DAWE importation application.

Methodology

A study was conducted to determine if GRAIN EDGE® technology as applied to grain was capable of reproducibly reaching and maintaining the grain being treated at 90°C for a minimum of 60 seconds, as per the recommended requirements[1], at a throughput scale of several tonnes of grain per hour and showing that treated grain had been fully devitalised to a pre-established error range. Grains with varying incoming moistures were tested including wheat (10.0-12.6%, barley (10.4-13.0%), sorghum (11.6-13.0%), and maize (14%).

Results/key findings

The present study has shown that GRAIN EDGE® technology can be successfully applied to devitalise corn, barley and sorghum at low rates of dry grain transfer (270 to 750 kg/hr) while fulfilling Australia Biosecurity's minimum requirements regarding prescribed temperature and treatment duration. For wheat, at low incoming moisture levels (≤ 10%) some germination was evident; however, complete devitalisation occurred in wheat samples with moisture contents of 11.0 and 12.6%.

Initial tests on the relevant grain quality measures using NIRS for all relevant animal nutrition purposes suggest that the ***irtech*** treatment did not adversely affect the quality of the grain. An average of 2% moisture loss caused by the treatment was seen across all grain types. Raising moisture by 2% before treatment resulted in grain having the desired moisture content after the treatment, which might be of interest to potential users.

When minimally affected by weather conditions and in longer consistent runs, the energy use per tonne of grain averaged 40 kW after a short warm-up period (equivalent to about 46 kW per tonne of dry matter). In the future there is potential for further energy usage improvements via grain preheating using waste heat produced during processing and unit insulation.

The grain exited the process at 90°C, and (while it differed slightly between grain types) this temperature was still often above 60°C 8-10 hours later. This demonstrates the amount of potential heat energy that could be recovered and fed back into the system to reduce costs. This is being considered in new designs that would use this energy to preheat the grain in the feed silo via heat transfer. Waste heat could be also captured from the generator, which might reduce the overall energy cost further by up to 20 per cent.

[1] The 90°C for 60 seconds guide was provided by Department of Agriculture, Water & Environment (DAWE) following extensive consultation on what would provide sufficient confidence to the department.

Benefits to industry

Availability to the intensive animal industries of a suitable and cost-effective devitalisation, disinfestation and sterilisation treatment method for imported bulk whole grain that meets quarantine requirements at arrival points will be critical in the next drought event. This project was designed to produce several key pieces of information (outputs) to help the intensive animal industries make an informed decision regarding future investment in ***irtech***'s GRAIN EDGE® technology to make the importation of bulk grain affordable in times of gain scarcity.

Future research and recommendations

While the data from the pilot plant has provided some guidance on what is possible in a scaled port-based facility, there are still some unanswered questions around the design of this concept. Particularly, there are indications that significant energy savings (potentially more than 20%) could be gained from the recovery and reuse of waste heat. In addition, the pilot was conducted under low rates of dry grain transfer (270-750 kg/hr); further commercial scaling will be required. Finally, further research examining management of low moisture grains (≤10%) will be required. While some of these questions are being addressed through ongoing concept development by ***irtech***, some commercial questions will remain outstanding until a client(s) is willing to commit to building an importation processing plant.

The basic trials undertaken in this work were designed to provide a solid proof of concept and the supporting scientific data required to progress a potential certified importation process. The industry is recommended to consider commissioning a further study to fill in the gaps identified in the pilot, but which were beyond the scope of this study. These include:

- The logistical issues of importation of bulk shipments through Australian ports (predominately designed and built for export only). This includes challenges around on-site storage, offloading and out-loading into trucks.
- A design for a processing plant capable of handling 500-1000 tonnes per day. While this study was limited to assessing the ***irtech*** technology, there is a need to consider the practicalities of handling importation to the biosecurity level considered acceptable by DA. This could be done as a co-design project with the department.
- The management of low moisture grains (≤10%). As demonstrated in this research project the risk with low moisture grains can be potentially mitigated by water addition via the tempering process prior to treatment. Further, research across all grain types with low moisture is required.
- The nutritive value of treated grain was not explored in any depth; however, the same infrared light source penetration treatment facility could also be used to modify grain to increase digestibility and suitability to add directly to a ration if an importer so wishes. The feasibility of a importation quarantine treatment to devitalise and increase digestibility of feed grain in a one pass operation could be investigated. The landed cost and net energy of infrared grain incorporated into the feedlot ration could be compared with a range of conventional grain processing methods (e.g., tempering, steam flaking).

Table of contents

List of Tables

List of Figures

1. Background

1.1. Issue

The annual demand for feed grain is estimated to vary between 10 and 14 million metric tonnes. The scale depends on a complex combination of supply (localised production restraints) and demand (the combined needs of all animal production systems). Access to affordable feed grain is particularly critical to maintaining the profitability and productivity of the intensive animal industries in Australian agriculture. Significant reductions in localised supply can contribute to excessively high grain prices, threatening the economic viability of many operations.

For the intensive animal industries, the crux of the issue stems from the barriers to accessing material from outside their immediate surrounds. At a high level, these are essentially either high freight costs or biosecurity limitations. The pest and disease-free status of Australian production regions is a significant advantage both for grain production and access to export markets, and therefore they are closely protected. The importation of plant material of any type (into Australia, or even interstate) is considered a substantial threat to this status and is therefore protected through regulations anchored in legislation. One of the most heavily regulated areas is around the importation of bulk grains (unprocessed), which are required to be brought in through a full quarantine assessment process including proof that risks around pathogens, pests and weeds are being managed to the required standards. Historically, therefore, only very limited quantities of bulk grain have been imported into Australia and generally linked to severe drought conditions (MLA, 2003).

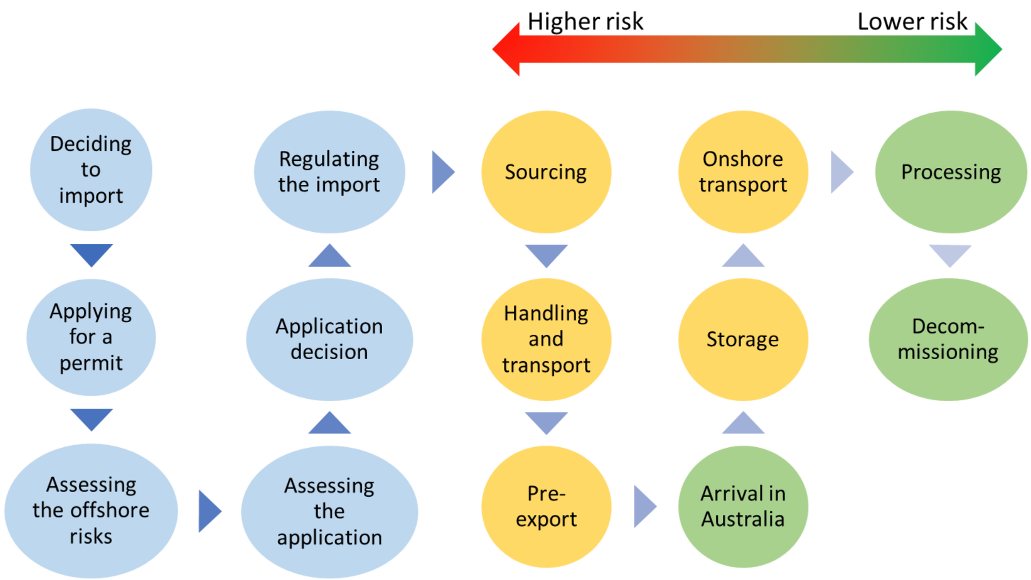


Figure 1. ***Importing bulk grain to Australia.*** **Assessing and managing the biosecurity risks**

The successful importation of bulk grain and plant-based stockfeed for the intensive animal industries is underpinned by a rigorous risk management process balancing the intersection of best-practice disinfestation, eradication and sterilisation of grain pests, pathogens and grain and weed seeds, respectively, and an acceptable risk level that maximises the protection of national plant and animal production industries (Figure 1).

1.2. Current Situation

As DAWE describes the situation, *"the department's decision to approve an import permit for bulk grain is based solely on whether the biosecurity risks can be managed. If the risks cannot be managed, imports will not be permitted."*

Every potential importation of a bulk grain shipment is considered individually and on its own merits; all steps from production to end-use are considered for biosecurity risk potential (see Appendix 10.2). The cost of this investigation and consideration is borne by the importer. The department offers little in the way of specific conditions and recommendations on what a successful application entails, partly because the complexity and specifics of each situation makes it difficult to have a one-size-fits-all approach. At the heart of each importation application are two key issues, namely, understanding and managing the risks relating to the contaminants in a particular parcel of grain, from production through to delivery for processing, and the processing itself. The two processing options that have been accepted for grain shipments in the recent past are a batch heat treatment (suitable for small packages of grain) and full processing of grain where it is taken through a series of temperature and physical steps (extraction of gluten and distillation for ethanol) where the likelihood of survival of seed, insects or pathogens for all intents and purposes equals zero. Both processes include SOPs and contingencies to ensure the process is self-contained and that the end-products are capable of being freely moved and utilised without risk or requiring special treatment.

Clearly, batch heat treatment[2] or full processing[3] are not suitable for the cost-effective treatment of bulk whole grain for the use by intensive animal industries.

[2] Batched treatment is a 12hr process utilising steam and has been reported to cost between $300-$1000/t.
[3] Full processing is the use of steam flaking (which has very limited shelf life) and pelleting.

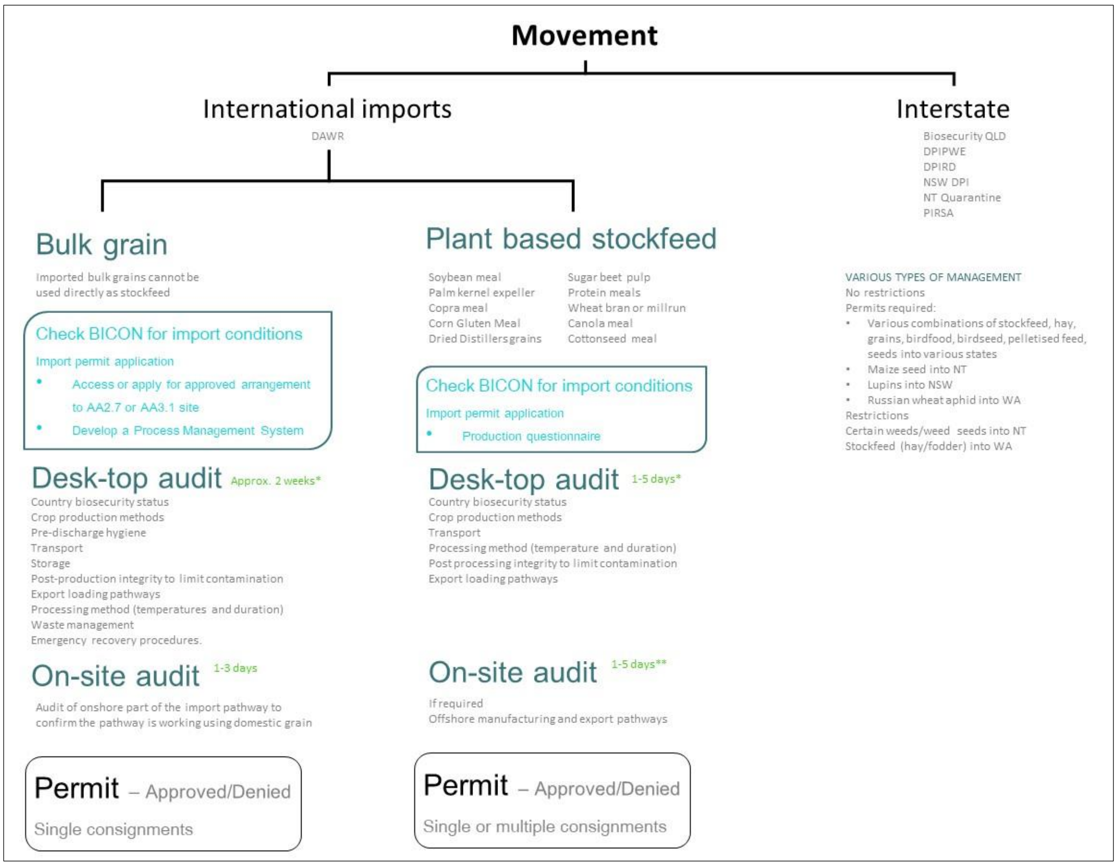


*Figure 2: **Steps required to receive an import permit** Adapted by Colere Group from Department of Agriculture, Australian Interstate Quarantine and state departments sources.*

1.3. Introductory Technical Information

Heat treatment of grains for devitalisation, sterilisation and disinfestation

Importing seed into Australia always involve the risk of carrying pests and pathogens as well as potential dispersal of undesirable non-native seed, especially noxious weeds, into the environment. The Wildlife Research Centre in WA constantly faces those challenges, as they need to import birdseed to feed birds held captive or fed additional seed in the wild as part of recovery programs. This is the background to an article in which the authors treated birdseed with heat from a microwave oven or an electric oven to determine the time taken to devitalise the seeds (Blythman & Sansom, 2019). No seeds were viable after just 2.5 minutes of heat treatment from either the microwave or electric oven.

Disinfestation does not require conditions as harsh as devitalisation to get rid of all insects (Qaisrani & Beckett, 2003), while some microorganisms, especially spore formers, may require higher temperatures and retention times (see also section 3.4).

Some older and more recent work about seed devitalisation utilising heat suggest that some seed are able to germinate after prolonged treatments at high temperatures, which makes it important to test the influence of temperature, retention time, relative humidity, and seed moisture when introducing a new devitalisation method (Atanasoff & Johnson, 1920; Moon *et al*, 2013), as is the case in this set of trials.

Infrared irradiation of food and feed materials

Infrared energy does not depend on air for transmission and is converted to heat upon absorption by the material being heated. Because air and gases absorb very little IR energy, the IR heating process provides for efficient heat transfer without contact between the heat source and the material being heated.

Foodstuffs containing mostly water absorb mid-infrared (MIR) and far-infrared (FIR) energy most efficiently through various modes of vibrations, which leads to the radiative heating process. Vibrations may involve changing the length of the bond (stretching) or the angle of the bond (bending). Some bonds may be either symmetric or asymmetric (Stuart, 2004). When used to heat or dry moist materials, IR radiation impinges on the exposed material and penetrates it, and then the radiation energy is converted into heat (Ginzburg, 1969). Infrared radiation can penetrate significantly into the food product, and such penetration may have dramatic effect on surface moisture and surface temperature.

Infrared (IR) heating provides significant advantages over conventional heating, including reduced heating time, uniform heating, reduced quality losses, absence of solute migration in food material, versatile, simple, and compact equipment, and significant energy savings (Krishnamurthy *et al*, 2008; Aboud *et al*, 2019). IR heating can be applied to various food processing operations, including drying, baking, roasting, blanching, pasteurisation, and sterilisation. IR heating can also be combined with microwave heating and other common conductive and convective modes of heating for increased energy throughput.

Heat treatments are based on energy transfer occurring through conduction, convection or radiation. Foods and biological materials are heated primarily to extend their shelf life or to enhance taste. Heating of such materials is conventionally obtained by combustion of fuels or by an electric resistive heater, i.e., heat is generated outside of the object to be heated and is conveyed to the material by convection of hot air or by thermal conduction.

Characteristics of IR heating such as efficiency, wavelength, and reflectivity set it apart from and make it more effective for some applications than others. It has a higher thermal efficiency and fast heating response time in comparison to conventional heating. This explains why IR radiation is widely applied to various thermal processing operations in the food industry such as dehydration, frying, and pasteurization (Sakai & Hanzawa, 1994).

IR radiation transfers thermal energy in the form of electromagnetic waves with wavelengths between microwaves and visible light, i.e., between 0.78 to 1000 µm. The IR spectrum is subdivided into near infrared (NIR; 0.75-1.4 µm), mid-infrared (MIR; 1.4-3 µm) and far infrared (FIR; 3-1000 µm) (Sakai and Hanzawa 1994). An object exposed to IR radiation absorbs the heat energy to different extents along that portion of the spectrum, depending on its biochemical composition. Amino acids, polypeptides, and proteins reveal two strong absorption bands localized at 3 to 4 and 6 to 9 µm. On the other hand, lipids show strong absorption phenomena over the entire infrared radiation spectrum, with three stronger absorption bands situated at 3 to 4, 6, and 9 to 10 µm, whereas carbohydrates yield two strong absorption bands centred at 3 and 7 to 10 µm (Sandu, 1986; Rosenthal, 2012). In general, FIR radiation is advantageous for food processing because most food components absorb radiative energy in the FIR region (Sandu, 1986).

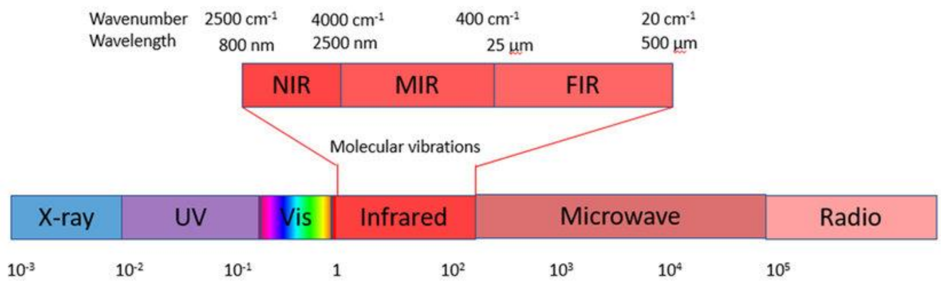


Figure 3. ***The infrared spectrum.*** The graph shows the location of the infrared spectrum within the wider electromagnetic wavelength range. Energy decreases to the right and is inversely correlated to the wavelength.

The emitters used in ***irtech***'s GRAIN EDGE® machine work in the boundary region between NIR and MIR, toward the higher-energy portion of the infrared spectrum (see image above), a region with high interactivity with hydroxyl groups (absorption wavelength 2.7-3.3 µm), and thus water and carbohydrates, and less interactions with proteins and lipids, resulting in efficient heating of water-containing materials and minimal potential damage to other compounds.

Applications of IR heating in food processing operations

Application of IR drying in the food industry is expected to represent a new process for the production of high-quality dried foods at low cost (Sakai & Hanzawa, 1994). The use of IR radiation technology for dehydrating foods has numerous advantages including reduction in drying time, alternate energy source, increased energy efficiency, uniform temperature in the product while drying, better-quality finished products, a reduced necessity for air flow across the product, high degree of process control parameters, and space saving along with clean working environment (Dostie *et al*, 1989; Navari *et al*, 1992; Sakai & Hanzawa, 1994; Mongpraneet *et al*, 2002). Generally, solid materials absorb infrared radiation in a thin surface layer. However, moist porous materials are penetrated by radiation to some depth and their transmissivity depends on the moisture content (Lampinen *et al*, 1991).

Prolonged exposure of a biological material to IR heat results in swelling and ultimately fracturing of the material (Jones, 1992). Fasina and co-workers (1996) showed that IR heating changes the physical, mechanical, chemical, and functional properties of barley grains. IR heating of legume seeds to 140°C can cause cracking on the surface (Fasina *et al*, 1997). However, a combination of intermittent infrared heating and continuous convection drying of thick, porous material resulted in better product quality and energy efficiency (Dostie *et al*, 1989).

Application of combined electromagnetic radiation and conventional convective heating is considered more efficient over radiation or convective heating alone, as it gives a synergistic effect with a major reduction in energy use (Afzal *et al*, 1999).

Infrared heating can be effectively used for enzyme inactivation. Lipoxygenase, an enzyme responsible for deterioration in soybeans, was inactivated 95.5% within 60 seconds of IR treatment (Kouzeh-Kanani *et al*, 1982). Certain enzyme reactions (involving action of lipases and alpha amylases) were affected by IR radiation at a bulk temperature of 30 to 40°C (Kohashi *et al*, 1998; Sawai *et al*, 2003; Rosenthal, 2012). FIR radiation for 6 min resulted in a 60 per cent reduction in lipase activity. FIR has been successfully used to inactivate enzymes responsible for the development of off-flavours in peas prior to the freezing process (Van Zuilichem *et al*, 1986), as well as other enzymes and bacteria in solution (Sawai *et al*, 2003).

Inactivation of pathogens using IR irradiation

IR heating can be used to inactivate bacteria, spores, yeast, and mold in both liquid and solid foods. Efficacy of microbial inactivation by IR heating depends on several factors, including radiation power level, temperature of food sample, peak wavelength, and bandwidth of IR heating source, sample depth, types of microorganisms, moisture content, physiological growth phase of the microorganisms, and types of food materials. Depending on the temperature reached and the permanence of the material at that temperature, the presence of microorganisms can be reduced by several logs, even at temperatures around 60°C (Sawai *et al*, 2003).

IR radiation has a poor penetration capacity, its power decreases with sample thickness. In a grain like wheat, penetration is around 2 mm. However, the surface temperature of food materials increases rapidly, and heat is transferred inside food materials by thermal conduction. Typical thermal conductivities of solid foods are much lower than liquid foods.

Bacterial spores are more resistant to IR irradiation than vegetative bacterial cells. A 10-min treatment with IR heating *Bacillus subtilis* spores resulted in more than 90 per cent reduction of the population (Daisuke *et al*, 2001). Cereal surfaces are often contaminated with spore formers like Bacillus, Aspergillus, and Penicillium. A double IR irradiation treatment showed good results in eliminating such spore-forming microorganisms. The first treatment kills vegetative cells and induces spores to become vegetative, while the second treatment kills the latter (Hamanaka *et al*, 2000). Generally, exponentially growing cells are more sensitive to IR heating than stationary phase cells.

Mycotoxigenic fungi pose a severe threat to human health while causing economic losses to growers. Selected IR wavelengths can be used to inactivate mycotoxigenic fungi such as *Aspergillus flavus* (Wilson *et al*, 2021). The system is scalable for large-scale industrial application for reliable and rapid mycotoxigenic fungal inactivation on maize and other cereals.

1.4. GRAIN EDGE® technology

The embodiment of infrared irradiation technology being used in this set of trials is based on the GRAIN EDGE® machine developed and built by ***irtech*** Australia Pty Ltd. This machine is an industrial infrared irradiation processor that can achieve optimal heating and drying conditions in a very short time. For example, it can be used to dry or roast nuts, grains and other, similar products with short retention times. The process chamber does not require preheating, the drying process can commence instantaneously as soon as the infrared processor is switched on. This translates to time and cost savings while preventing the product integrity being compromised by overheating.

The infrared processors integrated in the GRAIN EDGE® technology are robust, fully automated, low-maintenance units controlled by a programmable logic controller (PLC); they are also self-adjustable, meaning that it will deliver a uniform treatment of the product. The machine is designed to run over extended periods with minimum monitoring, while also including a safety automatic shutdown in the case of unexpected events. Due to their sturdiness and quick response time, these machines may be operated non-stop for weeks at a time or for only a few hours each day. They are easy and quick to clean, compact, user friendly and require minimal floor space. A complete, functional unit may be permanently mounted or easily transported to another location in a container, which allow use diversification of the processing unit during downtimes.

*Figure 4. **Setup of the GRAIN EDGE® machine for the grain devitalisation trials***

An important factor in the consideration of most products and processes is that their effectiveness is the result of a combination of rate and time of exposure to the treatment. The most benign treatments (such as temperature or atmospheric control) can be effective against seed vitality, insects and pathogens when applied over an extended period.

The Australia-based company ***irtech*** Pty Ltd has developed an infrared-based technology (GRAIN EDGE®) to pasteurise, devitalise or micronize (gelatinise starch to increase digestibility) grain. The process reduces rather than adds moisture to the grain (unlike steam treatment), thus potentially having a less deleterious effect on shelf life. ***irtech*** currently markets various model sizes of their units, focussing on a small 5-8 tonne grain per hour machine for use by small feedlots and dairies as an alternative to the larger scale steam flaking processes.

A fully functional pilot GRAIN EDGE® machine has been present at a feedlot in southern Queensland for over six months. The treated grain from this plant has been used to do comparative trials on feedlot animal performance. The machine was then modified to achieve the required times and temperatures for the grain quarantine treatment trial described here as well as to demonstrate both continuous performance and any required safety and performance management systems.

1.5. Project Approach

The project described here was designed to define the circumstances in which the GRAIN EDGE® technology was to be used, including several assumptions to keep the number of factors needing to be considered in check.

The most important assumption relates to the metric to be applied to measure success in the performance of the technology. While the required treatment when importing bulk grain into Australia is designed to attain a combination of devitalisation of the grain itself and kill any insect, weed seed or pathogen being carried along with the grain, proving the actual efficacy achieved in bulk shipments of many thousands of tonnes of grain is almost impossible. Even the use of positive controls raised issues of the need to test for insects, pathogens and weeds that are prohibited in Australia. Fortunately, discussions with the department provided a practical and acceptable target: *reaching and holding the temperature of grain at 90°C for a minimum of 60 consecutive seconds is known from many previous studies to be adequate* (within an acceptable margin of risk). Our experiments have therefore been designed to demonstrate that the GRAIN EDGE® technology can achieve this target threshold on a continuous flow of grain at scale.

The second assumption made was that the technology would be used in a facility where untreated grain would enter from one side of a sealed room and all product leaving that room would necessarily have been dealt with appropriately. The risk of untreated or partially treated product leaving the room would have to be managed as part of the process.

1.6. Industry Impact

This project was designed to produce several key pieces of information (outputs) to help the intensive animal industries make an informed decision regarding investment in ***irtech***'s GRAIN EDGE® technology to make the importation of bulk grain affordable in times of gain scarcity. These include:

- A clear understanding of the potential of a purpose-modified GRAIN EDGE® machine to achieve continuous treatment of grain to a specification meeting DAWE's quarantine requirements.
- The cost, technical requirements and feasibility of producing a scaled, modified GRAIN EDGE® machine to meet the volume requirements of imported bulk grain.
- The variable costs per tonne of treated grain using the modified and scaled machine.
- Differences in physical handling, effectiveness and cost of treating four different test grain species (maize, wheat, barley and sorghum).
- A basic understanding of the physicochemical and physiological changes in the treated grain.

The data produced from this project will be made available to groups seeking to apply for an import permit for bulk grain.

2. Objectives

1. Obtain an independent evaluation of the effect of ***irtech***'s GRAIN EDGE® selective infrared light source penetration technology on grain devitalisation (preventing the germination of the grain and weed seeds) and sterilisation (insect pests, plant and animal pathogens) in maize, wheat, barley and sorghum grain.
2. Generate modelled costs of treatment ($/tonne) and processing rate (tonnes/hour) for ***irtech*** port facilities of different sizes.
3. If the outcome of the first two objectives is acceptable to DAWE and the industry, provide Australian grain importers who want to use selective infrared light source penetration—as deployed using GRAIN EDGE® technology— for imported grain treatment with the necessary resources to support a DAWE importation application.

3. Methodology

3.1. Equipment design

Because of the known differences between different species of grain and the likely amount of energy required to bring packages of each (at different moistures) up to the required 90°C, the decision was made to add an additional auger with six more IR emitters to the original GRAIN EDGE® machine (see Figure 5). This would ensure that regardless of the time and energy taken to bring the grain up to temperature, there would still be capacity to hold the grain for more than 60 seconds.

Grain was fed from a feed-in silo, up a conveyer to the feed chute of the GRAIN EDGE®. Within the GRAIN EDGE® machine the grain was prewarmed utilising waste heat from the IR chamber. Along the main IR chamber, the grain is exposed to a series of emitters (up to eight, individually switched) and the temperature of the grain is brought up to the required 90°C. Grain exiting the GRAIN EDGE® machine then travelled along an insulated, IR heated auger lined up with the GRAIN EDGE® machine. This auger has six IR emitters and two temperature probes.

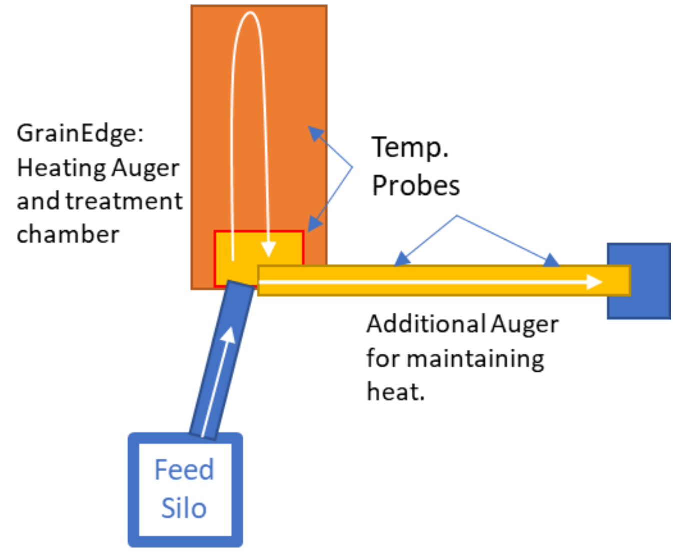


Figure 5. ***Overhead schematic of machine layout***

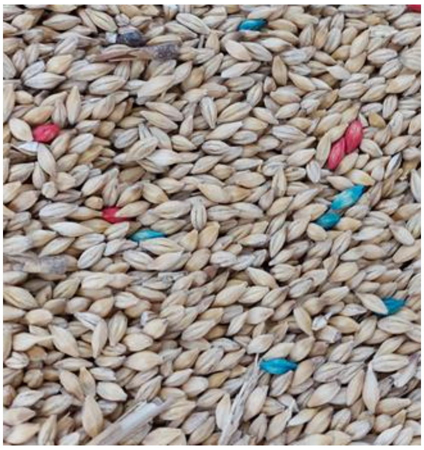


Figure 6. ***Dyed grain was used to determine retention time in the treatment chamber***

3.2. Setup for the *irtech* GRAIN EDGE® technology trials

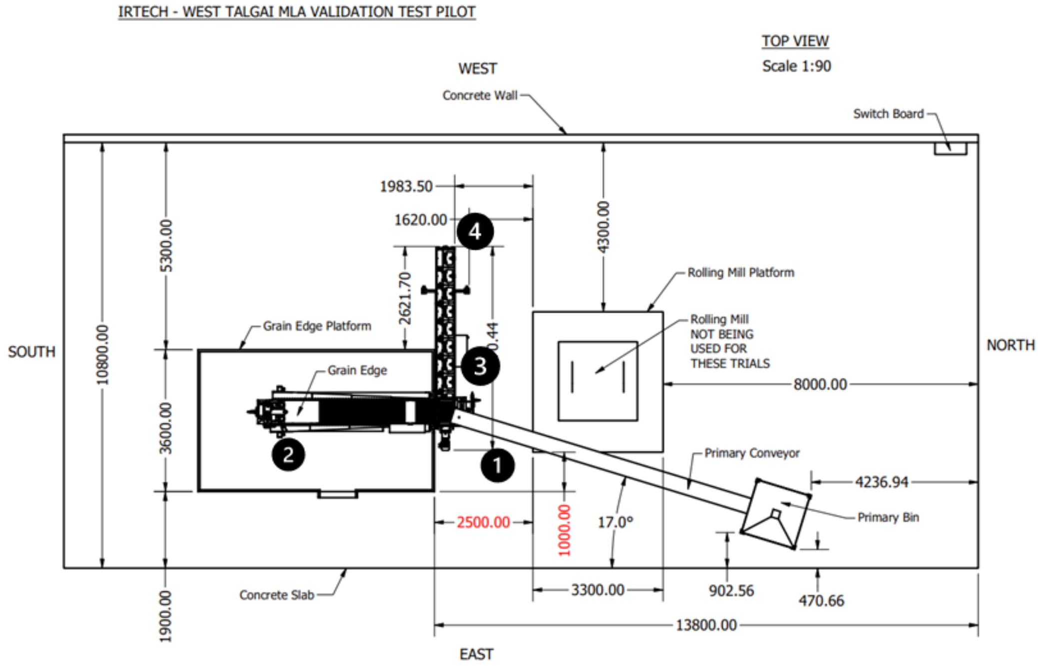
The purpose of this study was to determine if GRAIN EDGE® technology as applied to grain was capable of reproducibly reaching and maintaining 90°C for 60 seconds at a throughput scale of several tonnes of grain per hour, as per quarantine requirements for imported grain. Complementary testing was conducted to determine devitalisation and sterilisation efficacy under these conditions.

Batches of different grain types were run through the GRAIN EDGE® machine to test if the minimum quarantine treatment requirements of 60 seconds retention at 90°C could be met reproducibly. Batches of between 400 and 650 kg were run using barley, wheat, sorghum, and maize grain to test for the efficacy and reproducibility of the treatment for different grain sizes, testa thickness, grain hardness, and oil content. Long term stability runs for wheat, barley, sorghum and maize had batches between 900 kg and 3000 kg (See Table 1). Tests included varying throughput rates.

Moisture of the grain received was measured and adjusted to common moisture levels seen in grain imported from North America by tempering the grain to the desired levels.

The GRAIN EDGE® machine used for this pilot was dimensioned to handle from 300 up to 3000 kilograms of grain per hour; however, in the pilot only transfer rates of 270 to 750 kg/hr were trialled (See Table 1). Grain throughput is adjustable via auger speed and volume of grain added. Temperature is regulated via eight individually controlled IR emitters lined up in pairs along the treatment chamber, each with a nominal power output of 4.25 KW. In addition to the internal temperature management of the GRAIN EDGE®, two thermocouples were positioned at the end of the GRAIN EDGE® machine and two thirds through the jacketed auger to ensure the target temperature had been reached and maintained. The necessary power is provided via the switchboard (on the right of the second diagram shown below) by a generator capable of a constant output of at least 36 KW for the eight IR emitters (in the pilot configuration) plus additional power (5-8KW) to heat the jacketed auger. Generally only 4-6 emitters were required during the trials.

The setup consisted of the GRAIN EDGE® machine, a jacketed heated auger, silo, and collection bins (cf. graphs below). The silo fed the GRAIN EDGE® machine via the primary conveyor (1). Within the GRAIN EDGE® machine, the grain was preheated in an auger and then continued to flow into the treatment chamber (2), where the IR emitters bring the grain up to the required temperature. Exiting the GRAIN EDGE®, the grain flows down into the jacketed/heated auger (3), which utilises additional IR emmitters designed to maintain the temperature through the length of the auger. Grain exits the jacketed auger into half-tonne bins (4).



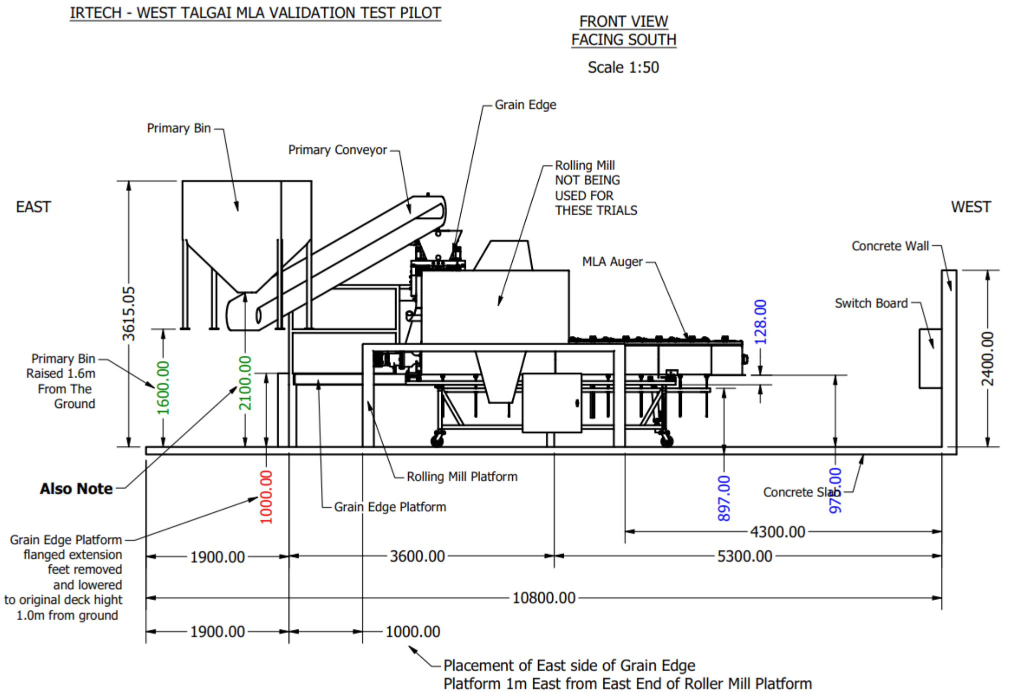


*Figure 7. **Schematic of GRAIN EDGE® machine setup***

Ambient conditions (relative humidity and temperature) were continuosly recorded using a Digitech XC-0424 data logger and the data added to the trial spread sheet.

Individual experiments were designed to determine effectiveness of treatment across the different types of grain tested in terms of ramp-up to and retention time at the target temperature. Factors and parameters tested against efficacy included ambient conditions, grain throughput, and power use per volume. One objective was to find conditions that might be applicable across a wide range of grain types while achieving the target retention time and temperature. Retention time was confirmed for each run by adding a handful of coloured grain at the entry point into the machine. Running conditions were adjusted to ensure that the first coloured grains to exit had reached a minimum retention time of 60 seconds, with the peak of the coloured grain reaching a retention time of up to 2-5 minutes (depending on the grain type and outside ambient conditions).

3.3. Grain tempering

The moisture content of dry grain (barley 10.4%, wheat 10.0% and sorghum 11.6%) was adjusted by tempering to demonstrate the applicability of the GRAIN EDGE® technology under a range of realistic conditions for the livestock industries. Barley was tempered to 11.0 and 13.0% moisture, wheat to 11.0 and 12.6% moisture and sorghum to 13.0% moisture (See Table 1).

Calculations were based on moisture content values as determined using a FOSS NIRS Model Infratec™ 1241 Grain Analyzer machine on site.

To temper the grain, a 65-litre cement mixer was utilised to obtain an even distribution of added water. The calculated amount to bring moisture content to the desired value was slowly added to small, 20-kg batches of grain into the rotating cement mixer. The total volume of treated grain was then allowed to normalise over a minimum period of 18 hours before taking samples for germination tests at the given moisture content, followed by the scheduled infrared treatments.

3.4. Sampling protocol

Sampling for grain temperature control

Samples were taken in duplicate at the end of the line to determine the temperature of the grain at the exit point and used to fill a prewarmed (to 60°C with warm grain) thermos flask. The sample temperature was measured over 15-20 minutes using a thermocouple and recorded. The relevant parameter was the temperature of the plateau reached after the sample had reached thermal equilibrium. This was used to confirm that the target temperature had been reached during the treatment.

Sampling for proximate, germinability and microbiological analyses

Random treated and untreated samples from the experiments were sent to Symbio for the analysis of proximates and feed values using AusScan NIR calibrations (no calibrations for maize available). Similarly, samples were sent to Futari Grain Technology Services, Narrabri NSW, to determine germinability of treated samples, which included samples from the grains treated as part of this project as well as weed seed proxies, namely canola and lawn grass seed. Reduction of microbial load after treatment was measured at the Centre for Crop Health at USQ.

3.5. Methods used to measure key parameters

Measurement parameter:	**Standards and Technology used**
Grain moisture and protein pre- and post-treatment.	 NIR measurement using a FOSS NIRS Model Infratec™ 1241 Grain Analyzer.
Grain Viability	Standard ISTA germination test via Futari Grain Technology Services – NATA accredited Laboratory (Narrabri)
Grain temperature in feeder bin and post machine.	Testo- immersion/penetration probe (Pt100) 
Grain temperature at three locations in the treatment cylinder.	 Dwyer- Series ILA In-Line IR Sensor

		Protech- QM16001- Two channel temperature meter.

4. Results

4.1. Runs conducted

Table 1: GRAIN EDGE® runs at Talgai Qld (Aug-Sep 2021)

GRAIN TYPE	RUN ID	DATE	MC (%)	MC temp (%)	RUN TIME (h)	RETENTION (min)	VOL (Kg)	THROUGHPUT (Kg/h)	SAMPLES TAKEN	PARAMETERS TESTED
BARLEY	Bar-1-110821	11-Aug-21	10.4	-	02:02	02:00	630	315	4	Grain temperature; throughput; germination; protein
	Bar-2-120821	12-Aug-21	10.4	11.0	01:24	02:00	-	270-430 (var)	4	Grain temperature; throughput (var speed); germination with tempered grain;
	Bar-8-270821	27-Aug-21	10.4	13.0	00:55	02:45	~400	~300-500 (var)	4	Grain temperature; throughput; retention
	Bar-12-070921	07-Sep-21	10.4	-	03:46	02:15	1960	528		Long run for temperature stability
WHEAT	Whe-3-180821	18-Aug-21	10.0	-	01:01	02:35	400	398	4	Grain temperature; throughput; germination; protein
	Whe-4-190821	19-Aug-21	10.0	11.0	00:55	02:35	400	~400	4	Grain temperature; protein
	Whe-5-200821	20-Aug-21	10.0	12.6	01:15	02:45	650	522	5	Grain temperature; protein
	Whe-12-070921	07-Sep-21	10.0	-	02:28	02:25	900	360		Long run for temperature stability
SORGHUM	Sor-6-250821	25-Aug-21	11.6	-	00:55	02:45	620	673	4	Grain temperature; throughput; germination; protein
	Sor-7-260821	26-Aug-21	11.6	13.0	01:15	02:45	~600	~700	4	Grain temperature; protein
	Sor-13-080921	08-Sep-21	11.6	-	04:07	02:35	3000	729		Long run for temperature stability
MAIZE	Mai-9-010921	01-Sep-21	14.0	-	01:05	02:05	-	290-750 (var)	4	Grain temperature; throughput; germination; retention; oil and protein
	Mai-11-030921	03-Sep-21	14.0	-	01:32	02:15	1100	717	-	Long run for temperature stability

RUN ID: see master spread sheet.
MC temp: Grain tempered to desired moisture content as described in the methodology section.
Samples taken: number of samples taken during the effective run at 15-min intervals.
Grain source: Allora Grains.

4.2. Grain quality testing

An analysis of proximates and feed values was conducted to exclude the possibility of undesired changes happening to the grain due to the GRAIN EDGE® heat treatment. The results, summarised in Appendix 9.1, show that proximates like ash or protein were not affected by the treatment (within the error margin of the method). Proximates that were not expected to change serve as a kind of internal control for the interpretation of feed energy values (highlighted in the table below), which could in principle have been modified by the heat treatment due to heat-induced chemical reactions, for example.

The table below shows the differences between the untreated and treated samples (see Appendix 9.1). Negative changes that stand out have been highlighted in light blue while larger positive changes are highlighted in in light orange. All grain types treated consistently lose about one per cent moisture due to the treatment, as expected. Other values that stand out are probably related to a smaller coefficient of determination of the corresponding NIRS calibrations.

*Table 2. **Changes of AusScan measured parameters after GRAIN EDGE® treatment***

PROXY PARAMETERS	BARLEY	WHEAT	SORGHUM
Moisture (%)	-1.3	-0.8	-1.1
Ash (%)	0.0	-0.1	-0.1
Fat (Acid Hydrolysis) (%)	0.4	-0.2	-0.2
Protein (%)	0.3	-0.4	0.4
Fibre (%)	-1.1	-0.1	0.0
Starch (%)	3.1	1.0	-0.2
Pig Faecal DE (MJ/kg)	-0.1	0.2	0.2
Pig Ileal DE (MJ/kg)	-0.5	0.3	0.3
Broiler AME (MJ/kg)	0.2	0.2	-0.4
Broiler AME Intake Index ()	2.9	1.4	-2.5
Layer AME (MJ/kg)	0.0	0.1	0.1
Layer AME Intake Index ()	-0.8	1.7	1.4
Cattle est. DMD (%)	1.2	0.0	-1.3
Cattle est. DOMD (%)	1.1	0.0	-1.3
Cattle est. ME (DM) (MJ/kg)	0.1	0.0	0.1
Sheep DMD (%)	1.4	0.0	-1.5
Sheep DOMD (%)	1.3	0.0	-1.4
Sheep est. ME (DM) (MJ/kg)	-0.1	0.2	0.1

All values adjusted to dry matter content of the samples.

Imported grain generally has a higher moisture content than domestic grain. Several trials were conducted using tempered grain (see methodology section), adjusted to target moisture levels, to investigate potential effects of moisture content on energy consumption or achievement of the target temperature and retention parameters. For each run, protein was measured along with moisture content as a sort of internal standard for the moisture measurements. The following two tables summarise the results from those trials.

The heat of the GRAIN EDGE® treatment consistently reduced grain moisture by 1-3 per cent. Other than that, no deleterious effect on the grain or achieving of the treatment parameters was observed. Any effect of a higher moisture content is much smaller than environmental effects like wind and ambient temperature.

4.3. Grain devitalisation

Independent grain germination tests on random samples from various runs were undertaken with Futari Grain Technology for both untreated controls and irradiated grain.

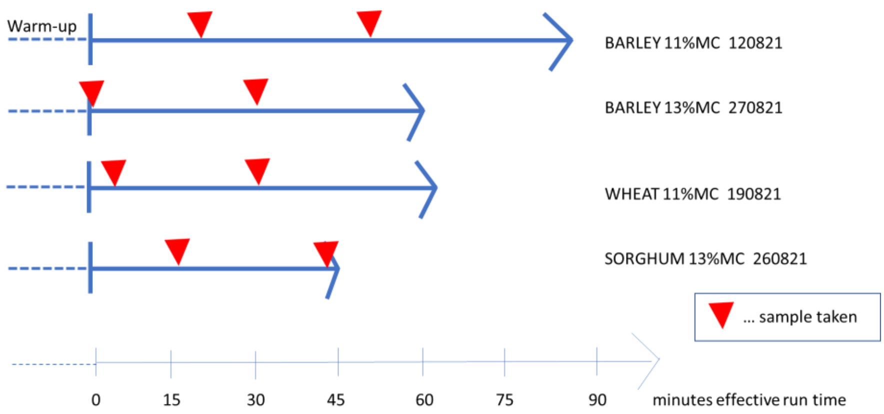
It has long been known that dry seed are rather resilient to dry heat treatment (Atanasoff & Johnson, 1920), with some seed showing even improved germination upon such treatment, depending on the temperature and duration of the treatment. Some weed seeds can germinate after 48 hours at 95°C, while all seed tested and treated by Moon and co-workers (2013) were fully devitalised after 30 minutes at 130°C.

Generally, seeds are much more susceptible to heat at around 40 per cent moisture content, although most seed in the article mentioned still required two hours at 90°C for devitalisation, and one, namely prickly oxtongue (*Helminthotheca echioides*, syn *Picris echiodes*) still required a 16-hour treatment at that temperature.

IR irradiation using GRAIN EDGE® leads to a loss of moisture of slightly over one percent in all seed tested. This should not constitute a problem if the initial moisture is around 13 per cent or more. Contrary to other heating methods used, IR irradiation acts quickly by heating up the seed from the inside via excitation of the water molecules in the grain. Thanks to this targeted interaction, it is not necessary to use high moisture contents as in steaming, for example, but a certain amount of water is still required to capture the IR energy and for the heat conductance within the seed. Lipids also show strong absorption in the wavelength range of the IR emitters used in the GRAIN EDGE® machine, which means that grains rich in oil, which also has a high heat conductivity, are also effectively heated up to the target specifications.

From the above, we can conclude that while it is possible to effectively heat up seed to the target temperature, quantitative devitalisation might still be a problem below a certain moisture content.

Samples were taken at different points during effective run time to show that the effectiveness of the treatment is constant from the moment the machine is prewarmed to the end of the run. Untreated samples were taken as control just before they entered the machine. The example in the graph below shows that runs can be of different length, but the expectation is always that devitalisation should be quantitative from beginning to the end of the effective run time.



We observed that grain was consistently devitalised except for one run in which up to 10 per cent of the wheat seed germinated (highlighted in the table below). Ten per cent moisture content seems to be close to the limit value for effective devitalisation, as not enough heat is transmitted to the germ due to the lack of available water molecules. We recommend a moisture content of around 13 per cent before treatment to be on the safe side. Devitalisation worked effectively for the two weed seed proxies utilised, namely an admixture of canola or rye grass seeds.

Table 3: Grain devitalisation: Germination tests

Sample	ID	Grain type	MC %	Treatment	Days	Abnormal %	Hard %	Fresh %	Dead %	Germination %
A1	110821	Barley	10.4	U	7	0	0	0	1	99
B2	110821	Barley	7.4	T	7	0	0	0	100	0
C3	110821	Barley	8.3	T	7	0	0	0	100	0
D3	110821	Barley	7.8	T	7	0	0	0	100	0
B1	120821	Barley	10.9	U	7	4	0	0	4	92
B3	120821	Barley	7.8	T	7	0	0	0	100	0
D1	120821	Barley	10.9	U	7	2	0	0	5	93
D3	120821	Barley	8.0	T	7	0	0	0	100	0
A1	270821	Barley	12.7	U	7	11	0	0	19	70
A2	270821	Barley	9.5	T	7	0	0	0	100	0
C1	270821	Barley	12.5	U	7	8	0	0	13	79
C2	270821	Barley	10.0	T	7	0	0	0	100	0
A1	180821	Wheat	10.1	U	8	3	0	0	1	96
B4	180821	Wheat	9.2	T	8	4	0	0	88	8
C3	180821	Wheat	9.3	T	8	7	0	0	82	11
D2	180821	Wheat	9.1	T	8	12	0	0	78	10
A1	190821	Wheat	10.9	U	8	4	0	0	2	94
A3	190821	Wheat	9.5	T	8	0	0	0	100	0
C1	190821	Wheat	10.9	U	8	4	0	0	1	95
C2	190821	Wheat	9.4	T	8	0	0	0	100	0
B1	200821	Wheat	12.7	U	8	4	0	0	2	94
B2	200821	Wheat	10.5	T	8	0	0	0	100	0
D3	200821	Wheat	10.4	T	8	0	0	0	100	0
E4	200821	Wheat	10.5	T	8	0	0	0	100	0
A1	250821	Sorghum	11.6	U	10	5	0	13	0	82
B4	250821	Sorghum	9.8	T	10	0	0	0	100	0
C2	250821	Sorghum	10.0	T	10	0	0	0	100	0
D3	250821	Sorghum	10.2	T	10	0	0	0	100	0
B1	260821	Sorghum	12.8	U	10	13	0	0	5	82
B2	260821	Sorghum	10.6	T	10	0	0	0	100	0
D1	260821	Sorghum	12.9	U	10	3	0	0	13	84
D2	260821	Sorghum	10.6	T	10	0	0	0	100	0
UT	010921	Maize	13.9	U	7	0	0	0	7	93
B2	010922	Maize	12.1	T	7	0	0	0	100	0
C2	010923	Maize	12.1	T	7	0	0	0	100	0
D4	010924	Maize	12.4	T	7	0	0	0	100	0
Admix	080922	Canola		U	7	6	0	0	3	91
Admix	080921	Canola		T	7	0	0	0	100	0
Admix	080924	Ryegrass		U	14	0	0	0	7	93
Admix	080923	Ryegrass		T	14	0	0	0	100	0

Germination tests (carried out by Futari Grain Technology Services). Sample IDs as in master spread sheet. **Admix**, canola and ryegrass seeds added to the run as weed seed proxies and reisolated for germination testing; **MC**, moisture content; **U**, **T**, untreated or treated grain, resp.; **Abnormal**, seeds germinate but do not have adequate plant structures, such as missing roots or shoots; **Hard**, seed coats impermeable to water; **Fresh**, seeds fail to germinate but have imbibed water, appearing firm, fresh and capable of germination, but remaining dormant; **Dead**, seeds cannot produce any part of a seedling.

4.4. Reduction of grain microbial load

Although the main purpose of the trials conducted was to determine if the GRAIN EDGE® machine was capable of reproducibly achieving the minimum Biosecurity Australia requirements for imported grain (grain retention of 60 seconds at 90°C) while effectively devitalising the grain, microbial load is another consideration worth investigating. The microbial load associated with grains reflects the environmental conditions in which the crop was grown, stored and transported, and thus, these can vary widely in terms of numbers and type of microorganisms involved.

We conducted preliminary trials by sending treated and untreated wheat grain samples to the Centre for Crop Health at USQ for analysis. Grain samples were blended in phosphate buffered saline solution, and insoluble component separated by centrifugation. Serial dilutions were carried out before plating various dilutions on standard Sabouraud-Dextrose agar plates for microbial growth counts after incubation.

The reduction of microbial count was calculated back to the number of colony forming units (cfu) per kernel analysed. The average value from five treated replicate samples gave a reduction factor of 3.65 log cfu/weight (equivalent to a reduction from 2.39^7 to 5.31^3 cfu/kernel).

The microbial flora of grain is made up of >100 bacterial species and dozens of fungal species. To investigate if there is a differential effect on different types of microorganisms, further tests would be required. While our preliminary tests tried to capture a general microbial population, a comparison with values from the literature, obtained using some of the latest methods being studies in the food industry (see table below), shows that the GRAIN EDGE® treatment is among the better performing methods.

Many methods have been tried to sterilise cereal grains, mostly in relation to the grain milling industry. The objective is to reduce microbial load and thereby risk to consumers while not affecting the functionality of the grain. These methods possess different levels of practicality and efficacy. Some of the drawbacks of such methods include high costs, damage to grain functionality or environmental pollution (Los *et al*, 2018).

Bacterial and mold load reductions up to more than 5 log cfu/g have been achieved with tempering agents, without compromising flour functionality. Technologies can have different efficacy for different types of microorganisms, e.g., nonthermal technologies like pulsed light treatments can effectively reduce Salmonella load on flour, while cold plasma was more effective against fungal conidia on grain. Among thermal technologies, vacuum steam treatment reduced enterobacteria on grain without affecting flour properties. A review by Magallanes-López and Simsek (2021) provides us with some efficacy values for comparison purposes:

Method	Target microorganisms	log cfu/g reduction
Radio frequency heating (0.5 kW) on Salmonella	Salmonella	7
Tempering with ozonated water or acidic saline solutions	Bacteria, yeast, mold	2-4
Pulsed light 0.4 Jcm^{-2}	Mold	<4
Pulsed LED 395 nm (varying doses)	Salmonella	2.5
Low-pressure cold plasma	Fungi	2
Pulsed argon plasma	*Geobacillus* spp endospores	3
Vacuum steam 65°C	Salmonella	3.6
Tempering with slightly acidic electrolysed water	Enterobacteria	1-2

4.5. Internal grain temperature

To test if the treatment process evenly heated the entire grain (not just the surface), samples of grain processed using the GRAIN EDGE® machine were transferred to thermos container that had been prewarmed to the target temperature, and the evolution of the temperature recorded with a probe. The results show that the grain had reached the target temperature and that the temperature was consistent throughout the bulk and the individual kernels. Unequal heating of the grain kernels would have shown up as a raise or drop in temperature as it equalised throughout in the container over time.

Grain temperature following infrared treatment using the GRAIN EDGE® machine

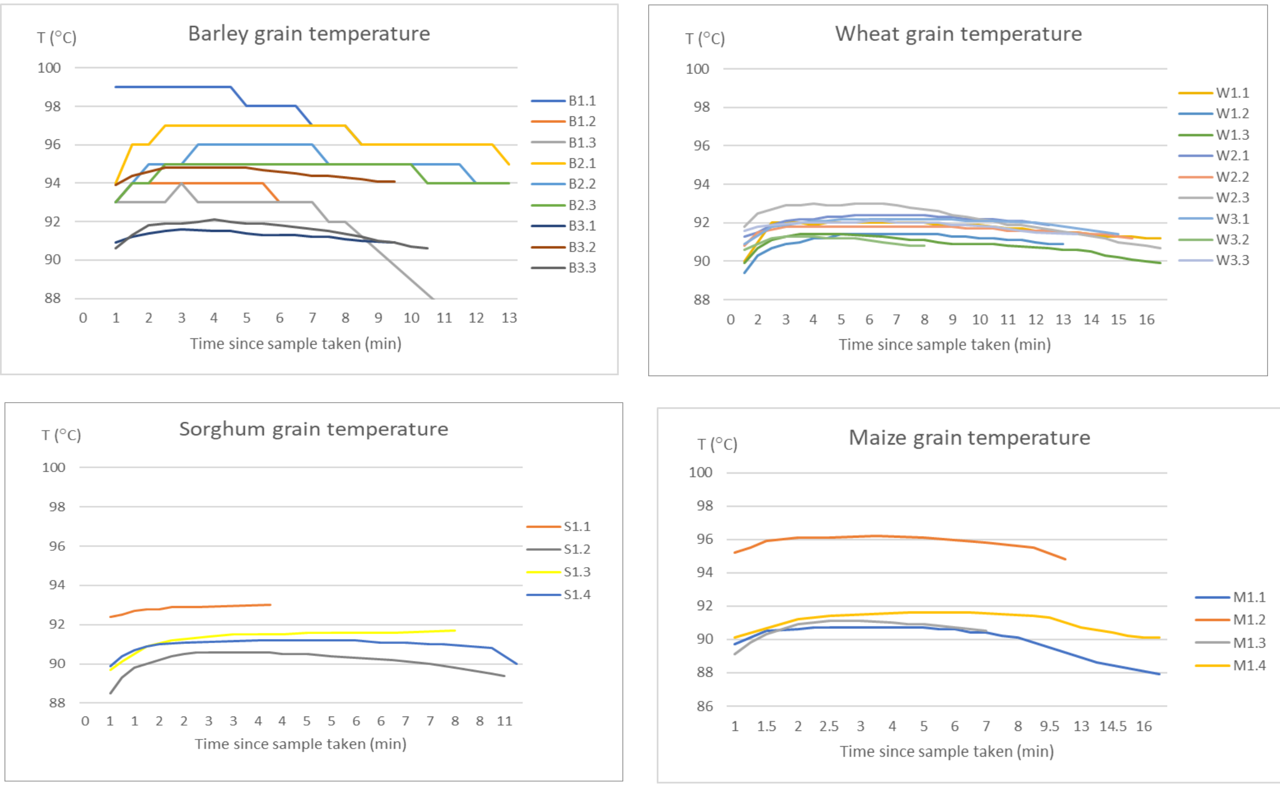


Figure 8. Measurement of grain core temperature. Temperature over time was monitored in a thermos flask as described in the methodology section. Samples were taken in sequence, spread along the run in as indicated by the corresponding Run ID (see section 4.1 for run descriptions).

Samples and their corresponding Run ID

BARLEY		WHEAT		SORGHUM		MAIZE	
B1.1 - B1.3	Bar-1-110821	W1.1 - W1.3	Whe-3-180821	S1.1 - S1.	Sor-7-260821	M1.1 - M1	Mai-9-010921
B2.1 - B2.3	Bar-2-120821	W2.1 - W2.3	Whe-4-190821				
B3.1 - B3.3	Bar-8-270821	W3.1 - W3.3	Whe-5-200821				

Run ID: see master spread sheet for details.

4.6. Energy use

The GRAIN EDGE® machine is designed to heat up a flow-through chamber to a set temperature by varying the number of IR emitters used and the power applied through each emitter. Treatment duration of the material being conveyed through the apparatus is determined by flow-through rate.

In our trials, energy usage per grain volume treated was affected by ambient temperature and wind conditions. Treatment of grain to the specified target specifications can begin during the warm-up phase of the system, which takes approximately 45-60 minutes. After the warm-up period the system runs optimally, with energy use decreasing from about 65 kW to 40 kW per tonne of grain (equivalent to about 75 kW to 46 kW per tonne of grain dry matter).

Trials were conducted at throughput rates between 0.270 and 0.750 tonnes of grain per hour. The highest energy use efficiency was obtained at the higher rates for several grain types, suggesting further scalability of the process.

Grain temperature was constantly monitored. As the examples below show, different types of grain consistently reached grain temperatures between 90°C and 92°C over extended periods (several hours) while running at a constant throughput rate.

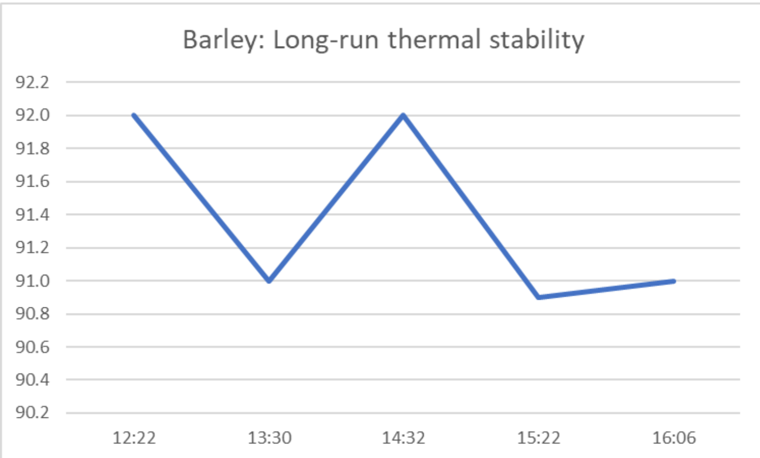


Figure 9. ***Treatment chamber thermal stability experiment: Barley***. Run conducted on 7-Sep-2021 with a throughput of 490 Kg per hour and monitored over a five-hour period (temperature as measured at exit of jacketed auger).

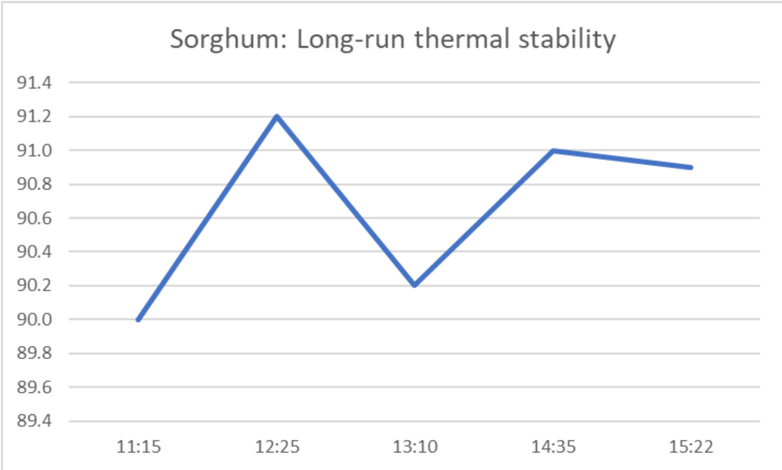


Figure 10. ***Treatment chamber thermal stability experiment: Sorghum.*** Run was conducted on 8-Sep-2021 with a constant throughput of 720 Kg per hour and monitored over a five-hour period. Energy input was 29 kilowatt-hours from two emitters (temperature as measured at exit of jacketed auger).

5. Development of large-scale treatment facility

Based on learnings from trials conducted by the Colere Group for MLA, designed to establish the usefulness of infrared irradiation for grain devitalisation, the consulting team have developed a preliminary guidance on what a large-scale facility for treating grain at a port facility would look like in terms of essential components and functional capabilities.

5.1. Biosecurity containment of treatment unit

For quarantine containment purposes, the design of a grain import treatment unit needs to be based on a one-way flow of grain, whereby the only possible way that grain can pass from the port facility (or input side) to the import (output) side is through the unit and only after having been subjected to the prescribed treatment.

As mentioned previously, installing the entire machine in an enclosed facility would also make a significant difference to the energy utilisation by reducing heat wastage.

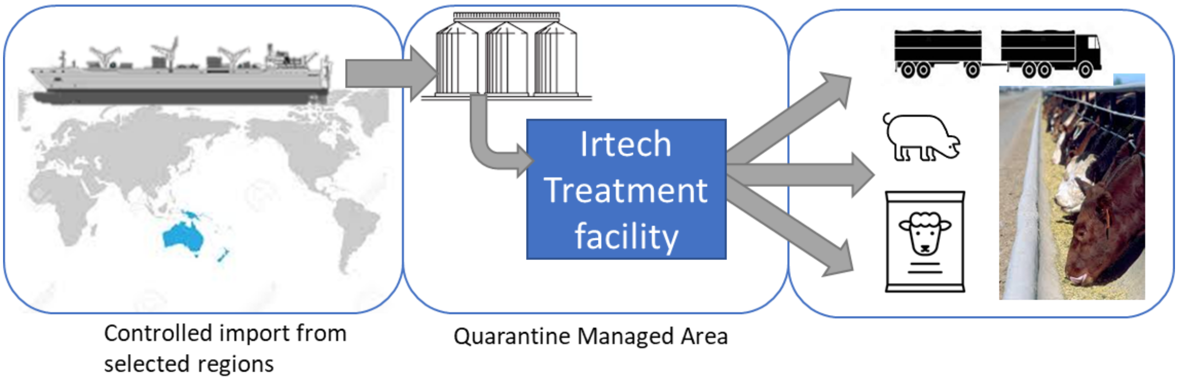


Figure 11. ***Flow of grain importation process***

5.1.1. Design elements

The basic design, as outlined in the diagram below, foresees a clear physical separation of untreated and treated grain for biosecurity containment purposes. Grain is delivered at one end (bottom in the diagram) and enters the facility via a silo for treatment using the GRAIN EDGE® machine. The treated grain then exits the enclosed facility via a conveyor (top in the diagram). This arrangement guarantees that no untreated grain will leave the facility by mistake.

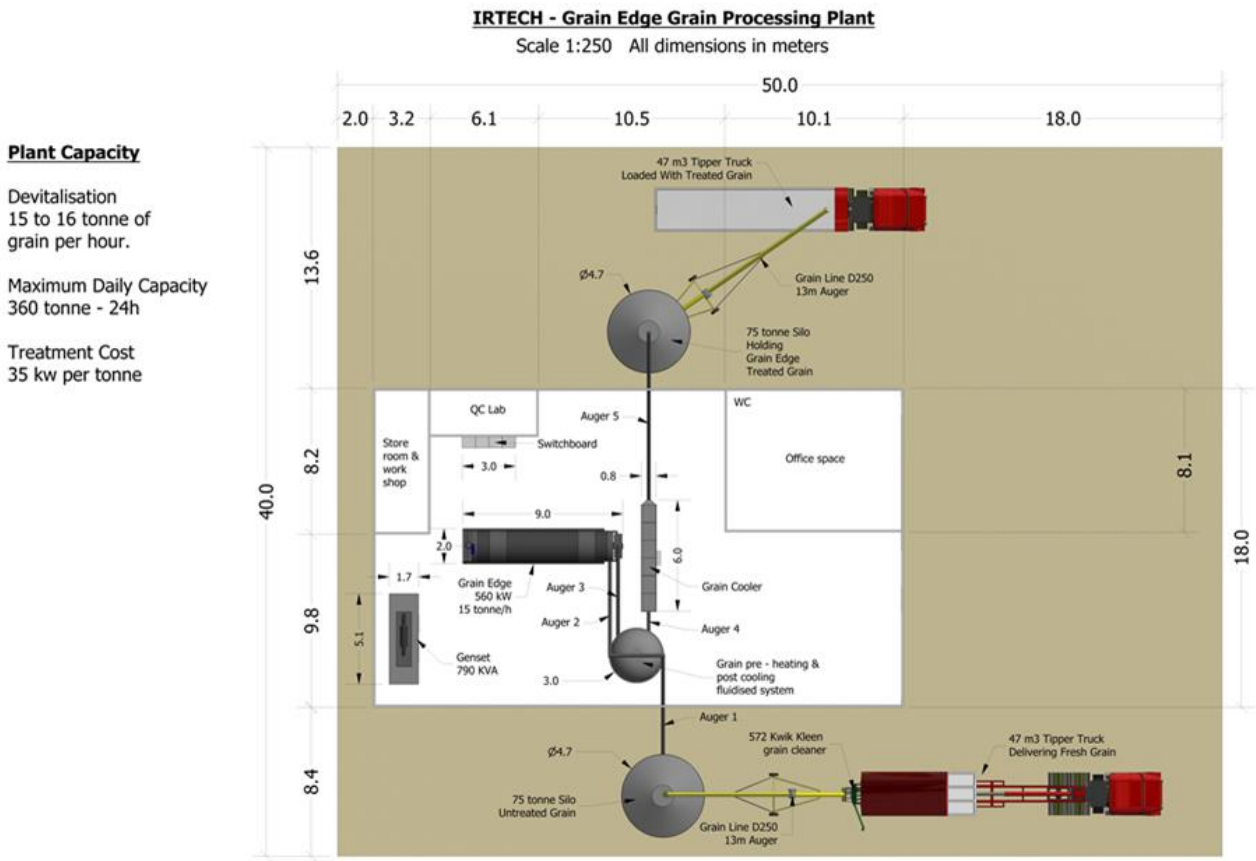


Figure 12. ***Basic design of a GRAIN EDGE® based treatment setup***

5.1.2. System dimensions

Trials were conducted at grain throughput rates between 0.270 and 0.750 tonnes per hour, with the best energy efficiency results obtained at the higher rates. Throughputs in the pilot setup were limited by the volume of grain available for the trials, but at full capacity, throughput could be lifted to over one tonne of grain per hour.

It is estimated that use of waste energy recycling to preheat the grain and maintain system temperature, as discussed above, could result in efficiency gains that would reduce the current 40 kW per tonne of grain (equivalent to about 46 kW per tonne dry matter) by up to 25%. Furthermore, newer emitter technology is suggested (by the manufacturer) to be able to reduce this by a further 10-15%. The throughput of the modelled machines was not limited by the physical capacity, but rather by the ability to practically supply the required power. Therefore, these potential savings in energy would have the capacity to lift through-put by almost one third.

We use here as an example an industrial HIMOINSA generator HTW 790 T5, which can deliver 794 kVA prime power or 635 kW. This generator can deliver around 476 kW continuously (around 333 kW if run continuously for more than 24 hours, which is equivalent to 70 per cent prime power).

The projection is to design a setup that will be able to handle 16 tonnes of grain per hour, allowing to process 384 tonnes per 24-hour day. The setup can be designed according to expected load sizes. Such a setup would require power delivery of up to 640 kWh.

This system has the advantage that the GRAIN EDGE® machine and the generator can easily be transported (e.g., in a container) to be used for various applications elsewhere during downtimes to maximise cost effectiveness.

5.1.3. Estimated setup costs

The cost of one full GRAIN EDGE® unit has an estimated CapEx cost of $1.05m, as detailed below.

		Single unit	2 Units	4 Units
Grain Handling	2 X 80-t silo	$ 21,000	$ 21,000	$ 21,000
	Augers	$ 15,000	$ 15,000	$ 15,000
	Site Works	$ 20,000	$ 20,000	$ 20,000
	Electrical	$ 22,000	$ 22,000	$ 22,000
		$ 78,000	**$ 78,000**	**$ 78,000**
Preheating and Post cooling	2 X 20-t Silo	$ 4,500	$ 4,500	$ 4,500
	Fittings and pumps	$ 15,000	$ 15,000	$ 15,000
	Oil reservoirs	$ 5,500	$ 5,500	$ 5,500
		$ 25,000	**$ 25,000**	**$ 25,000**
GRAIN EDGE® single machine	Unit	$ 750,000	$ 1,500,000	$ 3,000,000
15 t grain/h	Feed system	$ 15,000	$ 30,000	$ 30,000
	Electrical	$ 12,000	$ 12,000	$ 12,000
	Generator (790kVA)	$ 175,000	$ 350,000	$ 700,000
		$ 952,000	**$ 1,892,000**	**$ 3,742,000**
	Total Estimated	**$ 1,055,000**	**$ 1,995,000**	**$ 3,845,000**

Scaling of a GRAIN EDGE® based treatment facility for treatment of large shiploads could see some capital cost savings from shared space and larger silos, for example.

5.1.4. Estimated running costs

At a fuel consumption rate of about 125 litres per hour for a 490-kW output (70 per cent prime power for long-term average continuous use), a generator of this size would allow to treat up to 12 tonnes of grain per hour. Based on an energy-use efficiency of 40 kW per tonne of grain, the cost of fuel would lie around $14 per tonne of grain treated (Qld diesel terminal gate price on 7 December 2021), equivalent to about $16 per tonne of dry matter treated.

5.1.5. Improving energy efficiency

Grain exiting the ***irtech*** treatment unit will still be at 90˚C, both too high for storage and representing a large amount of potentially wasted energy leaving the system (ideally, grain needs to be delivered for transport at ambient or lower temperature). By using a heat transfer approach, waste heat can be used to preheat grain before the ***irtech*** treatment unit, dramatically reducing the energy required for the IR emitters to reach the target temperature. In addition, the exhaust heat from the generator could also be brought into such system.

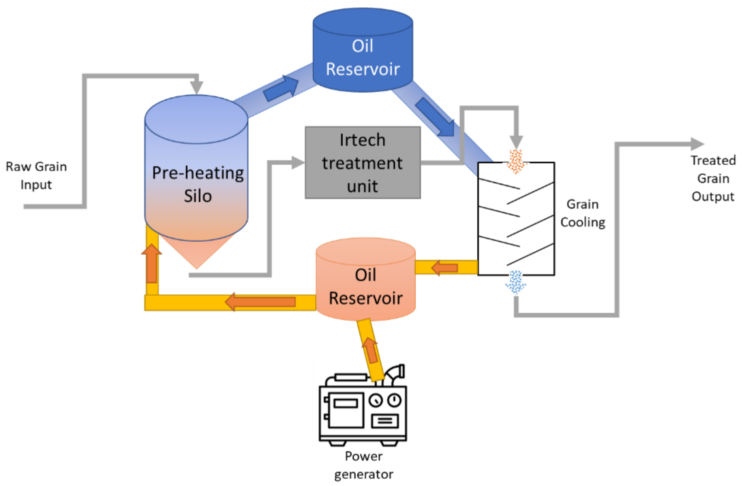


Figure 13. ***Preheating and post-treatment cooling of grain can utilise existing energy***

Engineering estimates have suggested that a combination of enclosing the entire operation and utilising this waste heat could provide cost savings of over 20 per cent per volume of grain treated in a purpose-built large-scale facility.

As part of this project, the consulting team have used the knowledge gained from the trials to provide preliminary guidance on what a large-scale facility –capable of treating grain at a port facility would look like in terms of essential components and functional capabilities.

6. Conclusions

6.1. Key findings

***irtech* Concept**

- The treatment process based on infrared irradiation of grain using ***irtech***'s GRAIN EDGE® technology in a non-stop, conveyor and auger-driven single-pass process was capable of heating grain of several species and moisture content to 90°C and hold that temperature for more than 60 seconds, thus potentially fulfilling Biosecurity Australia quarantine regulations for imported grain.
- The pilot machine required manual management to ensure the temperature and retention time were maintained (particularly in periods of inclement weather). In each treatment period the stability of the temperatures increased over time (as the thermal mass of the machine helped hold the energy). Setting the target temperature at slightly higher than 90˚C was enough to ensure that despite slight variations due to ambient conditions (wind gusts etc) the grain temperature at all three measurement sites did not drop below 90˚C.
- Transfer rates were variable, as explained above (ranged from 270 to 750 kg/hr). Given transfer rates in a commercial operation will likely be constant (up to 15 t/hr), further research to confirm devitalisation efficacy will be required once a commercial unit is manufactured.
- The original, internally mounted thermocouples (wired into the PLCs controlling the emitters) were not suited to the fine-tuning of the temperature at beginning of each session as their over sensitivity did not help stabilise the system to the required temperature/time retention requirements. When the pilot machine had been operating for several hours and the thermal mass had helped stabilise the system, the automated temperature control was useful. This suggests that full automation of the process is possible, as long as the machine is in an insulated room/container and a start-up protocol is used to stabilise the system first.
- **In summary, the *irtech* pilot GRAIN EDGE® machine demonstrated the ability to devitalise and sterilise grain when moisture levels were greater than 10% or in oilseed, as oil also has high heat transfer capacity. Further research is required with low moisture grain given the partial germination of wheat observed in this pilot. The trials have provided invaluable knowledge towards the establishment of a viable, cost-effective process for safe importation of grain in the future.**

Grain Quality

- Initial tests on the relevant grain quality measures using NIR for all relevant animal nutrition purposes suggest that **the *irtech* treatment did not adversely affect the quality of the grain**.
- An average of one percent moisture loss caused by the treatment was seen across all grain types. Raising moisture by 2% before treatment resulted in grain having the desired moisture content after the treatment, which might be of interest to potential users.

Energy Consumption and Efficiency

- A setup like the one used for the pilot GRAIN EDGE® machine at Talgai has a nominal fuel consumption rate of about 125 litres per hour for a 490-kW output (70 per cent prime power for long-term average continuous use). A generator of this size would allow to treat up to 12 tonnes of grain per hour. Based on an energy-use efficiency of 40 kW per tonne, the cost of fuel would lie around $14 per tonne of grain treated (Qld diesel terminal gate price on 7 December 2021), equivalent to about $16 per tonne of dry matter treated.

- Given that the most significant factors in our trials in relation to energy usage per volume of grain were ambient temperature and wind conditions, any future designs of this treatment concept should be based on the machines being housed within an enclosed and insulated facility or shipping container. Knowing the significant differences between running cost of a warm machine in warm ambient conditions and those on a cold windy day, simply enclosing the machine would likely bring the energy use down to around 30 kW per tonne grain or about 35 kW per tonne grain dry matter.

- The grain exited the process at 90°C, and (while it differed slightly between grain types) this temperature was still often above 60°C 8-10 hours later. This demonstrates the potential amount of heat energy that could be recovered and fed back into the system to reduce costs. This is being considered in new designs that would use this energy to preheat the grain in the feed silo via heat transfer. Waste heat could be also captured from the generator, which might reduce the overall energy cost further by up to 20 percent.

7. Future research and recommendations

Potential new research

As outlined in section 6, regarding the development of large-scale treatment facilities using the GRAIN EDGE® technology, there are potential efficiency gains to be made from using waste heat captured from the treated grain to preheat untreated grain and the machinery to reduce energy consumption. Cooling of the treated grain is necessary for transportation, and thus capturing this energy via oil-based heat exchangers will deal with both grain preheating before IR irradiation and cooling of the treated grain, making the running of the system more cost effective. This will require additional engineering studies and design. Given that the GRAIN EDGE® technology is likely to be broadly adopted in feedlots as a scaled replacement for steam flaking, this investigation would have strong benefits for energy use efficiency across the sector.

The basic trials undertaken in this work were designed to provide a solid proof of concept and the underlying scientific data required to progress a potential importation process. The output format of the grain was not explored in any depth, however there are indications that a treatment facility could also be used to modify grain (in terms of digestibility and suitability to add directly to a ration). There are potential cost savings to be made when combining an importation treatment with a process equivalent to steam flaking into a one-pass operation.

As demonstrated in this research project incomplete devitalisation in low-moisture grain (≤10%) can be potentially mitigated by water addition via the tempering process prior to treatment. Further, research across all grain types with low moisture is required.

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9. Appendix

9.1. Grain quality testing

Seed quality testing of grain following GRAIN EDGE® treatment trials.

*Table 4. **Feed quality and proximate parameters before and after GRAIN EDGE(R) treatment***

		On-site NIRS			Symbio AusScan results								
Grain type	**Source**	**Moisture Content (%)**	**Protein (%)**	**CF031_1-Starch (%w/w)**	**Moisture (%)**	**Cattle Estimated ME (DM) (MJ/kg)**	**Cattle Estimated DOMD (%)**	**Cattle Estimated DMD (%)**	**Ash (as is) (%)**	**Fat (Acid Hydrol.) (as is) (%)**	**Fibre (as is) (%)**	**Protein (as is) (%)**	**Starch (as is) (%)**
Barley – U	Dalby	10.4	14.8	45.9	10.3	12.5	79.6	80.6	1.9	2.4	4.5	12.4	50.2
Barley – T	Dalby	8.0	15.0	46.5	8.9	12.8	81.8	82.9	1.9	2.8	3.6	12.8	53.8
Wheat – U	Dalby	10.0.	13.3	51.7	10.2	13.2	84.4	85.7	1.4	1.9	1.2	15.0	60.1
Wheat – T	Dalby	9.1	13.6	52.2	9.3	13.3	85.2	86.4	1.5	2.1	1.3	15.6	59.7
Sorghum – U	Dalby	11.6	10.7	55.8	11.0	12.2	81.3	82.4	1.1	3.7	1.7	10.2	63.6
Sorghum – T	Dalby	9.6	10.7	56.9	9.8	12.3	83.4	84.6	1.2	3.9	1.7	9.9	64.6
Maize – U	Allora	14.2	12.3	51.8	12.5								
Maize - T	Allora	12.3	12.1	58.7	11.3								

U, untreated; T, treated

- Quick analyses for moisture, protein and starch content were conducted on site using a FOSS NIR Grain Analyzer.
- NIR feed energy and content analyses were performed by Symbio using AusScan calibrations.
- Germination tests were conducted by Futari Grain Technology Services, Narrabri NSW.

9.2. Step-by-step import requirements (DAWE pre-application guideline)

- Every permit application is considered on a case-by-case basis and is subject to a risk assessment to allow specific consideration of the biosecurity risks posed by the proposed import pathway.
- The department can refuse to allow shipments to be discharged, require corrective actions to be taken or greater departmental supervision of the shipment along the import pathway.
- A department-approved and audited Process Management System (PMS) must be put in place outlining the processes for sourcing, movement and loading offshore and movement, storage and processing within Australia.
- Grain must be sourced from areas of low plant and animal risk, in particular free from pathogens and pests of biosecurity concern to Australia.
- The export pathway from the farm to the point of loading must be approved by the department to ensure the grain has been sourced from and transported within the designated areas.
- Storage and transport units used along the export pathway must be thoroughly cleaned prior to use to prevent contamination with imported and/or local whole grain, stock feed or stock feed ingredients, insect pests, and other infestable residues, soil, animal or avian remains, faeces or any other extraneous contamination.
- Assurance of cleanliness is provided through third party inspection certification or recognition of industry quality management systems that manage contamination risks.
- Grain must be graded and certified by the exporting country's quality standards body at the point of export to ensure minimal levels of foreign material within the consignment such as weed seeds, soil, animal material.
- On arrival in Australia, grain must be transported in clean conveyances and conveyances must be sufficiently secure to control the leakage of grain or dust during transport from the point of discharge through to the point of processing. For example, approved sealed containers or roll-over tarp trucks.
- Grain must be transported along approved routes that have been assessed by the department and tracked from the point of arrival to final release from biosecurity control. All grain movements must be reported to the department and grain weight reconciliations undertaken.
- Imported grain must be stored and processed while subject to biosecurity control in a facility covered by an approved arrangement (approved arrangement site). Storage and processing of imported grain must also be managed in accordance with the approved arrangement, including to contain spills and manage associated biosecurity concerns.
- A department-approved Site Operations Manual must be in place for the approved arrangement site outlining the processes for managing the grain within the confines of the approved arrangement site. Approval of the site is only given if department requirements are met at desk and site audit.
- The assessment of the approved arrangement site and the transport route considers a range of factors relevant to the management of biosecurity risk including proximity to agricultural production, potential hosts (animal and plant) and transport routes (especially passage through agricultural areas).
- Processing and treatment of imported grain must be undertaken with specific time and temperature requirements to further reduce the biosecurity risks before release from biosecurity control.

- Associated waste must be disposed of according to departmental requirements and in accordance with an approved arrangement, such as deep burial, high temperature incineration or autoclave.
- The importer must have emergency action plans in place to manage spillage or any other possible incidents on the import pathway.
- Verification inspections to assess biosecurity risk will be undertaken by a biosecurity officer during discharge at each port; on completion of discharge at each port; during receival and outloading from each approved arrangement site and following decontamination at each approved arrangement site.
- When the import process has been completed, the storage and processing facilities must undertake comprehensive department-approved decommissioning processes prior to re-commencing normal operations.

9.3. Standards and documents for biosecurity treatments

The DA provides standards outlining best-practice methodologies for applying biosecurity treatments (heat, methyl bromide, sulphuryl fluoride). Below is an example of a form to be filled out to generate a heat treatment certificate:

Heat treatment methodology, August, 2019, version 2.8

Appendix 2: Example heat treatment certificate

COMPANY LETTERHEAD

(including address as it appears on the Australian Department of Agriculture's approved list of Brown Marmorated Stink Bug treatment providers.

BROWN MARMORATED STINK BUG HEAT TREATMENT CERTIFICATE

Certificate number: ☐ **Registration Number:** ☐

CONSIGNMENT DETAILS

Target of treatment: ☐ Commodity ☐ Non-commodity ☐ Both

Target description: .... Quantity: ....

Consignment link: ....

Country of origin: .... Port of loading: .... Country of destination: ....

Name and address of exporter:	Name and address of importer:
....	....
....	....
....	....

TREATMENT DETAILS

Date heat treatment completed: ...... /......./ .... Time heat treatment completed: ....

Location of heat treatment .... Exposure period (☐ minutes or ☐ hours): ....

Required temperature (☐ °C or ☐ °F): .... Minimum temperature achieved (☐ °C or ☐ °F): ....

Humidity Rate (☐ % or ☐ not applicable) .... Minimum humidity Rate (☐ % or ☐ not applicable) ....

Heat treatment method: ☐ Forced dry air ☐ Kiln drying ☐ Humidity controlled forced air / Variable humidity

Enclosure type ☐ Chamber ☐ Container ☐ Sheeted

DECLARATION

By signing below, I, the accredited treatment provider responsible, declare that these details are true and correct and the treatment has been carried out in accordance with the Heat Treatment Methodology.

ADDITIONAL DECLARATIONS

....

....

....

.... Signature .... Date

.... Name of Accredited Treatment Provider .... Accreditation Number

Company stamp