FINAL REPORT:

Technology Mapping for the Australian Jackfruit Industry

A Final Report from the Food Agility project:
Agriculture Production System Technology Mapping

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Technology mapping for the Australian jackfruit industry

EXECUTIVE SUMMARY

The Australian jackfruit industry is characterised by poorly developed value chains which rely on limited information about consumer demand. The industry's technological needs are similar to those of several more developed industries, but specific constraints and the limited size of the industry combine to leave gaps in technology. The goal of this study is to map the jackfruit value chain onto available technologies and identify the value proposition of change for the industry. A series of consultations were held with industry stakeholders, substantial literature concerning technologies was reviewed, and a scenario-based examination of financial implications of technology for the value chain, and particularly for producers, was conducted. Specific technologies are assessed for readiness for uptake, and for their apparent impact on producers. Conclusions are drawn about selected technologies and their likely contribution, their readiness and the combinations in which they may be adopted, and the organisational arrangements which might accompany their adoption. The study identifies facilitating factors in delivery of enhanced adoption of desirable technologies, and priorities for research into new technologies and the supporting knowledge base. Key findings are:

1. Opportunities offered by product diversification extend along the value chain. A new fresh product, along with immature fruit as a cooking ingredient, offer new producer income opportunities as well as a mechanism for exploiting the distribution of fruit sizes at the orchard level. Technologies such as maturity measurement facilitate those benefits.
2. Across a variety of industry development scenarios, labour costs remain surprisingly high. This reflects the current study's reliance on time-in-motion labour specifications, and these need to be investigated in empirical work.
3. Other aspects of cost studies identify tradeoffs between orchard density and various measures of performance are apparent, and important as orchard design is under active research. The parameters and dynamic adjustments used in this study's Excel-based analyses can only be improved upon by field trials, and the results of these are eagerly anticipated.
4. Identified benefits from technologies tend to be magnified by increased yield. As most technologies studied would facilitate yield-enhancing management, such as the introduction of new varieties, this remains an informative fining. Similarly, elimination of waste at farm or retail level is a considetnt generator of further benefits from new technologies.
5. A hypothetical fresh arals value chain was characterised which offers producers an indicative price about double the baseline price received for all fruit. This value chain requires an entirely new processing function fuelled by technology but facilitated by the development of appropriate delivery conditions, logistics to serve distant markets, and marketing organisation for delivery.
6. The study projects benefits from the supply of a fresh green product – heretofore not harvested – as a vegetable for use in cooking. This product requires no processing, but as for packaged arals it does need a co-ordinating business model.
7. Specific technologies were identified and assessed for Technology Readiness. Supported by the literature review and stakeholder commentary, lack of readiness is targeted by a proposed research agenda.
8. Aside from technology, priority organisational tasks identified include the development of product and quality descriptions, scheduling of product to market or into processing, and establishing pricing and payment systems which promote quality and supply chain performance in delivering it. Support for an arals processing business model is also a priority, based on analysis of available benefits.

9. Roles for enhanced information flow and its accelerated contribution to data-related technologies, are identified.

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1 INTRODUCTION

1.1 Background

Areas planted in Jackfruit remain small and concentrated in two geographic areas of Australia, and often appear on the farm as small, peripheral, areas adjacent to other orchard trees. Current industry developments include expanded planted areas, enthusiasm for value addition possibilities as part of economic expansion in Northern Australia, and interest in advanced processing and food uses of jackfruit product fractions and extracts.

Well established foreign jackfruit industries are both a guide to successful production, and a cautionary note on development and exploitation of the jackfruit value chain. In Australia, an active current research agenda is addressing issues identified at several points in the value chain spanning seedstock and production through to consumer acceptance and marketing. Production issues include seedling-based plantings, few on-label chemical options, tree architecture and threats from weather events. Marketing tasks encounter small volumes, specific logistics of the fruit and tree and orchard structure, distant markets served by road transport, timing in the supply chain in relation to the climacteric nature of the fruit, and an under-examined processing challenge for fresh products, preserved ingredient markets, and extracted fractions and by-products.

An Australian case study on jackfruit development referring to tropical fruit more generally (Best, 2015) identified industry drivers and constraints. Drivers are grouped around consumer- and demand-oriented change; co-ordination of supply with demand including standardisation; and information assembly and transfer. Constraints, in addition to the converse as prevailing conditions, include competition from imports, and lack of processing. That study identifies key value addition avenues as shelf life extension for fresh products, investment in processing capacity and new or adapted technologies. Further, supporting structures are advocated such as capacity building for the implementation and governance of new business models.

Table 1. A past study's identified drivers and constraints for industry growth in tropical fruits, with jackfruit used as a case study (Best, 2015)

Drivers for industry growth	Constraints on industry growth
1. growth in Australian market demand for jackfruit 2. consumer and retail education to promote jackfruit 3. industry partnerships to promote and supply value-added production of jackfruit in the short term 4. knowledge of production and demand factors affecting market-pricing trends 5. increased yields of jackfruit as trees mature, and through improving the industry in Australia 6. development of quality standards to ensure consistency of Australian jackfruit and building capacity for value-added products 7. development of recipes and information on preserved and value-added jackfruit products 8. development of technical and research resources for industry 9. efficient communications and management of whole-of-industry issues.	1. variable understanding of strategic value-added markets for individual jackfruit components 2. lack of consumer and market education about Australian jackfruit 3. different types and attributes of Australian jackfruit 4. lack of quality assurance and training for industry 5. lack of access to technical and research resources 6. competition from and/or substitution by exotic fruits from other countries 7. limited further processing facilities for Australian jackfruit especially commons/seconds 8. lack of a sustainable business model to engage growers to invest in value adding for the industry

Strengths such as a small but well-established professional base in production, extension and product delivery all offer a strong basis for development of the industry. Strong links and networking (Howells, 2004), even where they are maintained between small numbers of value chain actors, offer value addition possibilities. Recurrent calls for information exchange, introduction of processing technologies, and cost-driven automation, are seen as being facilitated in future by this network (Howells, 2004).

1.2 Purpose of the study

The current study addresses the Australian jackfruit industry's technological constraints and opportunities. It maps the current situation in the jackfruit value chain to actual and potential technologically-based improvements associated with tasks conducted by the value chain's actors. Technologies are selected for further analysis, and the associated state of knowledge is presented from literature review. Specific technologies are assessed for readiness for uptake, and for their apparent impact on producers.

Conclusions are drawn about selected technologies and their likely contribution, their readiness and the combinations in which they may be adopted, and the organisational arrangements which might accompany their adoption. The study identifies facilitating factors in delivery of enhanced adoption of desirable technologies, and priorities for research into new technologies and the supporting knowledge base.

1.3 Methods

The study entails a set of industry consultations with key stakeholders to identify the current value chain environment, and associated problems and opportunities. Its focus is on the tasks required to add value to jackfruit. A detailed literature review is used to identify current and likely future technologies. Emphasis is given to task sets in the value chain which are not receiving intensive research attention: for this reason the current work on plant breeding and orchard design is not reviewed in detail, but its central aspects are identified for analysis. The components are mapped together to designate particular technologies for further analysis. An assessment of technology readiness is conducted for the technologies designated for further analysis.

A financial model of the jackfruit value chain is presented. Its parameters and construction remain hypothetical in the sense that no such complete value chain yet operates. It is driven strongly by assumptions about technical parameters that remain the subject of active research. It employs yet more assumptions in projecting the impacts of technology, the components of which also are the subject of ongoing research.

Organisational aspects of the jackfruit industry are identified and discussed, and in some cases included in the analysis. Conclusions are drawn about desirability of the technologies, changes needed to facilitate adoption, and future research.

1.4 Outline of study

This report has seven sections. Section 2 addresses jackfruit production and technologies. As noted above, the intensively-researched production-oriented tasks receive less attention in the review than other value addition tasks. Section 3 sketches the stages and value-adding tasks of the jackfruit value chain and section 4 maps these items together. Section 5 presents the gross margins calculated along the value chain as a base case, and discusses the analysis of scenarios associated with technological changes. The results are presented in Section 6. Section 7 synthesises the study and draws conclusions about technology priorities and future research.

2 Production and technologies

2.1 Genetics

A large number of varieties of jackfruit are reported from the World's producing regions (Ranasinghe, Maduwanthi, & Marapana, 2019), and variation is observed in colour, size, maturity characteristics and ripening behaviour, as well as storability and robustness in the supply chain (Elevitch & Manner, 2006). Varieties are generally subdivided into the "firm" and "soft" fleshed varieties (M. A. Rahman, Nahar, Mian, & Mosihuzzaman, 1999), with some agreement that the firm varieties are more desired by consumers of fresh products, while not being as sweet in flavour as the soft varieties (Shyamalamma, Chandra, Hegde, & Naryanswamy, 2008). However, a somewhat contradictory demarcation has also been made that the firm and soft varieties target use categories such as cooking (hard) and fresh products (soft) (Rana, Pradhan, & Mishra, 2018).

2.2 Planting material

A large proportion of productive jackfruit trees are thought to be large and of awkward architecture for both husbandry and harvest. Reports suggest a partial windbreak function for trees with associated hedging-type pruning. An unknown mix of varieties is said to be present on most farms. Trials of new cultivars, and new tree spacings and configurations including trellis arrangements, are in progress.

2.3 Orchard layout

Research on orchard design is on-going, featuring dense layouts and various forms of trellising. An analysis of trellising of tropical fruit trees has been presented, focused on avoiding tree damage from cyclones in tropical Queensland (Drinnan, 2018). Density of trees, with associated change in size of trees and fruit per tree, offer significant changes in cost structures and husbandry actions.

2.4 Plant health

Various fruit rots affect jackfruit harvest, fruit quality and survivability during postharvest and transport, and tree health. A summary of the various pathogens, and their symptoms and impacts, is presented by (Borines et al., 2014). Those authors focus on *Phytophthora* species, in particular its identification as the causal pathogen for a regional disease outbreak in jackfruit in the Philippines.

Harvest timing confronts problems associated with fruit maturity (see below), while conditions during the season contribute to development of rots, and the predisposing conditions for that development. This management problem is exacerbated by a reported general lack of chemicals registered for use on jackfruit.

2.5 Harvest

It is widely acknowledged that jackfruit harvest management in Australia is constrained by lack of a workable fruit maturity index and equipment and protocols to gauge maturity and schedule harvest. Overseas, this is just one cause of low harvest utilisation: up to 30% of fruit are discarded along the supply chain in India (Swami, Thakor, Orpe, & Kalse, 2014).

Profiling of jackfruit alongside other tropical fruits reveals its unique pattern of non-volatile metabolites (Khakimov et al., 2016). Ripening of jackfruit is associated with substantial change in starch and dietary fibre content, and an array of other components (R. Kushwaha et al., 2021; M. A. Rahman et al., 1999). Management effects on ripening have been widely studied, including the influence of pollination techniques (Mijin, Ding, Saari, & Ramlee, 2021). Ripening's chemical processes vary between varieties (R. Kushwaha et al., 2021), between firm and soft use-designated varieties (Rana et al., 2018), as well as between examples of fruit of differing texture within a variety (A. Rahman, Huq, Mian, & Chesson, 1995; M. A. Rahman et al., 1999).

2.6 Fruit maturity

Studies of jackfruit ripening reveal a trajectory of several readily observable (e.g. colour, firmness, skin texture) fruit features, in addition to those detectable with equipment (Mijin et al., 2021). However these features are reported to vary considerably across varieties, and between fruit on a tree. The variety inherent in planted material is likely to be a contributor to this uncertainty.

2.7 Nutritional value

The nutritional content of jackfruit has been well established, and published both for the whole fruit (Ranasinghe et al., 2019; Swami, Thakor, Haldankar, & Kalse, 2012), for fresh products such as freshly extracted arals (Anaya-Esparza et al., 2018), and for processed products (Mondal et al., 2013). A recent Australian study provides similar results, emphasising differences between fresh ripe and unripe (green) fruit, processed products, and related tropical fruits (Norris et al., 2021).

Elements of jackfruit have been favourably evaluated in functional food roles such as weight loss (Sabidi, Koh, Abd Shukor, Adzni Sharifudin, & Sew, 2020), antioxidant function and alcohol-related liver health (Li et al., 2021), liver function (Zeng et al., 2022), and various anti-inflammatory roles (Srinivasan & Kumaravel, 2016). A review paper by Swami provides a summary of epidemiological studies on jackfruit's functional foods performance up to 2004 (Swami et al., 2012). Jackfruit processing by-products have been favourably evaluated as fish feed (Sulaiman, Yusoff, Kamarudin, Amin, & Kawata, 2022).

Table 1–Composition of jackfruit (100 g edible portion).

Sr. No	Composition	Young fruit	Ripe fruit	Seed
A	Proximate analysis			
1	Water (g)	76.2 to 85.2	72.0 to 94.0	51.0 to 64.5
2	Protein (g)	2.0 to 2.6	1.2 to 1.9	6.6 to 7.04
3	Fat (g)	0.1 to 0.6	0.1 to 0.4	0.40 to 0.43
4	Carbohydrate (g)	9.4 to 11.5	16.0 to 25.4	25.8 to 38.4
5	Fibre (g)	2.6 to 3.6	1.0 to 1.5	1.0 to 1.5
6	Total sugars (g)	–	20.6	–
B	Minerals and vitamins			
1	Total minerals (g)	0.9	0.87 to 0.9	0.9 to 1.2
2	Calcium (mg)	30.0 to 73.2	20.0 to 37.0	50.0
3	Magnesium (mg)		27.0	54.0
4	Phosphorus (mg)	20.0 to 57.2	38.0 to 41.0	38.0 to 97.0
5	Potassium (mg)	287 to 323	191 to 407	246
6	Sodium (mg)	3.0 to 35.0	2.0 to 41.0	63.2
7	Iron (mg)	0.4 to 1.9	0.5 to 1.1	1.5
8	Vitamin A (IU)	30	175 to 540	10 to 17
9	Thiamine (mg)	0.05 to 0.15	0.03 to 0.09	0.25
10	Riboflavin (mg)	0.05 to 0.2	0.05 to 0.4	0.11 to 0.3
11	Vitamin C (mg)	12.0 to 14.0	7.0 to 10.0	11.0

Source: Arkroyd and others (1966), Narasimham (1990), Gunasena and others (1996), Azad (2000).

Table 2–Epidemiological studies on antioxidants in human from jackfruit.

Sr. No	Diseases	Antioxidants
1	Gastric cancer	Vit E, β-carotene, selenium
2	Lung cancer in smokers	Vit E, β-carotene and both together
3	Prostate cancer	Vit E
4	Lung cancer in workers exposed to asbestos	β-Carotene + vit A
5	Myocardial infarction	Vit E
6	Coronary heart disease	β-caroten
7	Hypertension	Vit C

Source: Devasagayam and others (2004).

Figure 1. Extract from review paper on jackfruit content and functional foods research (Swami et al., 2012)

2.8 Value in non-food uses

Based on its rich and unique chemical makeup, jackfruit and its extracted fractions have been implicated in a variety of non-food uses in pharmaceuticals and cosmetics, usually associated with binding roles (Cruz-Casillas, García-Cayuela, & Rodriguez-Martinez, 2021).

Studies on specific uses include meat tenderisation (Ramli, Badrulzaman, Hamid, & Bhuyar, 2021), high quality pectin production (Reis et al., 2016), environmental cleansing, such as removal of chromium from contaminated sites (Saranya, Ajmani, Sivasubramanian, & Selvaraju, 2018), and production of bioplastics (Rajasekharan et al., 2022) and biodegradable colloids usable in food packaging (Santhosh & Sarkar, 2022). Jackfruit peel has been used as an example of a source of a high value polysaccharide product (pectin) from processing waste in a municipal waste management context (Govindaraj, Rajan, Hatamleh, & Munusamy, 2018). Uses for leaves and wood from the tree, and latex from the fruit, have been described (Best, 2015).

Cruz-Cassilas et al. (Cruz-Casillas et al., 2021) remark that although all jackfruit's components yield significant amounts of valuable fractions as "functional ingredients", the amount and quality of extracts depend on the extraction technology employed. They define and compare "conventional" (generally physical), "non-conventional", and blended extraction methods.

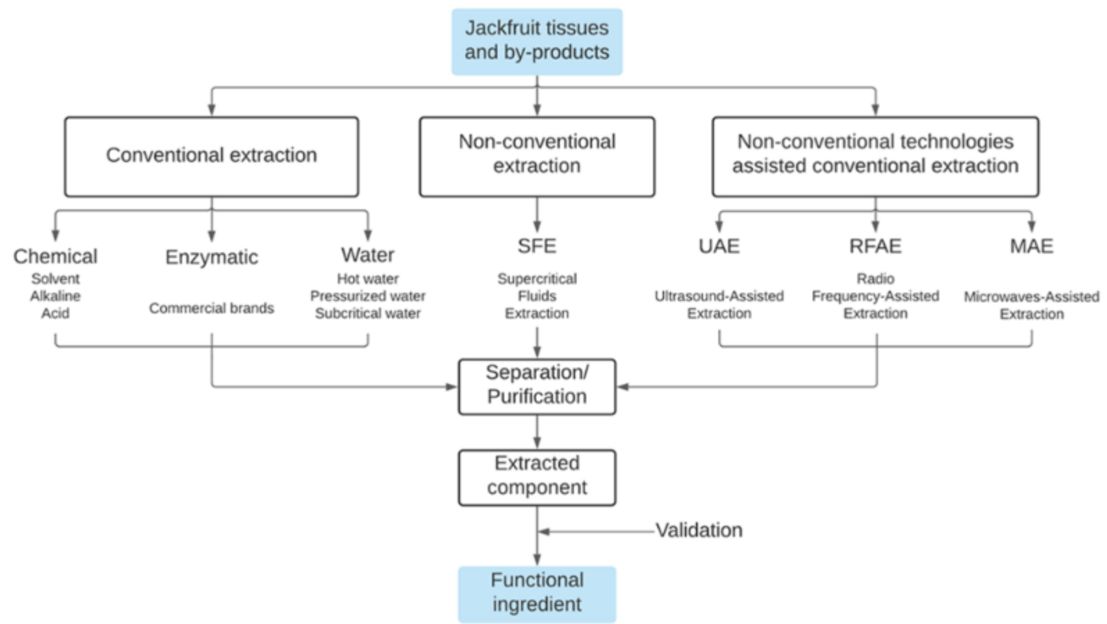

Figure 2. Conventional and non-conventional extraction methods and conventional extraction assisted by non-conventional technologies for functional ingredients from jackfruit tissues and by-products.

Figure 2. Technology generations for extraction of jackfruit fractions (Cruz-Casillas et al., 2021)

3 ASPECTS OF THE JACKFRUIT VALUE CHAIN

3.1 Consumer demand

Preliminary work on characterisation of consumer demand has been reported by various authors (Diczbalis, 2019; Howells, 2004; Norris et al., 2021). This work has had multiple foci, including the emerging industry-related issue of perceptions of consumers unfamiliar with the fruit. Although characterisation of an ideal or most desirable product would remain an objective, the more important medium term goal identified by Howells (Howells, 2004) is the development of specifications and product descriptions which both reflect quality criteria and satisfy supply chain goals of consistency and on-time delivery.

3.2 Studies on development of an Australian jackfruit industry business model

Similar to the later work by Best (Best, 2015) cited above, Howells (Howells, 2004) consulted growers, packers, freight handlers, wholesalers, retailers, food manufacturers and food service providers about possibilities for adding value along Australian tropical fruits' supply chains. The study emphasises the universal whole-of-chain requirement for on-time delivery and consistency of supply, while identifying a lack of industry critical mass and unco-ordinated marketing.

As noted above, strong foundations for value addition were cited as the networks within the industry and more importantly across related products and service providers. Howells' work draws particular attention to the role played by these networks (usually involving just a few vertically-aligned actors) in the transfer of information. However, notwithstanding these strengths value chain stakeholders refer to constraints for tropical fruit imposed by limited information transfer, low penetration [at that time] of e-commerce, and a lack of strong and enduring sales agreements along the chain. Industry collective action in terms of organisational and marketing efficiency have not been widely addressed for jackfruit, nor other emerging or small acreage crops The Australian Lychee Growers' Association[1] and the Australian Ginger Association[2] provide two examples.

3.3 Harvest timing and locality

Australian investigation of varieties' matching fruit maturity to local seasonal conditions is reported to be at an early stage. Seasonal progressions across production locations (e.g. within and between the Northern Territory and Queensland) are well known for some tropical fruits (mango and pineapple) but much less so for jackfruit and certain other low-acreage crops at similar stages of industrial development. Along with an unknown profile of the existing set of varieties and their plantings, this makes difficult an organised approach to marketing of the small volumes of fruit. As noted above, characterisation of existing and available varieties is the subject of ongoing research.

Jackfruit can be harvested at both mature and immature (green) stages (Anaya-Esparza et al., 2018), and markets for both mature and immature fruit is examined by Norris et al. (Norris et al., 2021). The immature product finds uses in cooking and pickling, and attracts marketing attention as a meat substitute. Most Australian studies of jackfruit marketing address the fruit's needs for packaging, handling and climate control, as well the climacteric nature of the fruit (Diczbalis, 2019; Horsburgh & Noller, 2005). The location of Australian jackfruit production means that long distance transport remains the norm.[3]

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[1] https://www.australianlychee.com.au/

[2] https://www.australianginger.org.au/

[3] Delivery of fresh cut fruits, including jackfruit, from tropical environments into Europe has been the subject of a major conference, from which only limited abstract material is available (Nicola, Toivonen, & Watkins, 2018).

3.4 Jackfruit quality

Across most consumer products, jackfruit quality indicators include colour, texture and apparent moisture content, as well as bacterial and fungal growth. Consumer acceptance generally refers to these variables, with particular emphasis on avoiding browning and rots, and dryness. Loss of quality has been quantified according to these domains (Mondal et al., 2013), and substantial literature from South Asia is available regarding the available technologies and protocols for maximising quality along the supply chain. Maturity stage, and speed of ripening, have been shown to affect the quality of processed products (Radha Kushwaha et al., 2021). The further processed jackfruit products face familiar quality considerations for processed foods: flour produced from jackfruit seeds in India, for example, has quality evaluation centred on product handling characteristics and capacity for absorption of oil and water as required in baking (Mahanta & Kalita, 2015).

3.5 Delivery for fresh consumption

Fresh jackfruit elements have been named as one example of a highly desired consumer market segment known as "minimally processed products" (Anaya-Esparza et al., 2018) or referred to in Australia as fresh processed products. Such delivery, particularly over significant distances, is enabled by basic initial storage, basic processing (cutting and peeling) as well as by designated steps and stages of further processing such as that required to extract fresh arals.

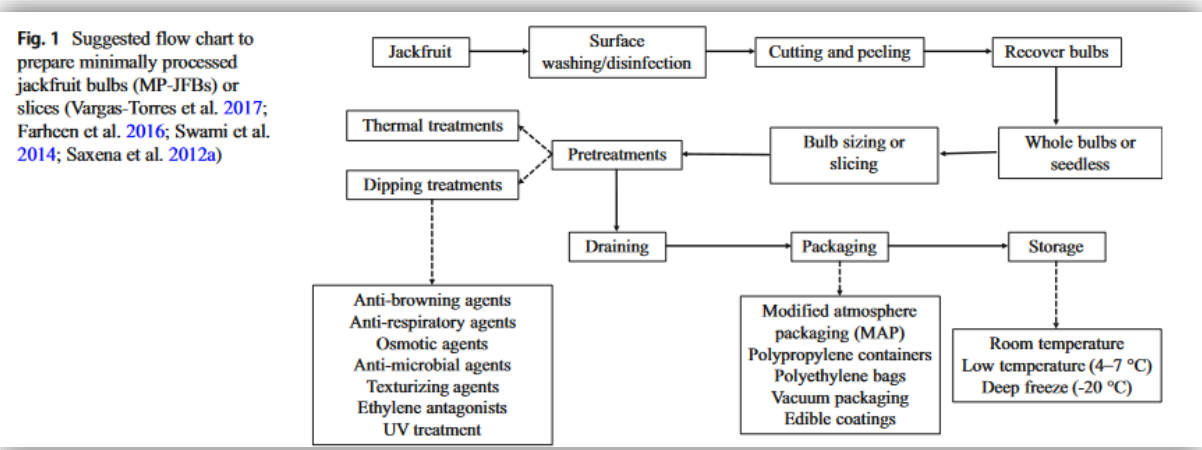


Figure 3. Technical tasks for the delivery of jackfruit as a "minimally processed" fruit product (Anaya-Esparza et al., 2018).

A significant literature surrounds the absolute and relative effectiveness of an array of chemical and environmental treatments, packaging, and storage protocols for fresh arals and fresh cut fruit. Packaging and treatment before packaging (Acedo, Acedo, Troyo, Valida, & Benitez, 2014) and the insertion of chemicals into the headspace of packages of fresh products (Latifah, Ab Aziz, Fauziah, & Talib, 2011) Beyond fresh products, pre-treatments and drying protocols for crisps made from jackfruit bulbs have also been examined for their impacts on quality (Saxena, Maity, Raju, & Bawa, 2015).

3.6 Quality and utilisation

With regard to preservation and utilisation, four immediate issues are recognised. These are the potential crop losses due to rots in the fruit; post harvest preservation and quality maintenance of fresh fruit *en route* to market; processing for the creation of value added products for fresh consumption or use as food ingredients; and utilisation of by-products in food or industrial uses.

3.7 Processing

Aside from industrial-scale fruit processors' unfamiliarity with jackfruit, the main challenges associated with processing jack fruit are its large size, and the removal of its skin (Anaya-Esparza et al., 2018). The large numbers and weight of seed produced, the presence of latex and fibrous material in the fruit, and the high valued fractions that are contained in the skin all obviate the need for processing to serve markets which may emerge for these products. Advanced optical techniques (e.g. NIR) are amongst the techniques used for assessing quality of processed and packaged fresh products, for example after thermal processing (Babu et al., 2022).

Nelluri et al (Nelluri et al., 2022) review currently available jackfruit processing technologies and relates them to fundamental tasks (cutting, peeling, coring, slicing and bulb removal, and seed extraction).

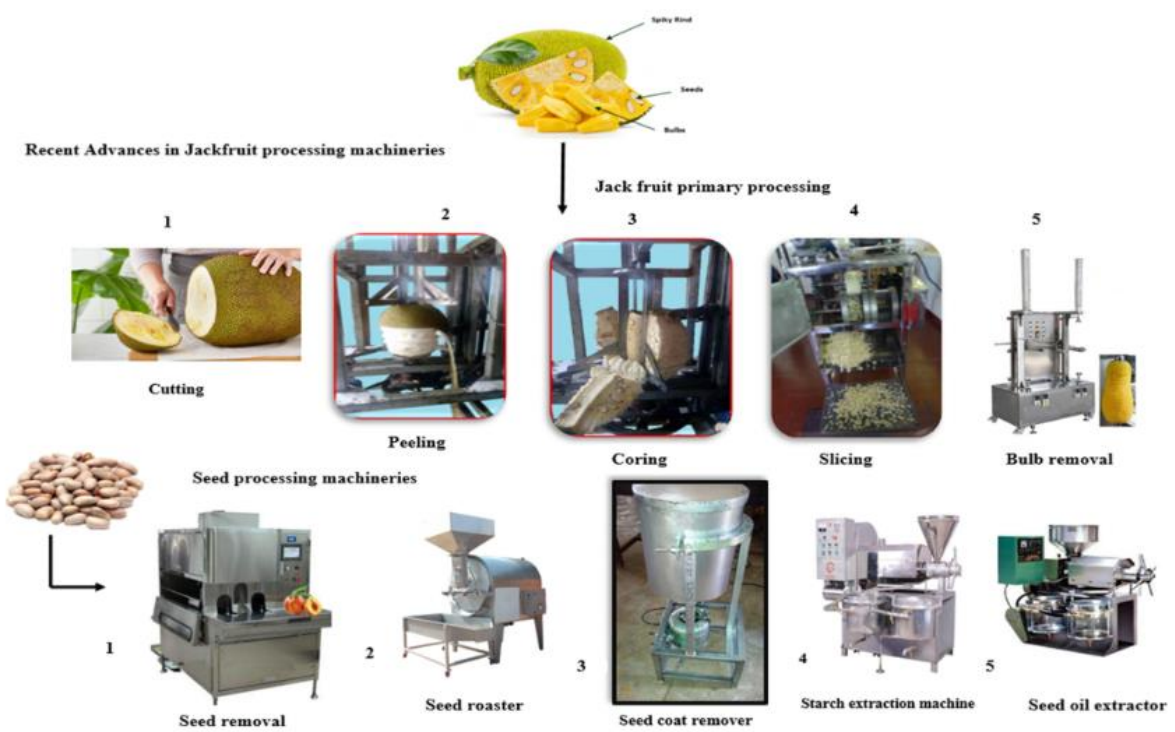


FIGURE 1 Recent developments in jackfruit processing equipment's image of fruit processing 2 and 3 (Alhassan, Ijabo, & Afolabi, 2018) 4 and 5 (Anjali et al., 2019); seed processing unit's images 2 and 3 (Anila et al., 2018); 4 (Suparna Devu, Safvanath, Rinitha, Faris, & Sreeja, 2018) developed by Kerala agriculture university

Figure 4. Graphic representation of processing tasks and equipment (Nelluri et al., 2022).

4 MAPPING OF TECHNOLOGIES TO JACKFRUIT CHAIN APPLICATIONS

4.1 Approach

The forgoing information on the jackfruit value chain, its technical and organisational functions, and its technological gaps and opportunities, are assembled as a map. The following table lists and describes the components of the map.

Table 2. Components of the technology map

	Definition	Interpretation/use
Technology theme	Term encompassing tasks	Generally aligned with supply chain stages
Target tasks	Tasks that offer potential for value generation	An identifiable task in production or along the value chain
Value generation mechanism	The mechanism by which either costs or revenue are affected	Identifies the variables which change as immediate consequence of a technology change, in association with the tasks identified
Technologies implicated	Technologies associated with the value generation mechanisms, selected from the literature review and stakeholder consultations	Components of the technology are reflected in changes to the baseline financial analysis as a package of inter-related shifts in specification from the baseline
Technology readiness	Evaluation conducted according to readiness guidelines	Not explicitly included in the analysis, but enters the discussion of results
Technology link to organisation	Cost and benefit changes imposed, which reflect organisational changes as part of technology uptake	Acknowledgement that many technologies are co-dependent on organisational change at the business or value chain level
Other notes	Clarification and additional points	Enables links to specification pf baseline and scenarios, and interpretation

Table 3. Mapping of technology themes to technologies and value generation

Technology theme	Target tasks	Value generation mechanism	Technologies implicated	Technology readiness (possible 36)	Technology-organisation	Notes
Jackfruit production	Production	Productivity	Orchard architecture Orchard layout Varieties' development	Not assessed 11 20	[under development] [under development] [under development]	
	Inventory management	Market targeted varieties Consolidated harvest	Varieties' characterisation	20	[under development]	
	Production	Quality assurance re fruit rots	Pre-harvest monitoring of pathogens Pre-harvest monitoring of physical conditions surrounding pathogens	19	Sensors established as part of whole-of-chain information system	Standards system in place for supply chain management and marketing
Jackfruit harvest	Production	Effective yield, harvest management	NIR Photo imaging Acoustic measurement	12 11 12	Handheld devices	The technologies applied to other fruits face some constraints with jackfruit. Calibration and model training also faces constraints as varieties and product standards are emerging
	Price elevation	Quality achieved, effective marketing	NIR Photo imaging Quality information sharing	12 11 12	Whole-of-chain information systems	
Jackfruit post-harvest	Reduced waste Added revenue stream	Extraction of value form wastes	Processing technologies	Not assessed	Consolidation of crop wastes	Critical mass needed
Jackfruit processing for fresh consumption	Price elevation	Individual serving package Edible product delivered to consumer Cost competitiveness	Peeling, cutting, seed removal and component separation equipment Automation and other co-ordination amongst tasks to improve product flow	17	Co-ordination of existing technologies within/between firms Co-ordination of technological sequencing	Identification of consumer product specification Organisational model for the supply chain is required Achievement of co-ordination around product volumes
	Market access	Supermarket outlets Access to supply chains	Dipping, chemical treatments, packaging	Generally known	Whole-of-chain information systems	
	Price elevation	Targeting supply chain requirements and specifications Targeting consumer needs	Packaging, quality assurance	Not assessed	Whole-of-chain information systems	Identification of consumer product specification
Jackfruit waste management	Reduced waste	Increased volumes of fruit sold Marketing of wastes	In-field sensors Regional monitoring	Targeted by several management and technology steps	Consolidation of crop wastes	Critical mass needed
Whole-of-chain information systems	Price elevation Transaction cost reduction Value retention	Regular delivery Standard packaging at each stage Objective quality description Evidence base on rots, maturity, provenance	Sensor-based data flows from field/tree, packhouse, agent, transport, retail. Feedbacks from consumer	Not assessed Well known for other crops	Joint grower action, whole of chain information systems	Critical mass needed at farm level Organisational model for standards and consumer-orientation of supply chain

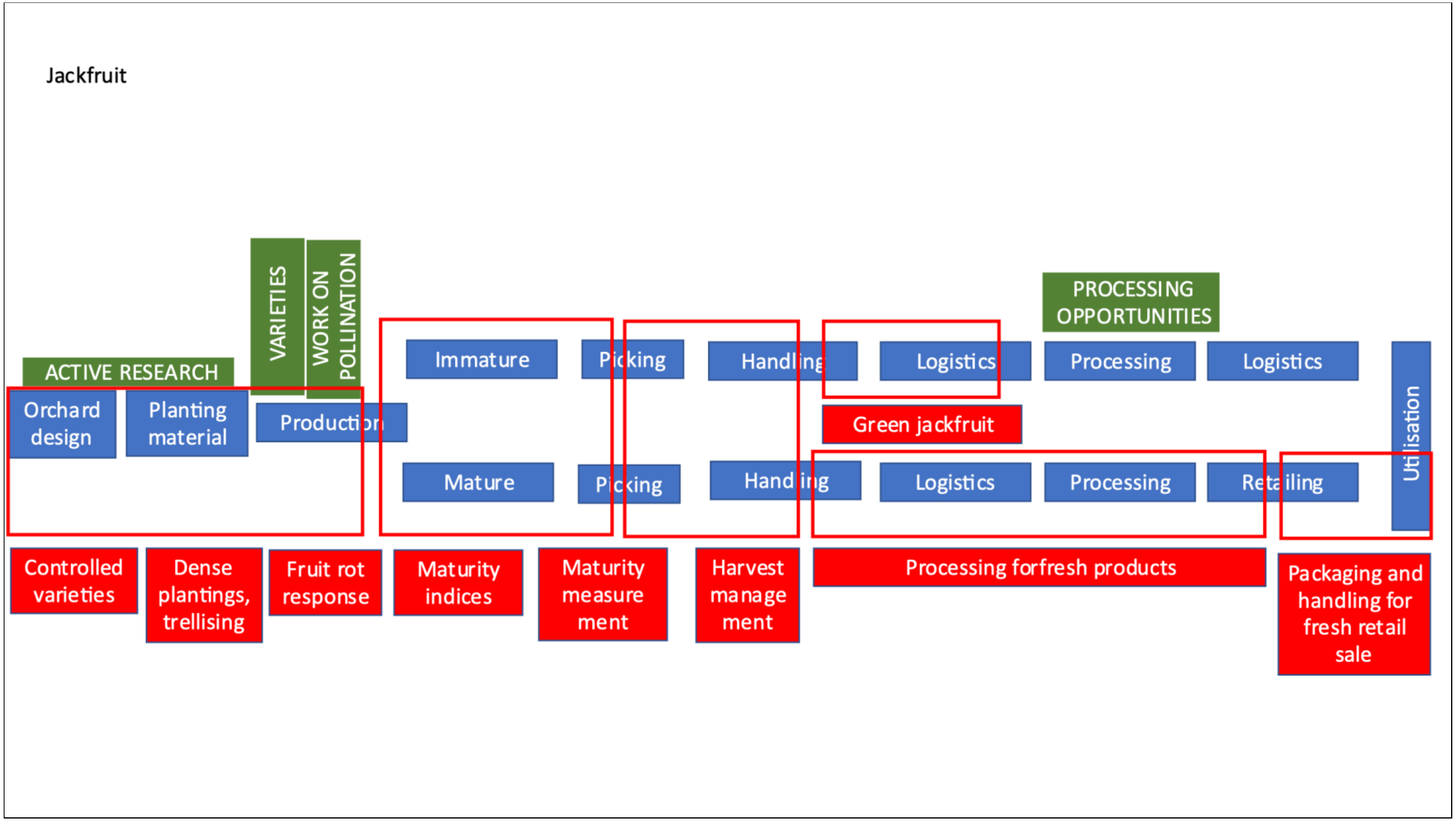


Figure 5. Sketch of jackfruit value chain, with superimposed technology gaps and opportunities

4.2 Orchard design and trellising

Denser orchard layouts are currently being trialled, entailing small trees, densely planted, with relatively few fruit per tree. Associated benefits include reduced input use due to tree size, and the accessibility of the tree, its fruit and its leaf canopy for various husbandry tasks including harvest, and importantly selection of fruit for harvest, as well as improved sunlight penetration (Nath, Marboh, Gupta, & Lal, 2019). Address to the size distribution of fruit, made more visible on smaller trees with reduced thickness through the row, occasions both judgement calls on harvest timing and the identification of small fruit which can be picked green for an alternative market.

Reduced tree damage from cyclonic and other weather events is the primary target of trellising. Further benefits are projected from enhanced reductions in tree row diameter with greater filling of the rows. Improved sunlight and spray penetration and reduced losses from spray, and further enhanced access to the fruit for harvest selection and harvest are also envisaged, with additional possibilities of trellis-mounted equipment such as for precision spraying (Mahmud, Zahid, He, & Martin, 2021).

4.3 Planting material

Benefits sought from more desirable plant genetics include the standard breeding advances of improved and more predictable yield, and enhanced responses to inputs such as fertiliser. In jackfruit’s current context they extend to the management advantages associated with a more predictable and more uniform timing and volume of crop, more uniform fruit size and quality, and more predictable flowering and production timing. To this end, substantial research effort is currently underway on the identification of varieties already in production in orchards, and the selection of superior trees in orchards for uniformity of fruit size, quality and timing of production. Matching these to climatic, disease pathogen and demand timing windows is also the subject of current research. Ongoing research into orchard design (see below) provides stimulus toward ideal planting material: smaller trees with fewer fruit associated with denser orchards; and suitability for trellising.

4.4 Other production items

Labour, machine use and inputs are affected by many of the technologies addressed here. Disease risks are here associated with lost production. Referring particularly to detection and monitoring of rots, a portable lateral flow test has been used for *Phytophthora*, as described by Diczbalis et al. (Diczbalis, 2019). Other available technologies include image analysis (Oraño, Maravillas, & Alia, 2020), and use of biosensors (Fang & Ramasamy, 2015) deployed on sensing platforms for real time detection. This monitoring is offered by commercial biosensor providers. Monitoring of predisposing conditions for fruit rot, calibrated to fruit size and position, also offers a guide to the onset of fruit rots. This monitoring is suited to whole-of-chain information for value addition through improved supply chain performance.

4.5 Fruit maturity and harvest prediction

Benefits of improved fruit maturity measurement include various cost and revenue outcomes associated with increased effective yield through reduction in waste, cost savings associated with improved scheduling of harvest, improved prices via better and more consistent quality delivery to market, and gains from improved scheduling of the harvest workforce and delivery along the supply chain.

The vexed problem of fruit maturity measurement required a literature search (see appendix 1 for details) which generated 585 English language research publications, of which 416 were retained after removal of duplicates, review papers, erroneous inclusions and non-empirical conference papers. Research papers dated from 1991, and more than half of the publications were produced after 2015. For the 416 papers, purposes of research are shown in figure XXXX. It is mostly associated with quality prediction (e.g. shares of crop achieving a high quality grade) and improving supply chain performance (e.g. shelf life). These research purposes lend themselves to maturity measurement following harvest. A further 21% of published research papers were concerned with establishing and calibrating maturity indices. Improvement of the harvest timing decision occupied just 14% of the papers published.

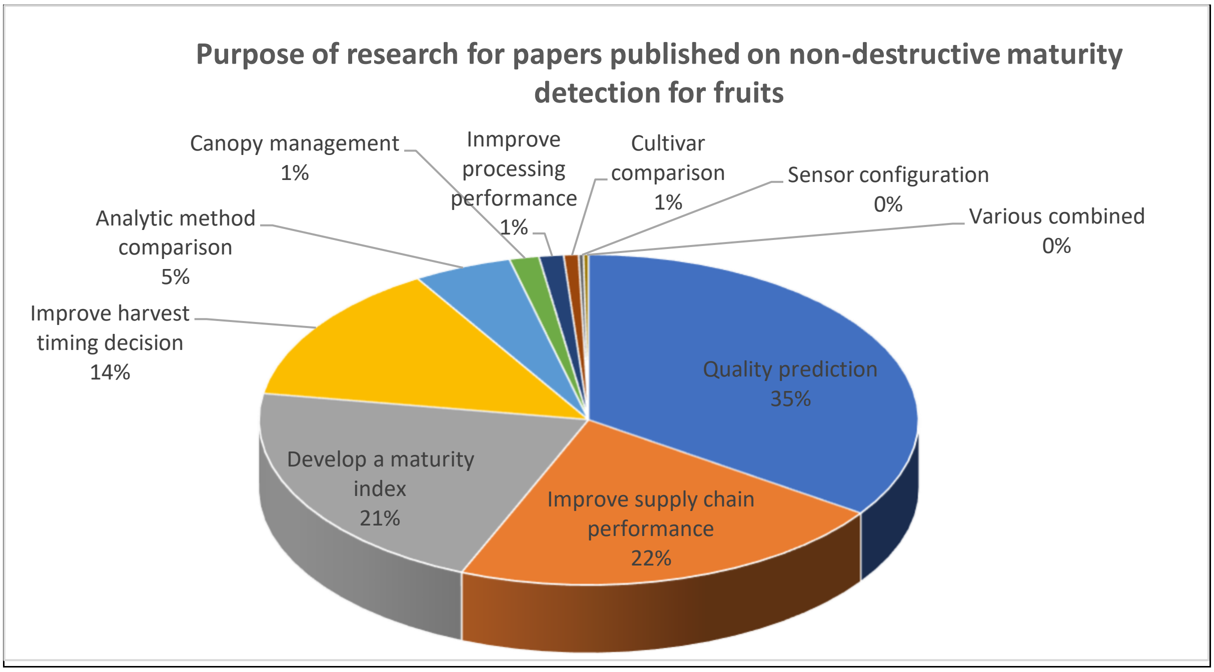


Figure 6. Purposes of published research on non-destructive fruit maturity measurement

The broad categories of maturity-measuring technologies examined in this research include optical, mechanical (often using acoustic stimulators), electromagnetic, ultrasound, detection of gases, and artificial detection of smells. Particularly in recent years, optical methods have predominated. NIRS (84 papers with some 10 using NIRS derivatives or refinements) dominates the technologies, with image analysis also prominent: this includes methods involving analysis of photographs, particularly relating to fruit colours' presence, intensity and distribution on the fruit or as seen within an orchard's canopy. Acoustic methods primarily measure displacement of the fruit following stimuli, so measuring firmness.

The fruits targeted in this body of research do not include jackfruit. Amongst tropical fruits, only mango is well represented (52 studies), as is banana. Amongst tropical fruits the presence of durian, pineapple, cantaloupe and pomegranate are of particular interest as these fruits have thick and non-smooth skins with multiple colours, and non-uniform flesh and/or interior which includes seeds and distinct seed structures. Detailed results for these fruits are presented below, along with classification of the research as utilising fruit pre- or post-harvest: it should be noted that this information is interpreted from the research papers and refers to suitability rather than to experimental practice as reported. Amongst these examples, and in the absence of studies of jackfruit, particular attention (shaded cells) is drawn to optical methods, both image analysis and NIRS.

Table 4. Summary of research on maturity measurement: cases of thick/irregular skinned tropical fruits

Fruit	Pre or post-harvest measurement of maturity	Purpose of research	Method used	Variable measured
Cantaloupe	Pre	Harvest decision	Optical	Reflectance
Cantaloupe	Post	Maturity index	Mechanical	Firmness
Durian	Pre	Harvest decision	Optical	NIRS
Durian	Post	Maturity index	Optical	Fluorescence spectroscopy
Durian	Post	Maturity index	Acoustic	Wave attenuation
Durian	Post	Processing performance	Optical	Video imaging
Durian	Post	Supply chain performance	Optical	Image analysis
Durian	Pre	Maturity index	Optical	Molecular markers
Pineapple	Post	Supply chain performance	Mechanical	Acoustic analysis
Pineapple	Pre	Quality prediction	Genetic	DNA analysis
Pomegranate	Post	Maturity index	Optical	Raman spectroscopy
Pomegranate	Post	Maturity index	Optical	VIS/NIR Index
Pomegranate	Pre	Harvest decision	Optical	Image processing
Pomegranate	Pre	Quality prediction	Optical	NIRS
Pomegranate	Post	Quality prediction	Magnetic	MRI

The electronic measurement of maturity relies on modelling of the measurement of light, sound, smell or stimulus-response. This requires observations on fitting measurements to observations made using destructive analysis. These modelling and calibration procedures – which occupy much o the description of experimental work in the abovementioned literature - are well developed, and even for the small number of fruits represented, they have been applied across the spectrum of the key variables (maturity measurement and indexing, quality prediction, and harvest decisions).

Address of digital technologies to fruits on the tree obviate either a hand-held device as currently seen with NIRS technology for many fruits, or a mobile machine-mounted device which assesses crops or individual fruit within the orchard canopy. Fruit with thick skin requires particularly strong optical or acoustic stimuli and/or sensitive detection equipment. These conditions do not lend themselves to compact and hand-held equipment powered by batteries. Moreover, non-smooth skins, non-uniform interior fruit structures, and non-uniform fruit by way of size or variety, all require a firm contact with the fruit surface which may not be suited to assessment on the tree. Points of contact and the orientation/posture of fruits also introduce variation that must be modelled (Ding, Feng, Wang, Cui, & Li, 2021).

For jackfruit, a data collection and model training exercise for NIRS is reported from 2019 (Diczbalis, 2019), applied to harvested fruits. Disposable (litmus paper-type) sensors have been used in post harvest and with supply chain applications to categorise and measure jackfruit ripeness, both from the maturity detection by chemicals point of view, and for predicting consumer satisfaction (Sim, Ahmad, Shakaff, Ju, & Cheen, 2003). Use of colour card-type calibrated image analyses – also subject to the modelling requirement – offer an electronic version suited to mobile phone implementation (Intaravanne, Sumriddetchkajorn, & Nukeaw, 2012), in this case applied to bananas at harvest.

4.6 Jackfruit harvest

A number of technological approaches to harvest efficiency and cost are being exploited. These include the improved visibility and access to fruit afforded by orchard design, better quality control associated with uniformity of varieties, and improved quality and logistics through the supply chain. Frequency of harvest, capacity for informed judgement on fruit maturity and quality, and the potential for picking a consistent green product for sale, all offer cost savings and enhanced value addition possibilities during harvest.

4.7 Jackfruit post-harvest

Ease of fruit handling and draining of latex, post-harvest chemical treatments and flexibility in choice of sales channels are all benefits that are available post-harvest from more uniform fruit with enhanced information about maturity. These benefits are likely to be accelerated by improved orchard layouts.

4.8 Jackfruit processing for fresh consumption

Current processing for fresh consumption in Australia is at small scale, and concentrated in specific urban market environments. Value adding by provision of a ready-to eat (arals or easily handled pieces and slices) product at scale requires mechanisation. Documentation of the mechanised processing of jackfruit is largely available from Indian subcontinent sources. The processes generally feature an accelerated speed of each process (up to 90%+ time saving, (Nelluri et al., 2022) over purely manual action; however the fruit and fruit parts are manually introduced to and removed from machines at each stage, and orientation and positioning of fruits is also by hand. Time-consuming tasks such as seed removal apparently remain manual.

Reported overall mechanised peeling and coring speeds are of the order of 50-90 kg/hr (Nelluri et al., 2022; Nickhil, Gowda, Ranganna, & Subramanya, 2020), which equates to 1-2 large jackfruit. For coring and cutting alone, machines have reduced time to 13 minutes/fruit from 28 minutes but with a maximum throughput of less than 40 kg/hr or less than one large jackfruit (Nickhil et al., 2020). Mechanised aral removal is reported to save around 20-30% of time (Nelluri et al., 2022) over manual methods. Examination of efficacy and efficiency of operations demonstrates some variation with fruit size: notably that coring of large fruits is much less efficient than for smaller fruits (Nickhil et al., 2020).

For processing beyond seed separation from arals, jackfruit is handled in bulk and uses somewhat standard food processing equipment. A notable feature of the literature reviewed from Asian sources is the very low throughput per hour for many of the machines described. Efficiencies discussed in the literature are divided between considerations of reduced wastage on one hand, and time taken for processing tasks on the other. Modest claims regarding time savings are combined with substantial (80%+ (Nelluri et al., 2022)) claims about reduced wastage, and this suggests that the overall benefit from mechanised processing is delivered by organisational change rather than mechanisation. Juice production, using minimal equipment but applied to a bulk of jackfruit material after bulb material, provides an example where utilisation was increased from 30% to 80% of harvested fruit weight (John & Narasimham, 1993).

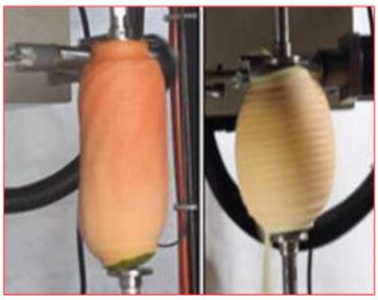


Fig 2.9 Papaya and Cantaloupe peeled

Figure 7. Fruits following mechanical peeling on a spindle (Hareesha & Mathew, 2016)

Mechanised peeling of thick-, hard- and irregularly-skinned fruits and vegetables has generally used a rotational movement of either fruit or knife around a central spindle, either hand-rotated or powered. Operating models are based on other fruits, with cantaloupe, papaya and pumpkin featuring in practical experiences (Hareesha & Mathew, 2016). Oblong and irregularly shaped fruits such as jackfruit require manual adjustments to the rotation to achieve effective peeling, effecting an elliptical rotation and/or varying force applied to knives (Nelluri et al., 2022).

Mechanical coring applications appear to be largely based on pineapple experience, with a corer forced down the length of the fruit, and a plunger apparatus to remove the core from the corer (Nelluri et al., 2022). This operation can be combined with cutting, with the associated radiate array knives added. Peeling and coring have been combined (Hareesha & Mathew, 2016), with alignment of the fruit and equipment enhanced by digital imagery.

Figure 8. Fruit core removal tool, which also cuts the fruit (Hareesha & Mathew, 2016)

Figure 9. Jackfruit coring device (Nickhil et al., 2020)

Mechanised bulb extraction is less clearly described in the literature, apparently entailing opposed revolving drums which separate bulbs from remaining core material and from each other. This operation offers the possibility of bulked material processing with somewhat continuous flow. Bulk cutting employs straightforward slicing of material presented as a series of batches; this also lends itself to bulk handling.

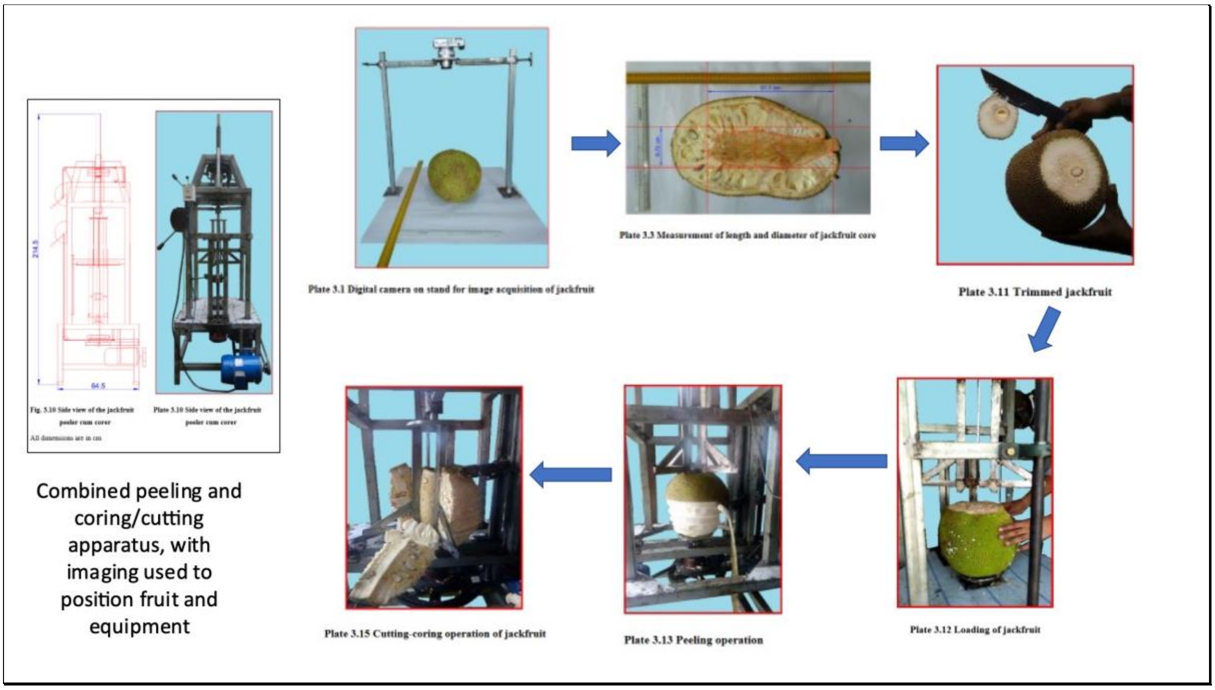


Figure 10. Semi-automated apparatus employing digital imaging (Nickhil et al., 2020)

Non-bulb fruit material is apparently extracted manually at this stage of processing, and no mechanical approaches to the task have been documented. Seed removal from each bulb is commonly carried out by hand. Mechanical devices which employ optical equipment to position each fruit element for a pneumatic coring-type seed removal have been reported (Kulathaisamy & Jesudas, 2012). Seed processing for direct consumption requires boiling or roasting for digestibility. Dehulling of seeds for other uses conventional seed handling and processing equipment, and is also characterised by bulk input and product handling. Extraction of starch similarly uses standard equipment. Juicing and pulping, blanching, and vacuum and air frying for production of snacks are all conducted using available food processing equipment.

4.9 Jackfruit product handling and processing for consumer products

Shelf stability of fresh products is achieved by pre and post harvest action, as well as by packaging, gaseous and chemical treatments both to the fruit and in the headspace of packages, and by heating and chemical treatment. A substantial literature targets improved conditions for overall shelf life, but specifically colour retention (primarily anti-browning), firmness and flavour. The key considerations in maintaining these quality attributes are reviewed above.

The delivery of a whole jackfruit to an uneducated, time constrained and price conscious food buyer is widely recognised as ineffective (Horsburgh & Noller, 2005). Delivery of green jackfruit, especially where identified as easily handled vegetables with desirable dietary characteristics, is seen as a feasible marketing channel with good prospects of consumer acceptance (Best, 2015; Norris et al., 2021). For fresh processed produce, the production of arals or pieces in easy-to-handle packages for individual servings – in the nature of berries as currently marketed in Australia – represents a somewhat generally target (Diczbalis, 2019; Norris et al., 2021). Its delivery centres on a value chain minimising time between harvest and despatch, packaged for bulk handling, with accompanying treatments suited to long delivery distances. Reviewed literature offers significant guidance on dips, moisture management, refrigeration regimes, packaging and chemical and gaseous treatment of package headspace.

For dried, pickled, fried or powdered products, these will be packaged for rather longer shelf life and in quantities associated with repeated household or commercial use rather than single servings.

Similarly as for fresh products, the research literature offers considerable insight into preparation and processing regimes with regard to quality management. Appropriate technologies are well established for the delivery of these forms of product, although aspects unique to jackfruit will not be well known in Australia (Norris et al., 2021). However, it is anticipated that the primary task for Australian jackfruit products' delivery to consumers is organisational in the sense of accumulating sufficient product volume at processing level and along the supply chain to generate the incentives for value addition, delivery and retention, in the presence of competitively priced imported processed jackfruit products (Best, 2015; Norris et al., 2021).

Efficacy and cost of extraction of chemical fractions from jackfruit have been shown to vary according to the methods used and the properties of the raw material (Cruz-Casillas et al., 2021). These authors found that roles for advanced technologies (e.g. ultrasound, microwave) in pre-treatments did not alter the volumes of products extracted but did improve efficiency in terms of energy use and the efficacy of chemicals.

4.10 Whole of chain information systems

Various benefits are delivered by information systems enabling improved inventory management, market targeting, pricing and logistics planning. Establishment and management of such systems are at heart an organisational task, enabled by information technology. Variables associated with data transmission along the value chain are quality and varieties, harvest dates, quality assurance and production system information, and items suitable for branding such as provenance.

4.11 Summary of Technology Readiness level assessment

Technology readiness score (referred to above) were compiled from the authors' assigned scores across some 36 items in four categories, being Technology Readiness, Market and Customer Knowledge, Supply, Manufacturing preparedness, and the availability of supporting Financial analysis. The scoring matrix is presented in Appendix B, and reproduces materials developed by Agrifutures[4]. Of a possible aggregate score of 36, just one of the jackfruit-related technologies considered scored better than 50%. This was the technology referred to as "new varieties" for which well developed systems and supply chains are in place, and for which selection and multiplication activities are underway.

The left two columns of the disaggregated scores however reveal a more advanced state of readiness of the technologies, as all the maturity measurement systems for example have commercial applications for other fruits, and roles in the supply chain are understood by all parties. An ideal (handheld, effective) device from any of the technological categories (optical spectroscopy such as NIR, physical sensors such as acoustic devices, and image processing referred to here as "colour cards") is not yet available and lacks the readiness associated with financial and engineering planning for production and delivery. Product developments (green products and a fresh cut aral product) have been demonstrated at a small and non-industrial scale and are present in foreign countries' jackfruit systems. However, the technologies are not widely known nor available in Australia, and the organisational and technical models for development of the consumer products, processing (referring to the fresh aral product), sourcing of fruit, and quality standards and pricing which are crucial to growers, have not yet emerged.

[4] Thanks to Agrifutures' Peter Vaughan.

Table 5. CRAM scores summary for technologies' readiness

Jackfruit	Technology	Score	Technology Readiness Level (T)	Market & Customer Knowledge (M)	Supply, Manufacturing & Distribution Knowledge (S)	Financial, Revenue and Cost Models (F)
Jackfruit maturity detection	NIR	12	6	4	2	0
Jackfruit maturity detection	Physical sensor	12	6	4	2	0
Jackfruit maturity detection	Colour cards	11	6	3	2	0
Jackfruit product	Green product delivery	15	5	5	4	1
Jackfruit product	Fresh aral processed produc	17	7	5	4	1
Jackfruit production	Dense orchard systems	11	6	3	2	0
Jackfruit production	New varieties	20	7	5	5	3
Jackfruit production	Pathogens' monitoring	19	6	5	5	3

5 FINANCIAL ANALYSIS ALONG THE JACKFRUIT VALUE CHAIN

5.1 Approach and description of baseline

A whole of chain analysis for picking and handling whole fresh fruit through to market was assembled in an MS Excel® spreadsheet. Production level data is based on three data sources[5] and extrapolation according to perceived price changes and expert advice. Horticultural management guidelines and general costs adapted from other sources[6]. Specialised items draw on references as cited.

A baseline scenario is constructed, upon which scenarios are imposed that entail changes to selected input variables. Scenarios can entail single or multiple changes, and in the context of technology are set up accordingly as combinations imposed. Some indicative results are presented at the end of this this section, with the analysis related to technology mapping deferred to the following section.

5.2 Farm level setting and costs

5.2.1 Production setting

The analysis depicts a 1.5 ha production unit, for which all trees are assumed productive for the purposes of grow margin calculation. For industry aggregation purposes some 15 such farms are modelled, in a climatic zone featuring 100 days of harvest which lean toward a wet tropical Queensland season of October-January. With harvest activity taking place every second day, this identifies 50 harvest events.

Area		1.5	ha
Number of producers		15	farms
Harvest days		100	OCT-jan
Harvest frequency		2	days
Number of harvests		50	harvests

Figure 11. Production setting

Fixed costs for the farm are assumed to comprise the depreciation on around $1 million of equipment with a 10-year life and some 25% utilisation in the jackfruit enterprise. Farm administration and permanent labour are assumed to be 20% assigned to jackfruit. Land costs are not included in the analysis.

FIXED COSTS						
Financial Cap value			Share on Jackfruit			
Machines		500,000	25%			
Buildings		250,000	25%			
Other		250,000	25%			
Life			10	years		
Depreciation						**25,000**
Admin		**50,000**	**20%**			**10,000**
Permanent labour		**300,000**	**20%**			**60,000**

Figure 12. Fixed costs in production

[5] University of Hawaii (2011) *Gross Margin analysis for extension*; QLD DAFF (1999) *Mango Information kit*; RIRDC Publication (2015) *Value-adding options for tropical fruit using jackfruit as a case study*

[6] NSW DPI (2019) *Plant Protection Guide* https://www.horticulture.com.au/globalassets/hort-innovation/resource-assets/ap15001-nsw-dpi-orchard-plant-protection-guide-for-deciduous-fruits-in-nsw-2018-19.pdf; the PAYSCALE website https://www.payscale.com/research/AU/Job=Farmworker%2C_Farm_and_Ranch_Animals/Salary/5edf129f/Darwin ; Agrifutures (2019) *The Impact of Freight Costs on Australian Farms*

Trees on the indicative production unit are planted in a conventional configuration delivering 183 trees/ha and 45 fruit per tree according to a pre-specified baseline distribution according to size, withe smallest (1 kg) fruit assigned to the “green” category. The baseline specification is at 38 tonnes/ha yield.

				INTERROW		BETWEEN TREES	
Spacing		183	trees/ha	7	by	5.5	
BASELINE SPACING	183	trees/ha					
Fruit/tree		45	numbers / tree	kg/fruit		Dist of fruit	
			9	12	Large	20%	
			9	8	Med	20%	
			14	3	Small	30%	
			14	1	Green	30%	
			45		Other		
				234	**kg/tree**	100%	
				38	**T/ha**		

Figure 13. Baseline orchard layout

Variable costs are assigned in a bottom-up fashion separating labour input on specific tasks (minutes per tree per year) from fuel and input use. The labour and material specifications include adjustments of tree spacings (ratio of trees/ha in scenario and baseline), tree size (an additional adjustment), fruit per tree (a ratio of scenario and baseline values) and harvest frequency. Machine hours are the same as labour hours on each task and input values per tree are adjusted for tree numbers/ha. Data is extrapolated from sources cited above, with some reliance on available analysis for mango crops.

	TREE ARCH ADJ			TREE ARCH ADJ				
	TREE SIZE ADJ			TREE SIZE ADJ	TREE ARCH ADJ			
	lab mins/tree		Fuel litres/hr	Mat. ($/tree)	TREE SIZE ADJ	**PER TREE**	**PER ha**	**PER tonne**
Hedge	10.0		3			4.96	906.70	23.94
Prune	20.0		3			9.92	1,813.39	47.88
Fert.	10.0		3	9.00		13.96	2,551.36	67.36
Herb./Pest./Fung.	10.0		3	9.00		13.96	2,551.36	67.36
Other chems	5.0		3	5.00		7.48	1,367.05	36.09
Irrigation	5.0			9.26		11.22	2,050.50	54.14
Picking	90.0					35.30	6,449.82	170.29
Handling sorting de-sap	30.0		3			14.89	2,720.09	71.81
Dip	10.0					3.92	716.65	18.92
Packing	10.0		3			4.96	906.70	23.94
Other and additional	15.0	incl. devices				5.88	1,074.97	28.38
	3.6			**32.26**	BASELINE	**126.46**	**23,108.57**	**610.10**
	hrs/tree				**OF WHiCH LABOUR**	**84.32**	**15,407.90**	**406.79**
N					% of costs labour	67%	67%	67%

Figure 14. Baseline variable costs

At an aggregate of 3.6 hours of hired labour time per year per tree, annual costs per tree of $126.46 are comprised of 67% labour in the baseline. This baseline model depicts variable costs at $23,108.57 per hectare in the baseline: there is heavy emphasis on labour intensive tasks such as harvest and crop husbandry.

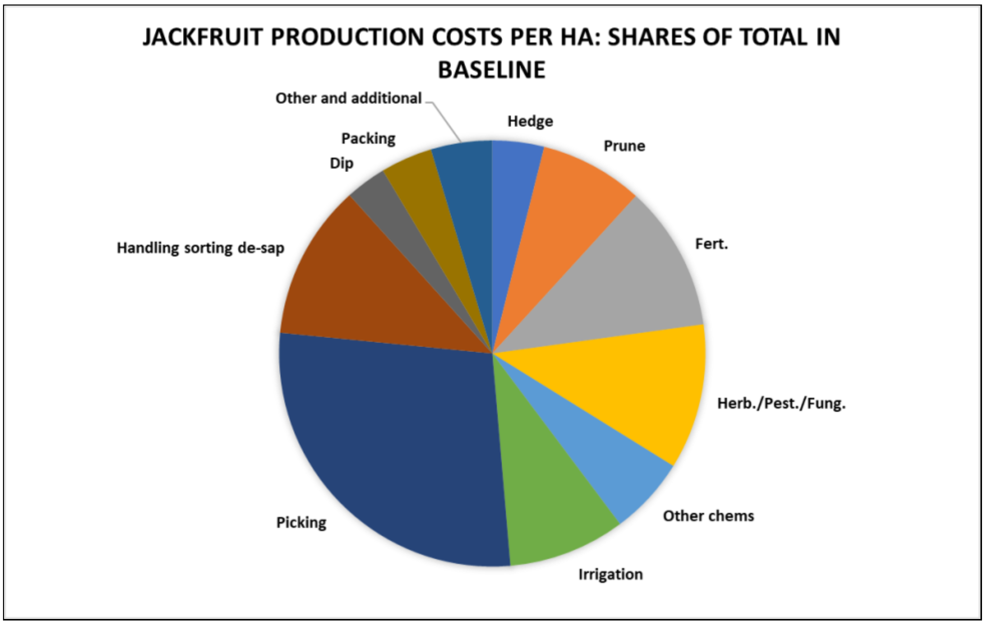


Figure 15. Baseline allocation of variable costs per hectare

5.2.2 Fresh processed products

Analysis of processing is limited to production of a packed fresh aral product, shipped to a retail outlet. In the baseline no such processing is included. Specification of processing technology adheres to time-in-process data derived from Indian research,[7] which retains a reliance on manual labour: particularly in the shifting of jackfruit from one process to the next. This presents around 6-10 jackfruit for processing per hour, dependent on size. Four potential processing lines are depicted here, with processing occurring during the 100-day harvest period. In a relevant scenario, arals make up 28-33% of the fruit weight. Fresh fruit are depicted as being sold onwards to retail and incur agents' handling fees. In scenarios where green fruit are sold, they are similarly moved onwards from wholesale. The number of jackfruit depicted here for processing into the fresh aral product is determined by demand assumptions (see below), and the analysis assumes that large fruit are processed first to meet demand, and as that volume is exhausted, medium sized fruit are brought in, and onwards to small fruit. Handling margins (20%) and profit margins (20%) for processing and distribution are derived from received summaries which offer transparent industry averages.[8] Flexibility in shift duration and number is incorporated. Volumes of useable waste, peel and other wastes are identified but not advanced further in this analysis.

Processing and handling														
Margin on handling/wholesale for fresh	20%													
Margin on processing and arals packs	20%													
		NUMBERS OF FRUIT IN FRESH ARALS + GREEN FRUIT USE												
Processing intake		capacity/hr/line	Fruit/day		Aral DELIVERY (FRUIT/YR)		kg Arals	Packs Arals						
	Large	6	360		36,000		142,560	356,400						
	Med	8	480		48,000		161,280	403,200						
	Small	10	600		60,000		158,400	396,000						
	Green	300	4,500											
								1,155,600	Packs/year					
PROCESSING FOR ARAL EXTRACTION														
Aral lines operating	4													
Shift length	7.5	hrs	rate	23.53	$/hr wages for processing				Waste disp	Power	**Total Aral**			
No. shifts/day	2	per 24 hrs		hrs proc time	$/kg proc labour	$/kg dip	$/kg pack	$/kg handling	**$/kg**	**$/kg**	**Costs/kg**			
Hours worked/day	15		Large	**74**	0.08	0.005	0.01	0.05	0.05	0.05	**0.25**			
Length of season	100	days	Med	**0**	0.00	0.005	0.01	0.05	0.05	0.00	**0.00**			
			Small	**0**	0.00	0.005	0.01	0.05	0.05	0.00	**0.00**			
			Green						500	15				
				5	days processing				kg/hr moved	$/hr proc				
Processing specifications	% Aral	% useable	% peel	% waste	Fruit/hr Intake	Fruit/hr Peeling	Fruit/hr Cutting	Fruit/hr Coring	Fruit/hr each line Aral extr	Fruit/hr Aral treat	Fruit/hr Pack	Fruit/hr handle useable	Fruit/hr handle peel	Fruit/hr handle waste
Large	33%	27%	20%	20%		16	20	20	6	20	50	100	100	100
Med	28%	28%	22%	22%	80	17	20	20	8	20	50	100	100	100
Small	22%	28%	25%	25%	100	18	20	20	10	20	50	100	100	100
Green	0%	90%	0%	10%	300						300	300	300	300
Other	0%	100%									100	100	100	100

Figure 16. Capacities and productivities for production of fresh cut aral products

[7] (John & Narasimham, 1993; Nelluri et al., 2022; Nickhil et al., 2020)

[8] Reserve Bank of Australia Bulletin (Carter, 2019); Agrifutures study (Spencer, 2016); The Australian Chamber of Fruit and Vegetable Industries Ltd (Ltd, 2010).

5.3 Product volume

Product volume in the model is driven by production assumptions, but (i) the quantities marketed are constrained to lie below demand projections, and (ii) the projected volumes for fresh aral products (where specified as a scenario) reflect only the demand projections. Similar restrictions apply to green fruit. Both these additional products are set at zero in the baseline. The projections themselves are driven by some simple constructions assuming a market of 8 million consumers at retail, with small proportions of the population consuming jackfruit products, and in small numbers of purchases per year. This population loosely approximates a broad Southern Queensland market and selected markets outside Queensland. Received commentary on the market size has guided this construction. Intended to provide a working figure without loss of generality, these assumptions provide for a market of 16,000 packs of processed fresh arals, 200,000 fresh fruit for consumption and 80,000 green fruit per year, as well as useable waste products.

Demand mapping							
	DEMAND	% of pop	packs/year	rel population	SEASON (days)	PACKS/year	PACKS/day
Packs of Aral	BASELINE	0.1%	2	8,000,000	100	16,000	160
	% change	0%	0%	0%			
	NEW	0.1%	0	8,000,000	100	0	0
		% of pop	fruit/year	rel population	SEASON (days)	fruit/year	fruit/day
Fresh fruit	BASELINE	0.5%	5	8,000,000	100	200,000	2,000
	% change	0%	0%	0%			
	NEW	0.5%	5	8,000,000	100	200,000	2,000
		% of pop	kg/year	rel population	SEASON (days)	kg/year	kg/day
Useable	BASELINE	0.5%	3	8,000,000	100	120,000	1,200
	% change	0%	0%	0%			
	NEW	0.5%	3	8,000,000	100	120,000	1,200
		% of pop	fruit/year			fruit/year	fruit/day
Green fruit	BASELINE	0.5%	2	8,000,000	100	80,000	800
	% change	0%	0%	0%			
	NEW	0.5%	0	8,000,000	100	0	0
DEMAND assumptions			kg product	kg fruit equiv	No. of fruit		
Packs of Aral	0	Packs	0	0	0	Large initially	
Fresh fruit	200,000	Fruit					
Useable	120,000	kg					
Green fruit	0	Fruit	0				
Other							
	Fruit						
TOTAL SUPPLY	182,619						
TOTAL DEMAND	280,000						

Figure 17. Demand specifications

5.4 Distribution and retail margins and arrangements

Distribution with margins as constructed elsewhere[9] and transport costs[10] are taken from online quotation platforms, and adapted from related analysis. Retail prices as observed on online platforms in Summer 2022/23 in Australian retail outlets. An embedded assumption of 8% waste (unsold product due to quality) at retail is included in the baseline.

[9] Reserve Bank of Australia Bulletin (Carter, 2019); Agrifutures' study (Spencer, 2016); The Australian Chamber of Fruit and Vegetable Industries Ltd (Ltd, 2010).

[10] (AgriFutures, 2019; Babacan & McHugh, 2020)

Transport costs to retail market							
Packaged Arals	355	$/T boxed	ROAD	0.355	$/kg of packs	0.888	$/kg fruit
Fresh fruit	355	$/T boxed	ROAD			0.355	$/kg fruit
RETAIL		Markup on wholesale		Waste			
		45%	on Arals	8%			
		40%	on Fresh				
Pack of arals		400	g	price			
		18.00	per pack	45.00	per kg		
Whole fruit			kg	24.99	per kg		
Green fruit			kg	6.00	per kg		

Figure 18. Retail pricing arrangements and transport to retail

5.5 Whole of chain costs and margins

The foregoing structure and assumption deliver a whole-of-chain distribution of the jackfruit retail price as shown below, separated by the sizes of fruit.

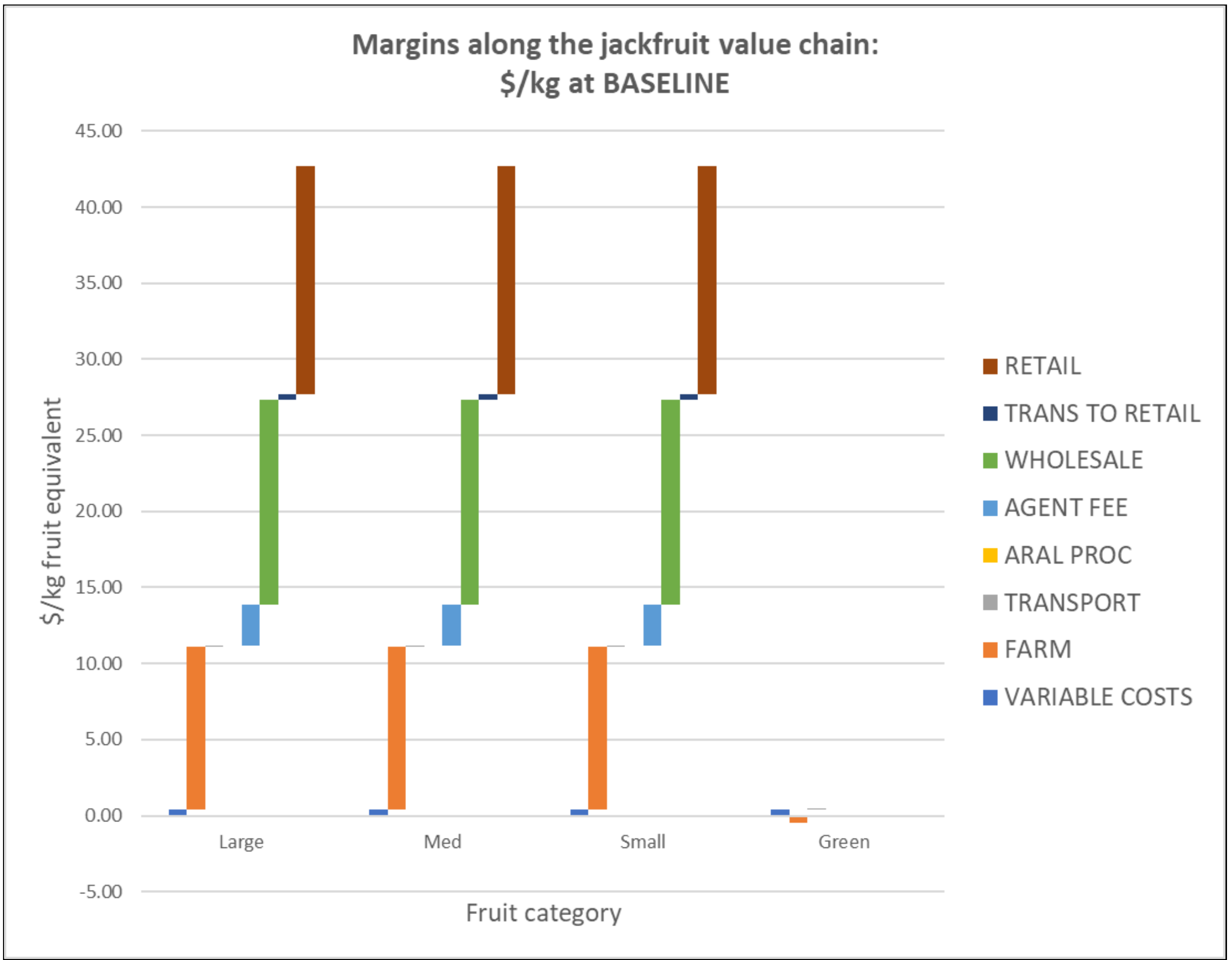


Figure 19. Jackfruit whole of chain margins and transport

5.6 Scope for benefits from selected change scenarios

The imposition of simple exogenously-imposed changes generates performance changes at farm level and along the chain as seen in the following three figures. Simple yield changes affect revenue in direct proportion (in this case 5%) while costs per hectare and per tree react at a somewhat lower magnitude. A projected 5% wage increase impacts all the cost items by about 3%, reflecting the significant contribution of labour to variable costs.

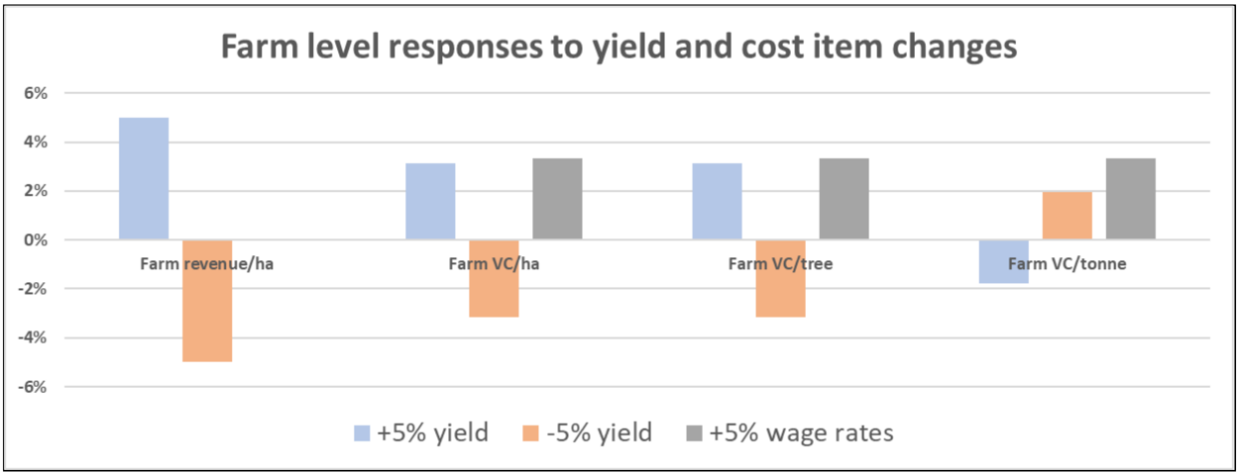


Figure 20. Demonstration of impacts at farm level of imposed shocks

For developments affecting relations, costs and values along the value chain, the figure below depicts the effects inside the farm gate. Contrasts appear between waste reduction at farm and retail levels: farm waste effects impact costs and revenues while retail level waste affects these variables as well as effective price. The effects of increased fruit size (by way of changed distribution of fruit sizes), are seen to reduce costs but the specifications of the analysis do not associate this change with a change in sales price.

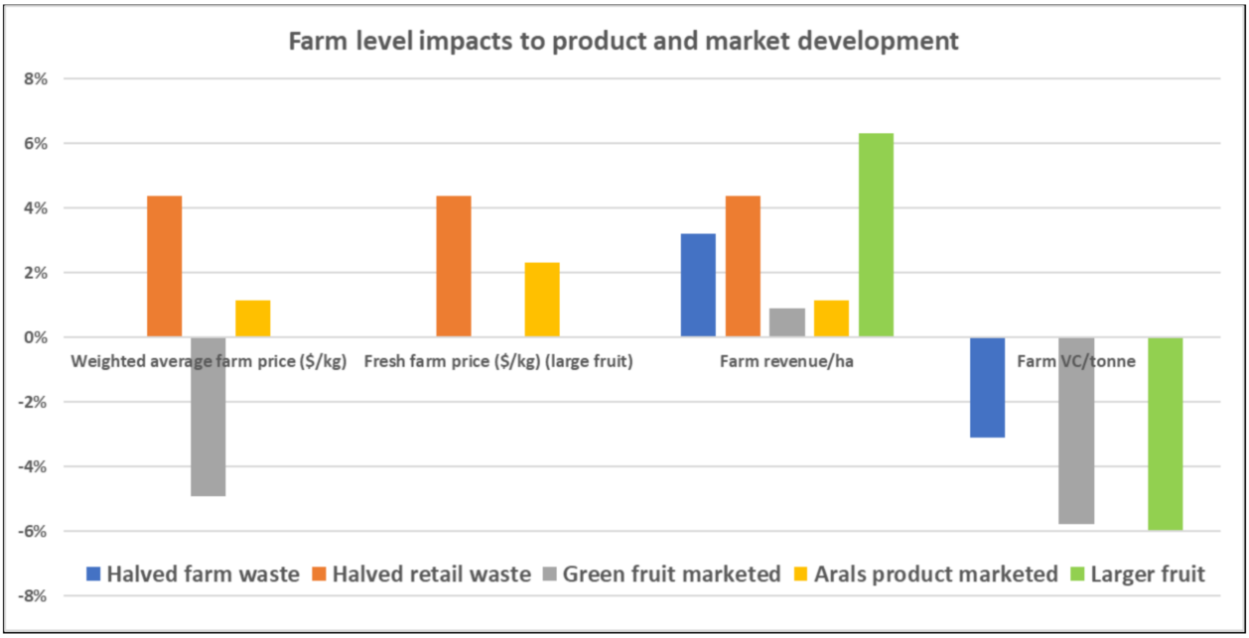


Figure 21. Demonstration of impacts at farm level of elements of value chain development

The projected impacts along the value chain of a combination of imposed changes are seen in the figure below. Halved retail waste and the introduction of a processed fresh aral product are seen to raise margins for all value chain actors and also provide a margin for the processor.

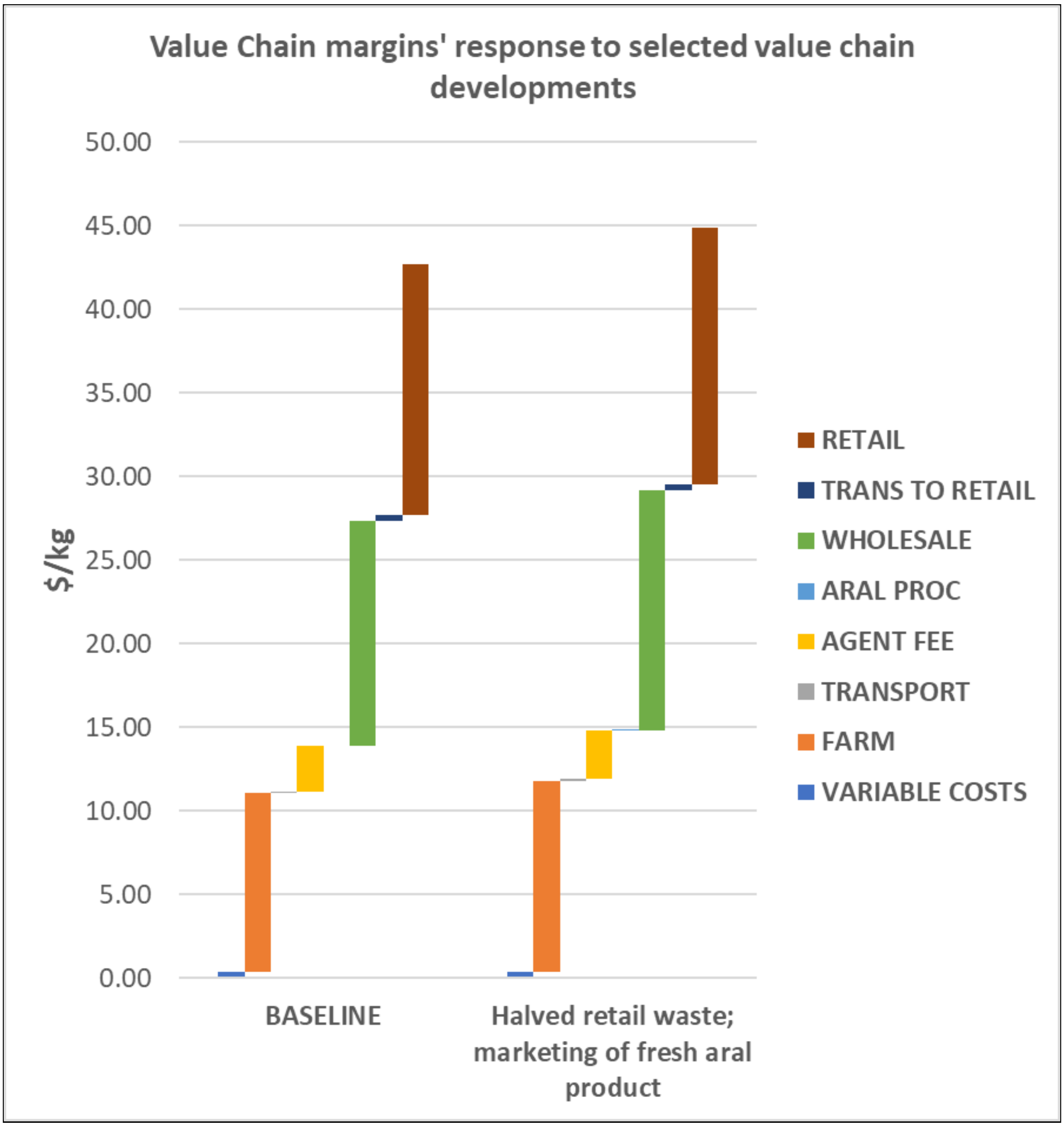


Figure 22. Demonstration of impacts at farm level of changes along the value chain

6 PROJECTIONS AND ANALYSIS OF TECHNOLOGY ADOPTION

6.1 Approach

From the spreadsheet-based baseline analytic framework as described, scenarios entail:

1. Examinations of the presumed response in cost and/or benefit, to a presumed change induced by adoption of a technology and related changes
2. Examinations of changes in selected elements or patterns of cost or revenue, due to presumed changes due to technology or organisational change
3. Investment analysis where investments whose estimated costs are able to be approximated, are compared to discounted flows of projected benefits over time.

A key aspect of the analysis is a set of assumed values for technical parameters. These include, for example, labour inputs to specific orchard tasks and the relative times spent in different tasks. Further, these parameters are varied in some scenarios: the changes in labour input associated with changed tree spacings and numbers of fruit. Empirical estimation of these parameters is, in many cases, the subject of ongoing research. The author's best attempts have been made in assuming values for them, and many of the results obtained are also tested for sensitivity to key assumptions.

Variables such as crop yield per hectare are not in general held constant across baselines and scenario comparisons, due to the multitude of production level changes embedded in a scenario specification. Crop yield is in reality stochastic, but is also embodied in some technical changes inherent in several scenarios: new tree varieties; changed numbers of fruit grown to maturity; changed fruit size distribution; and the trade-off between tree spacings and fruit/tree. As for technical parameters, these variables are currently under active research and the analysis represents a best attempt at assumptions, supported by sensitivity analysis.

Scenario analysis results are in general expressed as departures from a baseline. This approach minimizes the analytic impact of the errors inherent in the baseline: the same errors are included in both the baseline and the scenario. Improvements to the baseline are of course to be welcomed, but do not distract from central results.

Impacts of uncertainty are not analysed here. Tree damage from storms, crop yield changes due to abnormal disease patterns, changes in labour or fuel prices, and unexpected shifts in consumer preferences are all examples of negative shocks to production and value chain activities which several of the current initiatives in jackfruit research are addressing. Many such research actions embody technologies which are referred to in this report and examined on a scenario basis. However, this analysis omits impacts of reduced uncertainty and it is suggested that such analysis is a somewhat straightforward extension of the scenario analyses conducted.

6.2 Scenarios examined and key results

Table 6 describes the scenarios examined with the spreadsheet analysis. Each of the four initial scenarios embodies a particular technology, and scenario 5 is an amalgam of scenarios 1-4. The following section provides details of the results from the scenarios.

Table 6. Scenario descriptions and key results

Scen.	Technology or organisational change	Value generation mechanism	Scenario specification	Key results	Remarks
1	Dense orchard design	• Labour cost changes at production and harvest • Improved fruit size distribution • Reduced waste at farm and retail levels	• Orchard spacing • Fruit number/tree • Fruit size distribution • Reduced waste at farm • Reduced waste at retail	• Increase in GM/tonne and GM/ha of 5-10% • Reductions to per-tree revenues, costs and GMs in line with assumed changes in tree numbers, tree size and fruit/tree • Labour costs/ha rise, as does labour cost as a % of all costs	• Trade-off is evident between reduced size of tree and increased trees/ha. Results reflect assumptions in this regard and highlight ongoing research. • GM/ha increases in direct proportion to yield. • New orchards would employ new and well-suited varieties, and/or replace aged trees, so yields can be expected to rise in the scenario to a degree not included here. • Labour costs/ha in scenario are sensitive to labour input specifications • Labour costs as % of variable costs are persistently high • Significant benefits arise from reduced waste, assumed to be implemented with smaller trees with more visible fruit in smaller numbers
2	Green fruit marketing	• Adding value to a waste product	• Inclusion of green fruit in revenue stream • No additional cost	• Although marketed volumes of fruit rise, the weighted average price of all fruit falls due to the low price of green fruit per kg • GM/ha rises about 1% and GM/tonne falls about 5% • Cost impacts are seen as a reduction per tonne of around 8%	• Represented as a new revenue stream with no new costs • Results not sensitive to changed weight distribution of other fruit on the same tree following harvest of green fruit • Significant benefits arise from reduced waste • Scenario requires an organisational change toward development of retail market access and product standardisation, in turn requiring knowledge of the consumer market

Table 6. cont'd

Scen.	Technology or organisational change	Value generation mechanism	Scenario specification	Key results	Remarks
3	Processing a fresh aral product	• Inclusion of processing costs • Diversion of fruit from fresh channel to a processed channel • A high valued use raises weighted average price received at farm for all fruit	• Small volumes consumed, commensurate with demand assumptions • Diversion of product flows • Additional cost at processing stage • Imposed limited processing capacity	• A higher price for some fruit (3% of large fruit), and no new marketed volumes, delivers a rise in average weighted price of 1-2%. • A calculation of projected margins and costs delivers a possible farm level price for volumes 100% delivered for processing into fresh aral products as more than twice the existing weighted average price ($22.79/kg) • Margins are increased throughout the supply chain	• Results sensitive to volumes of arals marketed • Price rise impacts are smaller than those available from significant reductions in retail waste levels • Scenario requires an organisational change toward development of retail market access and product standardisation along the value chain • Scenario requires initiation of mechanised processing on an industrial scale amenable to both seasonal operation and possible rapid expansion
4	Maturity measurement	• Improved fruit size distribution • Reduced waste at farm level • Reduced waste at retail level	• Fruit size distribution • Reduced waste at farm • Reduced waste at retail	• Scenario presented here projects a 4% increase in GM/ha and GM/tonne • The significant assumed additional labour input significantly raises aggregate labour costs • Benefits are primarily due to waste reductions (weighted average price rises 8%)	• Benefits are sensitive to assumptions on yield (not directly associated with the technology) and waste reduction • Projected increased labour costs would be mitigated by combination of maturity measurement with other husbandry tasks: it is presented here as a new task which significantly affects labour cost • Changed fruit size distribution (toward larger fruit, which is directly associated with the technology) could deliver an additional 4% producer return, not including any weight-differentiated price effects

Table 6 cont'd

Scen.	**Technology or organisational change**	**Value generation mechanism**	**Scenario specification**	**Key results**	**Remarks**
5	Combination of 1-4 above	• Labour cost changes at production and harvest • Additional labour cost per tree • Improved fruit size distribution • Reduced waste at farm and retail levels • Two new market outlets	• Orchard spacing • Fruit number/tree • Fruit size distribution • Reduced waste at farm • Reduced waste at retail • Market volumes for new products constrained by demand assumptions • Combined scenario has numerous influences on yield, so yield is 50% higher than scenario 1, at 52 tonnes/ha.	• 40-50% increase in producer returns and GM/ha • 40-50% increase in farm costs/ha • Significant additional labour costs associated with use of maturity measurement devices: these apply per tree as well as per ha and per tonne • Weighted average farm level fruit prices rise by less than in some other scenarios, due to larger fruit volumes, and to inclusion of sales of green fruit • Projected share of labour in variable costs rises from 67 to 79%	• An all-in-one scenario • As for scenario 1, trade off between tree size and numbers of tree/ha is evident but not adequately addressed in the analysis. • Higher yield in scenario 5 delivers benefits, as indicated in sensitivity analysis of scenario. Overall scenario 5 results are also sensitive to yield (a 20% assumed increase delivers a projected additional 26% in gross margins).

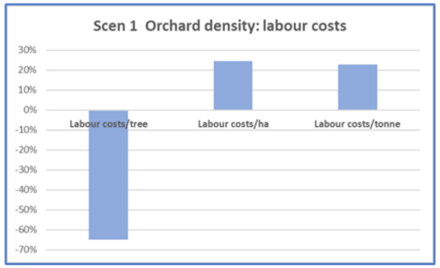
6.3 Detail of results

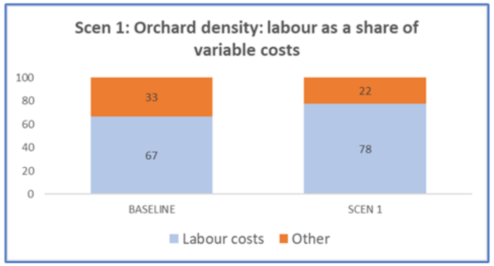
6.3.1 Scenario 1: Dense orchard design

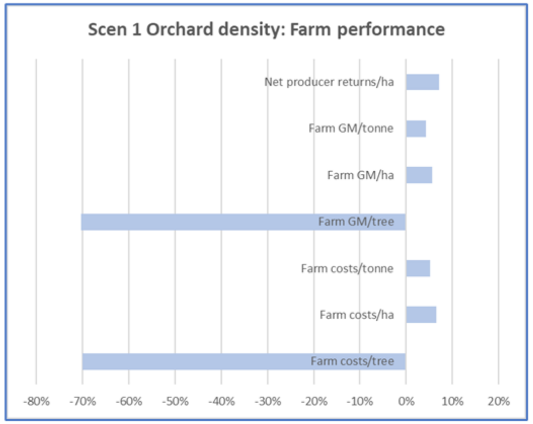
SCENARIOS	BASELINE	% change	SCEN 1	
INTERROW	7	-15%	6.0	trees/ha
BETWEEN	5.5	-55%	2.5	183
FRUIT/TREE	45	-75%	11.3	T/ha yield
Harvest frequency (days)	2	0%	2.0	38
WASTE FACTOR AT FARM				
Large	6%	-50%	3%	
Med	6%	-50%	3%	
Small	6%	-50%	3%	
Green	6%	-50%	3%	
WASTE FACTOR AT RETAIL	8%	-50%	4%	
SIZE DISTRIBUTION OF FRUIT				
% Large	20%	15%	23%	
% Med	20%	15%	23%	
% Small	30%	-10%	27%	
% Green	30%	0%	27%	

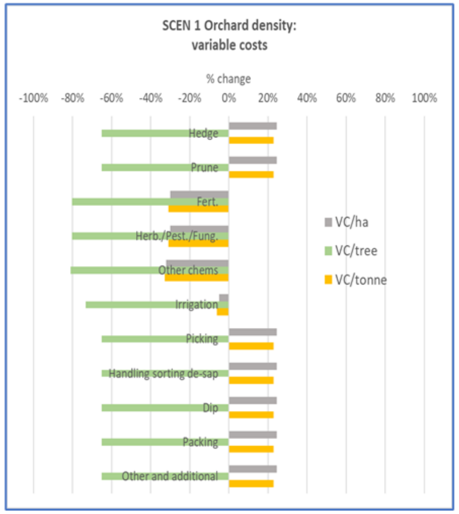
(i) Scenario 1 Orchard density

	BASELINE	Scen 1
Assumed labour input	3.6 hrs/tree	1.3 hrs/tree



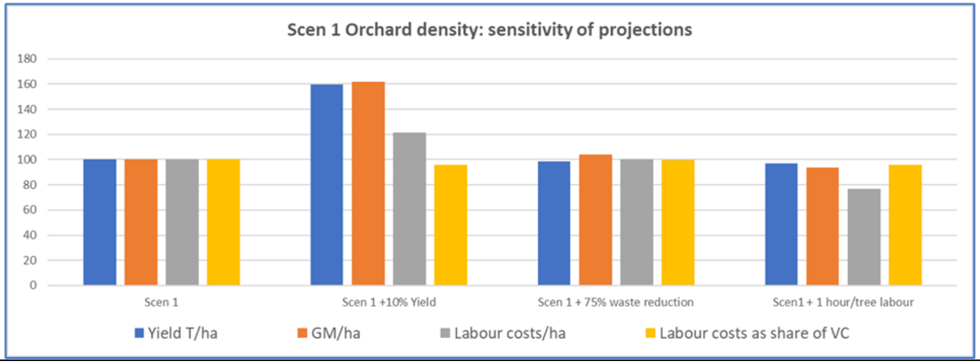






(ii) Sensitivity to specification

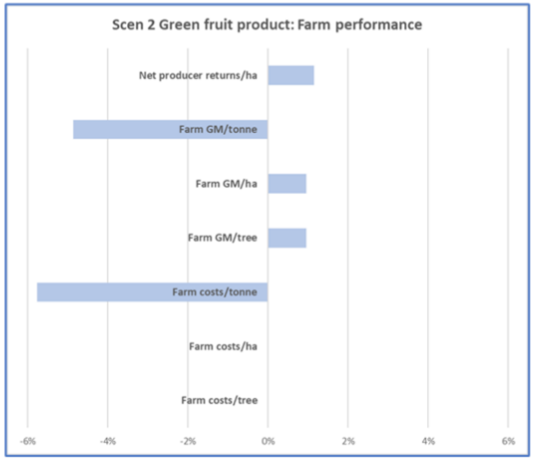
- Results heavily dependent on yield achieved
- Critical trade-off for labour costs/ha is between
    - much-reduced labour/tree and
    - much-increased tree/ha

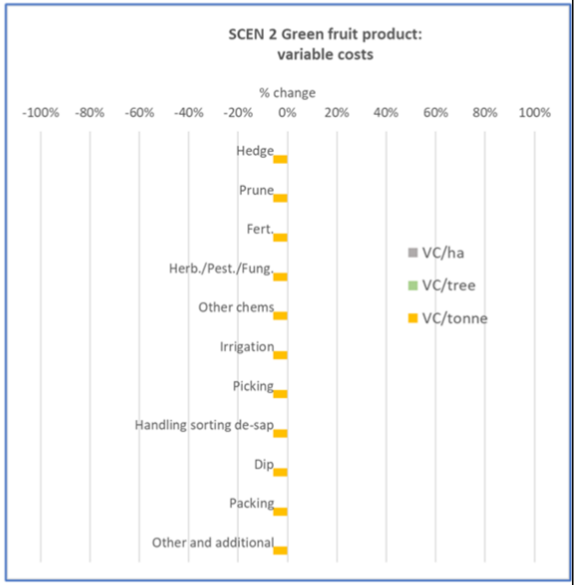


6.3.2 Scenario 2: Green fruit product

SCENARIOS	BASELINE	% change	SCEN 1	
INTERROW	7	0%	7.0	trees/ha
BETWEEN	5.5	0%	5.5	183
FRUIT/TREE	45	0%	45.0	T/ha yield
Harvest frequency (days)	2	0%	2.0	40
WASTE FACTOR AT FARM				
Large	6%	0%	6%	
Med	6%	0%	6%	
Small	6%	0%	6%	
Green	6%	0%	6%	
WASTE FACTOR AT RETAIL	8%	0%	8%	
SIZE DISTRIBUTION OF FRUIT				
% Large	20%	0%	20%	
% Med	20%	0%	20%	
% Small	30%	0%	30%	
% Green	30%	0%	30%	
Weight of Large fruit (kg)	12	0%	12	
Weight of Med fruit (kg)	8	0%	8	
Weight of Small fruit (kg)	3	0%	3	
Weight of Green fruit (kg)	1	0%	1	
Length of harvest season	100	0%	100	
Maturity detection device		0	1 or ZERO	
PRICE ACCELERATION DUE TO MATURITY MEASUREMENT		0%	On fresh prices	
GREEN FRUIT MARKETING		1	1 or ZERO	
FRESH ARALS PRODUCT		0	1 or ZERO	

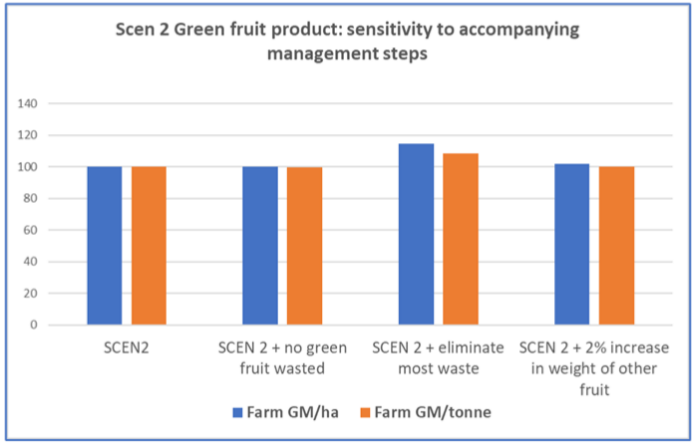
(i) Scenario 2 Green fruit product

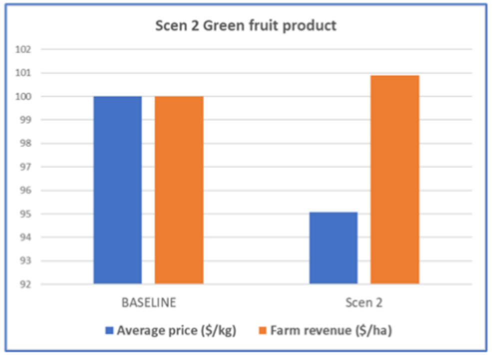




(ii) Sensitivity to specification of Scenario 2

- Sales of a waste product boost revenue without affecting costs
- Average price received falls
- Benefits available in managing wastes at farm level
- Benefits from influencing weight of other fruit

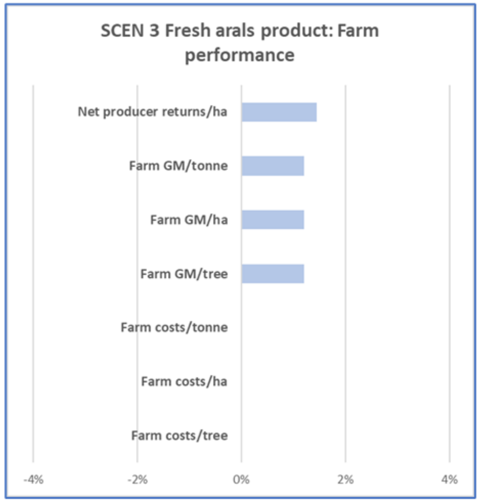


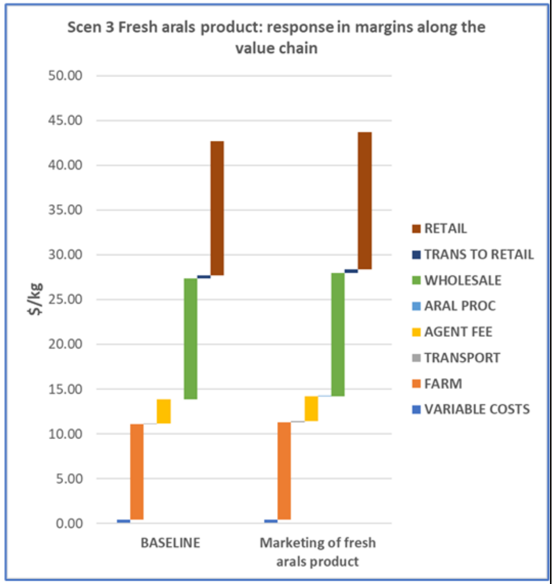


6.3.3 Scenario 3: Fresh arals product

SCENARIOS	BASELINE	% change	SCEN 3	
INTERROW	7	0%	7.0	trees/ha
BETWEEN	5.5	0%	5.5	183
FRUIT/TREE	45	0%	45.0	T/ha yield
Harvest frequency (days)	2	0%	2.0	38
WASTE FACTOR AT FARM				
Large	6%	0%	6%	
Med	6%	0%	6%	
Small	6%	0%	6%	
Green	6%	0%	6%	
WASTE FACTOR AT RETAIL	8%	0%	8%	
SIZE DISTRIBUTION OF FRUIT				
% Large	20%	0%	20%	
% Med	20%	0%	20%	
% Small	30%	0%	30%	
% Green	30%	0%	30%	
Weight of Large fruit (kg)	12	0%	12	
Weight of Med fruit (kg)	8	0%	8	
Weight of Small fruit (kg)	3	0%	3	
Weight of Green fruit (kg)	1	0%	1	
Length of harvest season	100	0%	100	
Maturity detection device		0	1 or ZERO	
PRICE ACCELERATION DUE TO MATURITY MEASUREMENT		0%	On fresh prices	
GREEN FRUIT MARKETING		0	1 or ZERO	
FRESH ARALS PRODUCT		1	1 or ZERO	

(i) Scenario 3 Fresh arals product

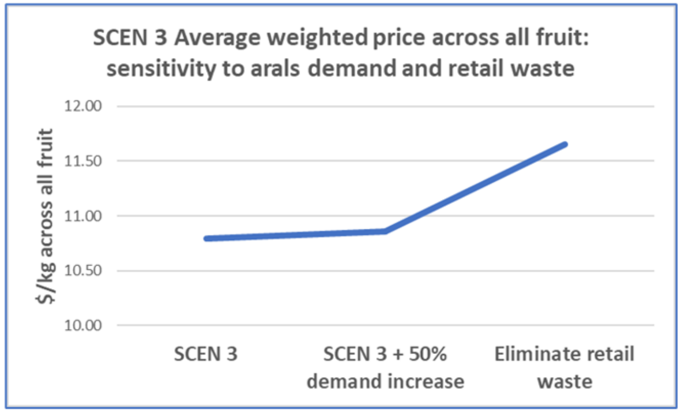




	BASELINE	SCEN 3
Weighted average farm price ($/kg)	10.67	10.80
Revenue/ha	404,306	408,891

(ii) Sensitivity to specification of Scenario 3

- Small quantities demanded (3% of projected production of large fruit)
- From low base, significant demand increases have small effect on weighted average price.
- Eliminating waste at retail raises weighted average price
- A dedicated supply chain for fresh arals product can pay $22.79/kg (double the projected weighted average price)

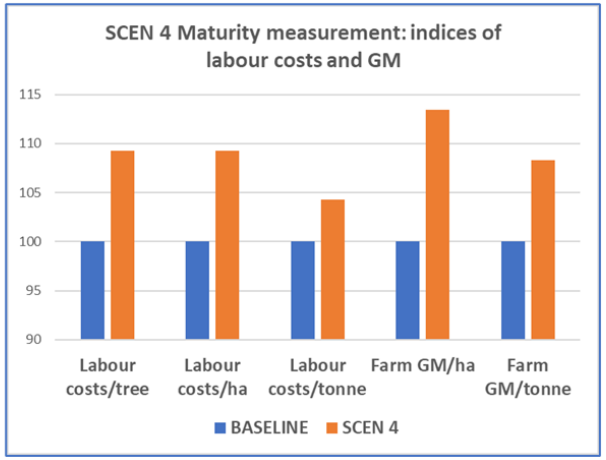


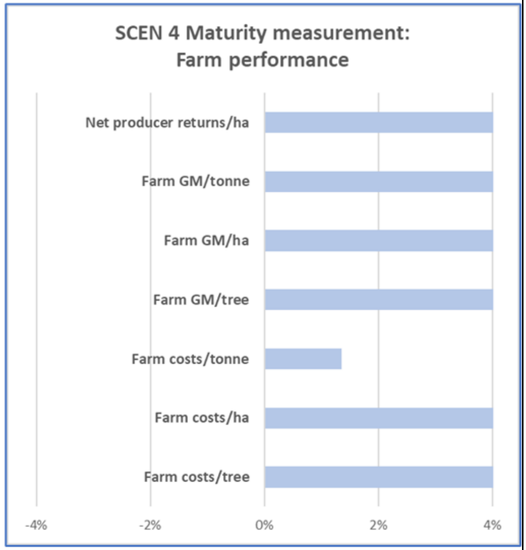
Item	$/kg fruit equivalent
Retail price/kg fuit	45.00
Retail margin	16.45
Transport to retail	0.89
Wholesale price (adjusted for waste	28.55
Margin on processing	0.05
Processing and packaging	0.25
Transport to wholesale	0.10
Agents' fee	5.15
Farm price	23.40
Farm production cost	0.61
Farmer margin	**22.79**

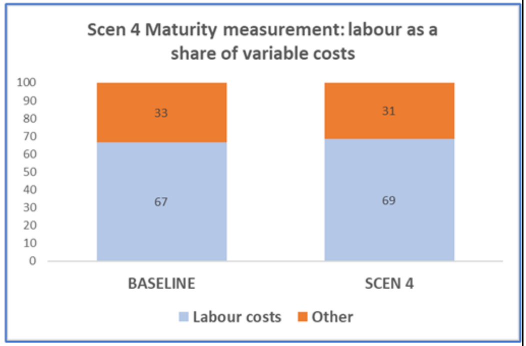
6.3.4 Scenario 4: Maturity measurement

SCENARIOS	BASELINE	% change	SCEN 4	
INTERROW	7	0%	7.0	trees/ha
BETWEEN	5.5	0%	5.5	183
FRUIT/TREE	45	0%	45.0	T/ha yield
Harvest frequency (days)	2	0%	2.0	40
WASTE FACTOR AT FARM				
Large	6%	-75%	2%	
Med	6%	-75%	2%	
Small	6%	-75%	2%	
Green	6%	0%	6%	
WASTE FACTOR AT RETAIL	8%	-90%	1%	
SIZE DISTRIBUTION OF FRUIT				
% Large	20%	0%	20%	
% Med	20%	0%	20%	
% Small	30%	0%	30%	
% Green	30%	0%	30%	
Weight of Large fruit (kg)	12	0%	12	
Weight of Med fruit (kg)	8	0%	8	
Weight of Small fruit (kg)	3	0%	3	
Weight of Green fruit (kg)	1	0%	1	
Length of harvest season	100	0%	100	
Maturity detection device		1	1 or ZERO	
PRICE ACCELERATION DUE TO MATURITY MEASUREMENT		0%	On fresh prices	
GREEN FRUIT MARKETING		0	1 or ZERO	
FRESH ARALS PRODUCT		0	1 or ZERO	

(i) Scenario 4 Maturity measurement



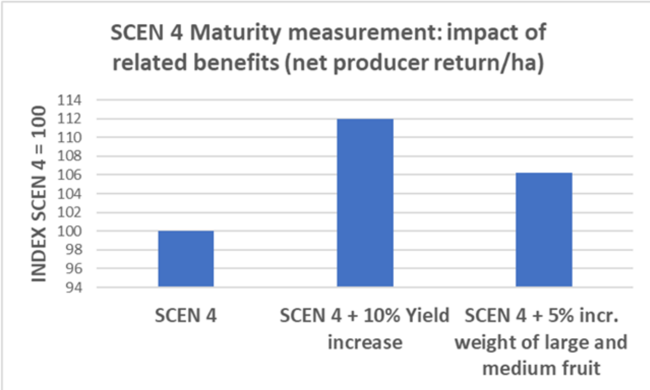




	BASELINE	SCEN 4
Weighted average farm price ($/kg)	10.67	11.52

(ii) Sensitivity to specification of Scenario 4

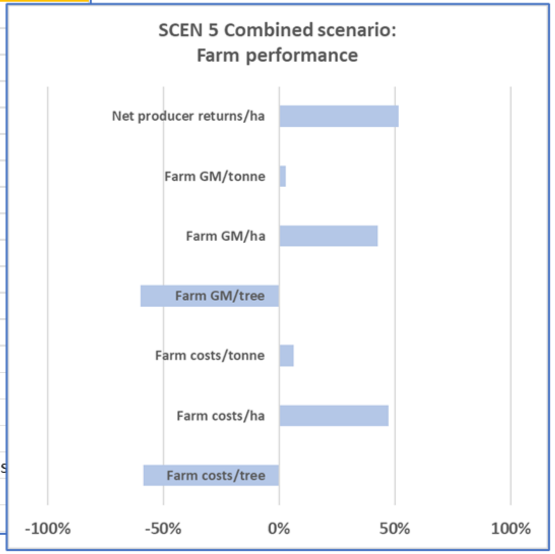
- Benefits generated from product quality improvement:
  - Potential for quality-price link (not show here)
  - Reduced waste at retail and farm levels
- Additional labour cost, impacts per tree and per ha
- Impacts are magnified at higher productivity and fruit weight



6.3.5 Scenario 5: Combined scenario

SCENARIOS	BASELINE	% change	SCEN 5	
INTERROW	7	-15%	6.0	trees/ha
BETWEEN	5.5	-55%	2.5	650
FRUIT/TREE	45	-65%	15.8	T/ha yield
Harvest frequency (days)	2	0%	2.0	52
WASTE FACTOR AT FARM				
Large	6%	-75%	2%	
Med	6%	-75%	2%	
Small	6%	-75%	2%	
Green	6%	-75%	2%	
WASTE FACTOR AT RETAIL	8%	-90%	1%	
SIZE DISTRIBUTION OF FRUIT				
% Large	20%	0%	20%	
% Med	20%	0%	20%	
% Small	30%	0%	30%	
% Green	30%	0%	30%	
Weight of Large fruit (kg)	12	0%	12	
Weight of Med fruit (kg)	8	0%	8	
Weight of Small fruit (kg)	3	0%	3	
Weight of Green fruit (kg)	1	0%	1	
Length of harvest season	100	0%	100	
Maturity detection device		1	1 or ZERO	
PRICE ACCELERATION DUE TO MATURITY MEASUREMENT		0%	On fresh prices	
GREEN FRUIT MARKETING		1	1 or ZERO	
FRESH ARALS PRODUCT		1	1 or ZERO	

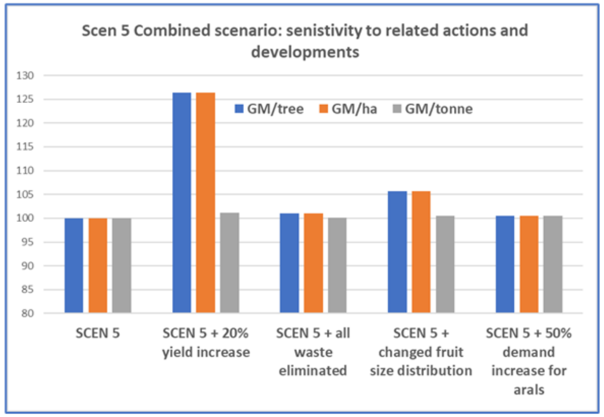
(i) Scenario 5 Combined scenario

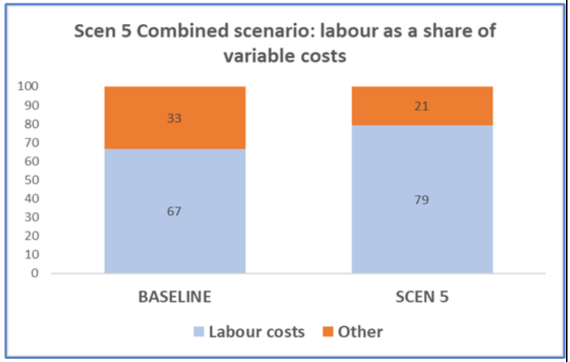


	BASELINE	SCEN 5
Weighted average farm price ($/kg)	10.67	11.06

(ii) Sensitivity to specification of Scenario 5

- Farm returns are magnified at higher yield levels
- Marginal change to waste levels is not a significant influence on returns
- On-farm activities affecting the value chain have little influence on farm GM
- Fruit size distribution is a significant influence, but differential pricing for fruit size is not considered here





7 SYNTHESIS AND CONCLUSIONS

7.1 Overview

The current study maps current situation in the jackfruit value chain to actual and potential technologically-based opportunities. It offers a review of available literature on selected issues and the associated technologies, and employs field-level consultation to present practical aspects of the value chain, the production and marketing system, and the relevant research underway. The study offers an examination of financial implications of change in the value chain, and particularly for producers, due to these technologies. It identifies facilitating factors in delivery of enhanced adoption of desirable technologies.

7.2 The jackfruit value chain mapped to opportunities for technology

The jackfruit value chain is characterised by an underdeveloped retail market and a poor understanding of consumer demand. In a crowded field of fresh fruit and vegetable delivery to the highly concentrated Australian food retail sector, incentives for supply chain actors to buy jackfruit are weak. Motivated wholesalers – a key link in the value chain – describe an array of potential retail products, while imported shelf-stable processed jackfruit are very cheap and readily available.

A recurrent theme in the jackfruit value chain is that at least three viable consumer products are available to the Australian industry. These are fresh whole fruit, fresh arals extracted and packed as a single serving in the nature of strawberry punnets, and a vegetable for cooking that utilises small unripe (green) fruit. For fresh fruit supply, emerging research suggests that retail shoppers prefer a small fruit or a cut fruit portion over a large fruit. For fresh fruit and the green product, supply chain technologies are well established but price-quality linkages, particularly at producer level, are not. These organisational counterparts to technologies, which include standard quality demarcations (such as fruit size) and product presentation protocols, have been identified by previous commentators as essential in successful supply chain operation. The present study has identified substantial financial implications at the farm level of changing trees' distribution of fruit sizes, even in the absence of a price differential.

The introduction of a fresh processed product has been demonstrated on a small scale based on manual labour which largely mimics practices in Asian counties. Some components of the technology (e.g. peeling, cutting) are readily available in while others (e.g. arals' extraction and de-seeding) are not. Small scale equipment specifically designed for jackfruit appears in literature from India and is discussed in this report. A notable aspect of the technology, even those automated aspects of it, is the manual transfer of fruit into and out of stages of processing. A further conclusion is that such technologies are slow and so operate at a scale well below that required by supply from multiple Australian orchards. The technical procedures for extracting arals, packaging them and providing suitable treatments and arrangements for appropriate shelf life, are available from literature and extant experience. As for fresh fruit, the organisational arrangements or business model which would surround the industrial scale, yet seasonal, processing of jackfruit into a fresh aral product remain undeveloped.

Stakeholders' reports of difficulties supplying into retail stores, particularly intermittently at low volumes with large fruit, are associated with waste at retail level. The current study has projected significant gains available from reducing this waste, as it impacts both the volumes sold and the average price received.

Jackfruit production faces constraints associated with its small footprint in the market and small numbers of producers. A lack of on-label chemicals, limited - and reportedly somewhat opaque -

supply of planting material, and much uncertainty about varieties and crop husbandry, all provide researchers and commercial suppliers with a challenging environment for technology development and its adoption. Waste at production and harvest, particularly from rots, advanced material and poor tree architecture, is also significant. The current study has demonstrated significant benefits from reducing this waste, although it affects product volume and not – in current industry contexts – the average price received. The current study has projected the unsurprising result that elimination of wastes and acceleration of crop yield will deliver benefits, and also magnify the benefits available from the uptake of single technologies addressing other tasks.

This study responded to substantial stakeholder commentary on the lack of a maturity measurement for jackfruit. This constrains harvest management, quality control, effective marketing and innovation in product management. The current study's analysis confirms the benefits available form these changes, on a largely conceptual basis but with some detail that identifies the source of benefits. A review of 416 research articles on the technology for fruit maturity measurement identified optical technologies (particularly spectrographic ones such as NIR) as the most frequently occurring, but none of the work was on jackfruit and a minimal number of papers was about pre-harvest use of convenient devices such as hand-held battery-operated equipment. One Australian study employed NIR on harvested jackfruit. Physical displacement technologies, mostly measuring firmness, are also widely cited and particularly acoustic implementations. Again, no such studies were found for jackfruit. Image processing – referred to here as a colour card action – offering electronically enhanced matching of fruit colours schemes to standard images was also not reported in use for jackfruit. The fruit's thick and uneven skin and its complex ripening processes, along with a variance in trees and fruit that makes difficult the calibration of colour, light and sound waves, all contribute to delays in the emergence of this technology for jackfruit. The current study demonstrates gains from the maturity measurement task, but these remain in the realm of the potential due to the lack of a ready technology.

Orchard redesign is the subject of current research, from which the delivery of knowledge is necessarily slow to emerge. The current study has projected substantial potential gains to producers based on changed cost structures where small trees with fewer fruit, but many more of them per hectare. Pending the outcomes of field trials, the analysis presented in this study is awkwardly reliant on assumptions about trade offs in productivity, input use and costs. The construction and analysis of technology-related scenarios also relies on parameters not yet measured in robust experiments. This study projects that orchard redesign is likely to deliver a changed production cost structure, with some unexpected patterns of labour use and costs emerging. These assumption-driven analyses however also consistently project enhanced benefits of orchard redesign from yield increases. It is expected that any commercial planting will endeavour to use superior varieties and improved husbandry, so these enhanced patterns of benefit delivery are likely to emerge as the technology is taken up.

In general, the technologies that this study mapped to the jackfruit value chain are either limited in their readiness (maturity measurement), not adapted to Australian conditions (arals' processing), not applied to jackfruit (disease pathogen detection systems), or are the subject of intense ongoing research (orchard design).

7.3 Central results from scenario analysis

Analysis encountered the common value chain analytic phenomenon of divergent performance metrics along the chain. Retail metrics address price margins and turnover while the production level features performance per hectare. Typically for highly divergent chains, quality standards and product descriptions for jackfruit are lacking. The current study's preoccupation with emerging research and technology adoption further expands the list to the performance per tree and numbers of trees. Notwithstanding this variety in terms of reference, the study revealed several cases of notable tradeoffs between orchard density and various measures of performance. Ongoing research will illuminate this issue more fully, but as an immediate commentary the current study highlights two findings: the consequences of the tradeoffs; and the persistence of labour costs. Across a variety of specifications, reduced labour input due to smaller trees and favourable canopy architecture is consistently offset by the number of trees. This study does not set out to measure precisely the magnitude of costs, but does capture the inherent principles and their implications for technology adoption. All casual labour was valued at the minimum wage in the analysis, and so may understate these costs. Most scenarios saw an increase in shares of labour in variable costs, although in many cases the level of aggregate variable cost was projected to fall.

An unsurprising result is the extent to which the current study demonstrated the importance to producer performance of securing a high yield and – relatedly from a value chain point of view – reducing waste at farm level and along the chain. As stated elsewhere, most technologies would be implemented with yield maximisation in mind so the study's findings reinforce those incentives. The baseline analysis depicted a low yield, and so some scenarios were examined in that context and this may understate some of the benefits delivered from some technologies.

This study has compiled a set of costs and margins along a hypothetical fresh arals value chain which offers producers an indicative price about double the baseline price received for all fruit. This value chain requires an entirely new processing function fuelled by technology but facilitated by the development of appropriate delivery conditions, logistics to serve distant markets, and marketing organisation for delivery. The study projects benefits from the supply of a fresh green product – heretofore not harvested – as a vegetable for use in cooking. This product requires no processing, but as for packaged arals it does need a co-ordinating business model.

Diversification of jackfruit's marketable products can accelerate, as well as be embodied by, a change in the size and weight distribution of fruit. The current study has assumed some working nomenclature and assumptions about fruit size and weight, but generally maintained the lack of price premium for any fruit size of quality category. One industry commentator suggested that a small jackfruit ("the size of a rockmelon") was an ideal for fresh fruit at retail. Most reported analyses favour large jackfruit for processing, particularly as the aral content is highest in large fruit and the proportion of weight allocated to peel is the lowest. Fruit size categories also vary in the numbers of seeds contained, offering yet more variety in buyers' preferences. The advent of price premia for size categories is then likely and has important implications for the benefits – an extension on the analysis offered in this study – of precision in selecting fruit for sale. Orchard redesign offers a canopy facilitating visibility; maturity measurement quantifies and standardises fruit selection for harvests; standardised varieties reduces variation in pollination, ripening and maturity configuration; harvesting of green fruit for sale shifts trees' production toward remaining fruit; and the identification of very large fruit as suppliers of arals for processing – possibly to include damaged fruit that might otherwise have been discarded. This study projected significant reinforcement of the financial benefits of separate technologies' being simultaneously adopted, and this is seen most clearly in the context of product differentiation around fruit size.

7.4 Organisational aspects of industry and technological development

Maximisation of benefits from marketing bulk or differentiated products are referred to in various ways by the analysis conducted in this study, which has technology as its focus. Organisational tasks in this regard include the development of product and quality descriptions, scheduling of product to market or into processing, and establishing pricing and payment systems which promote quality and supply chain performance in delivering it.

Most such organisation is empowered by information flows, and so by technologies. The current study has paid little attention to the means by which jackfruit growers might communicate with each other and along the value chain. Long delivery routes in hot conditions have meant that data loggers are widely used. However product descriptions, quality standards and prices received for deliveries to retail are not in evidence. Communication technologies are available for the technical tasks involved, but the establishment of the key variables and the management of data base is organisational. The proposed introduction of green jackfruit as a retail product offers a relevant challenge. Industries, including small industries, form producer associations which can promote product value addition and retention, and facilitate the associated product flows. This offers one organisational option to jackfruit.

The current study's attention to the (hypothetical) advent of new fresh cut arals product has helped identify the opportunity in financial terms. The equipment required is likely to be small and consist of multiple lines. The activity is highly seasonal. Its success rests on excellent communications and logistics both for purchases from producers and sales to retail. Packages and shelf life enhancing treatments are of an industry standard and readily available. These features lend themselves to an entrepreneurial business model with variable staffing and small amounts of capital tied up in vehicles and equipment, and low inventory. Despite these conditions, jackfruit producing locations lack access to this market. A coalition of producers and agents, or one single entrepreneur, can facilitate this enterprise on a variety of bases including leasing of equipment, varied locations, activities blended with other orchard and fruit market operations, and exploitation of regional development incentive monies. A group of producers offer one organisational option for helping establish this business.

7.5 Further research

The current study identifies a number of research topics, on which research action is advocated. Research on consumer demand, particularly at the point of identification and design of products and their indicators value, has been discussed above. This would offer valuable guidance to growers and plant breeders with respect to fruit sizes, which this study has identified as a source of future value added.

The tradeoff between orchard density and costs per hectare is emerging as vital in orchard design and the somewhat irreversible producer decision on planting. The current study has assembled and used a set of assumptions which in several ways can be improved upon. This research topic is being addressed in ongoing research. The present study has identified the persistence of high labour costs in scenarios for technological change. Although simplistic, the baseline data approximated a time in motion approach which would be usefully verified by ongoing research.

Several technologies require developmental steps before unleashing significant gains for jackfruit growers and consumers. These include maturity measurement and pathogens' detection, both of which have elements of information technology. Design and operation of whole of chain information systems also falls into that category and can utilise the maturity and disease management data.

Research that advances high technology management aids, and connects them to larger benefit ecosystems by way of information technologies, is then called for.

Bibliography

Acedo, A., Acedo, J., Troyo, R., Valida, A., & Benitez, M. (2014). *Microbiological quality of freshcut jackfruit and pineapple and the antimicrobial potential of organic acids and probiotics.* Paper presented at the XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014): 1120.

AgriFutures. (2019). The impact of freight costs on Australian farms. *A report for AgriFutures Australia prepared by Deloitte Access Economics, Canberra*.

Anaya-Esparza, L. M., González-Aguilar, G. A., Domínguez-Ávila, J. A., Olmos-Cornejo, J. E., Pérez-Larios, A., & Montalvo-González, E. (2018). Effects of minimal processing technologies on jackfruit (Artocarpus heterophyllus Lam.) quality parameters. *Food and Bioprocess Technology, 11*(9), 1761-1774.

Babacan, H., & McHugh, M. J. (2020). RE-THINKING AGRICULTURAL SUPPLY CHAINS IN NORTHERN AUSTRALIA. *Australasian Journal of Regional Studies, 26*(3), 239.

Babu, P. S., Pulissery, S. K., Chandran, S. M., Mahanti, N. K., Pandiselvam, R., Jaganath, B., & Kothakota, A. (2022). Non-invasive and rapid quality assessment of thermal processed and canned tender jackfruit: NIR spectroscopy and chemometric approach. *International Journal of Food Science & Technology, 57*(9), 6072-6081.

Best, A. (2015). *Value-adding options for tropical fruit using jackfruit as a case study*: RIRDC.

Borines, L., Palermo, V., Guadalquiver, G., Dwyer, C., Drenth, A., Daniel, R., & Guest, D. (2014). Jackfruit decline caused by Phytophthora palmivora (Butler). *Australasian Plant Pathology, 43*(2), 123-129.

Carter, M. (2019). Competition and Profit Margins in the Retail Trade Sector| Bulletin–June 2019.

Cruz-Casillas, F. C., García-Cayuela, T., & Rodriguez-Martinez, V. (2021). Application of conventional and non-conventional extraction methods to obtain functional ingredients from jackfruit (Artocarpus heterophyllus lam.) tissues and by-products. *Applied Sciences, 11*(16), 7303.

Diczbalis, Y., Lucia M Borines, Roberta D. Lauzon, Lorina A. Galvez, Francisco T. Dayap, Dario T. Lina, Elsie E. Salamat, Alicia Bulawan, Brenda Almeroda, Eric Kent Mapili, Virgilio Loquias, Colin Leung, Mark Hoult and Natalie Dillon. (2019). *Tropical tree fruit research and development in the Philippines and northern Australia to increase productivity, resilience and profitability* (Vol. FR2019-111): Australian Centre for International Agricultural Research.

Ding, C., Feng, Z., Wang, D., Cui, D., & Li, W. (2021). Acoustic vibration technology: Toward a promising fruit quality detection method. *Comprehensive Reviews in Food Science and Food Safety, 20*(2), 1655-1680.

Drinnan, J., Neil Wiltshire, Yan Diczbalis, Peter Holden and Matt Thompson. (2018). *Improving the Capacity of Primary Industries to Withstand Cyclonic Winds* (Vol. AgriFutures Australia Publication No 18/031). Canberra.

Elevitch, C. R., & Manner, H. I. (2006). Artocarpus heterophyllus (jackfruit). *Species profiles for Pacific Island agroforestry, 10*, 1-25.

Fang, Y., & Ramasamy, R. P. (2015). Current and prospective methods for plant disease detection. *Biosensors, 5*(3), 537-561.

Govindaraj, D., Rajan, M., Hatamleh, A. A., & Munusamy, M. A. (2018). From waste to high-value product: Jackfruit peel derived pectin/apatite bionanocomposites for bone healing applications. *International journal of biological macromolecules, 106*, 293-301.

Hareesha, T. S., & Mathew, S. M. (2016). *Development and evaluation of a jackfruit peeler cum corer.* Department of Post-Harvest Technology and Agricultural Processing,

Horsburgh, C., & Noller, J. (2005). *Exotic Tropical Fruits and Vegetables: Category Marketing Opportunities*: Queensland Department of Primary Industries.

Howells, H. (2004). *Northern Territory Tropical Fruits Industry – Market Opportunities*. Canberra: A report for the Rural Industries Research and Development Corporation.

Intaravanne, Y., Sumriddetchkajorn, S., & Nukeaw, J. (2012). Cell phone-based two-dimensional spectral analysis for banana ripeness estimation. *Sensors and Actuators B: Chemical, 168*, 390-394.

John, P. J., & Narasimham, P. (1993). PROCESSING and EVALUATION of CARBONATED BEVERAGE FROM JACKFRUIT WASTE (ARTOCARPUS HETEROPHYLLUS). *Journal of Food Processing and Preservation, 16*(6), 373-380. doi:https://doi.org/10.1111/j.1745-4549.1993.tb00217.x

Khakimov, B., Mongi, R. J., Sorensen, K. M., Ndabikunze, B. K., Chove, B. E., & Engelsen, S. B. (2016). A comprehensive and comparative GC-MS metabolomics study of non-volatiles in Tanzanian grown mango, pineapple, jackfruit, baobab and tamarind fruits. *Food Chemistry, 213*, 691-699. doi:10.1016/j.foodchem.2016.07.005

Kulathaisamy, T., & Jesudas, M. (2012). A pneumatic assisted electronically controlled continuous aonla seed removing machine. *Agricultural Engineering International: CIGR Journal, 14*(2), 94-101.

Kushwaha, R., Fatima, N. T., Singh, M., Singh, V., Kaur, S., Puranik, V., . . . Kaur, D. (2021). Effect of cultivar and maturity on functional properties, low molecular weight carbohydrate, and antioxidant activity of Jackfruit seed flour. *Journal of Food Processing and Preservation, 45*(2), 10. doi:10.1111/jfpp.15146

Kushwaha, R., Fatima, N. T., Singh, M., Singh, V., Kaur, S., Puranik, V., . . . Kaur, D. (2021). Effect of cultivar and maturity on functional properties, low molecular weight carbohydrate, and antioxidant activity of Jackfruit seed flour. *Journal of Food Processing and Preservation, 45*(2), e15146.

Latifah, M., Ab Aziz, I., Fauziah, O., & Talib, Y. (2011). *Effect of inclusion of ethylene absorbent to the quality of the fresh-cut jackfruit stored at 10Â° C.* Paper presented at the II International Conference on Quality Management of Fresh Cut Produce: Convenience Food for a Tasteful Life 1209.

Li, Z., Lan, Y., Miao, J., Chen, X., Chen, B., Liu, G., . . . Cao, Y. (2021). Phytochemicals, antioxidant capacity and cytoprotective effects of jackfruit (Artocarpus heterophyllus Lam.) axis extracts on HepG2 cells. *Food Bioscience, 41*, 100933.

Competition and Consumer Act 2010—Competition and Consumer (Industry Codes—Food and Grocery) Regulation 2015: Submission 6, (2010).

Mahanta, C. L., & Kalita, D. (2015). Processing and utilization of jackfruit seeds. In *Processing and impact on active components in food* (pp. 395-400): Elsevier.

Mahmud, M. S., Zahid, A., He, L., & Martin, P. (2021). Opportunities and possibilities of developing an advanced precision spraying system for tree fruits. *Sensors, 21*(9), 3262.

Mijin, S., Ding, P., Saari, N., & Ramlee, S. I. (2021). Effects of pollination techniques and harvesting stage on the physico-chemical characteristics of jackfruit. *Scientia Horticulturae, 285*, 10. doi:10.1016/j.scienta.2021.110199

Mondal, C., Remme, R., Mamun, A., Sultana, S., Ali, M., & Mannan, M. (2013). Product development from jackfruit (Artocarpus heterophyllus) and analysis of nutritional quality of the processed products. *Journal of Agriculture and Veterinary Science, 4*(1), 76-84.

Nath, V., Marboh, E., Gupta, A., & Lal, N. (2019). Canopy management for sustainable fruit production. *International Journal of Innovative Horticulture, 8*(2), 115-126.

Nelluri, P., Venkatesh, T., Kothakota, A., Pandiselvam, R., Garg, R., & Mousavi Khaneghah, A. (2022). Artocarpus heterophyllus Lam (jackfruit) processing equipment: Research insights and perspectives. *Journal of Food Process Engineering, 45*(6), e13920.

Nickhil, C., Gowda, N. N., Ranganna, B., & Subramanya, S. (2020). Development of semi mechanised tools for cutting and splitting of jack fruit for bulb separation. *Agricultural Mechanization in Asia, Africa and Latin America, 51*(1), 84.

Nicola, S., Toivonen, P. M., & Watkins, C. (2018). *II ISHS International Conference on Quality Management of Fresh Cut Produce: Convenience Food for a Tasteful Life* (Vol. 1209): International Society for Horticultural Science.

Norris, A., Van Hag, L., Su, C., Attenborough, E., Buckingham, E., Perry, O., & Marcsik, D. (2021). Processing Jackfruit into Ready-to-Eat Products and Ingredients. *AgriFutures Australia: Wagga Wagga, NSW, Australia*.

Oraño, J. F. V., Maravillas, E. A., & Alia, C. (2020). Classification of jackfruit fruit damage using color texture features and backpropagation neural network. *Int J Adv Sci Eng Inf Technol, 10*(5), 1813-1820.

Rahman, A., Huq, E., Mian, A. J., & Chesson, A. (1995). MICROSCOPIC AND CHEMICAL-CHANGES OCCURRING DURING THE RIPENING OF 2 FORMS OF JACKFRUIT (ARTOCARPUS-HETEROPHYLLUS L). *Food Chemistry, 52*(4), 405-410. doi:10.1016/0308-8146(95)93290-8

Rahman, M. A., Nahar, N., Mian, A. J., & Mosihuzzaman, M. (1999). Variation of carbohydrate composition of two forms of fruit from jack tree (Artocarpus heterophyllus L.) with maturity and climatic conditions. *Food Chemistry, 65*(1), 91-97. Retrieved from <Go to ISI>://WOS:000078862200014

Rajasekharan, R., Bahuleyan, A. K., Madhavan, A., Philip, E., Sindhu, R., Binod, P., . . . Pandey, A. (2022). Neem extract–blended nanocellulose derived from jackfruit peel for antibacterial packagings. *Environmental Science and Pollution Research*, 1-10.

Ramli, A. N. M., Badrulzaman, S. Z. S., Hamid, H. A., & Bhuyar, P. (2021). Antibacterial and antioxidative activity of the essential oil and seed extracts of Artocarpus heterophyllus for effective shelf-life enhancement of stored meat. *Journal of Food Processing and Preservation, 45*(1), e14993.

Rana, S. S., Pradhan, R. C., & Mishra, S. (2018). Variation in properties of tender jackfruit during different stages of maturity. *Journal of Food Science and Technology-Mysore, 55*(6), 2122-2129. doi:10.1007/s13197-018-3127-9

Ranasinghe, R., Maduwanthi, S., & Marapana, R. (2019). Nutritional and health benefits of jackfruit (Artocarpus heterophyllus Lam.): a review. *International journal of food science, 2019*.

Reis, M. F. T., Bonomo, R. C. F., de Sousa, R. d. C. S., Veloso, C. M., Fontan, R. d. C. I., & Gandolfi, O. R. R. (2016). < b> Optimization of protein extraction process from jackfruit seed flour by reverse micelle system. *Acta Scientiarum. Technology, 38*(3), 283-290.

Sabidi, S., Koh, S. P., Abd Shukor, S., Adzni Sharifudin, S., & Sew, Y. S. (2020). Safety assessment of fermented jackfruit (Artocarpus heterophyllus) pulp and leaves in Sprague-Dawley rats. *Food science & nutrition, 8*(8), 4370-4378.

Santhosh, R., & Sarkar, P. (2022). Jackfruit seed starch/tamarind kernel xyloglucan/zinc oxide nanoparticles-based composite films: Preparation, characterization, and application on tomato (Solanum lycopersicum) fruits. *Food Hydrocolloids, 133*, 107917.

Saranya, N., Ajmani, A., Sivasubramanian, V., & Selvaraju, N. (2018). Hexavalent Chromium removal from simulated and real effluents using Artocarpus heterophyllus peel biosorbent-Batch and continuous studies. *Journal of Molecular Liquids, 265*, 779-790.

Saxena, A., Maity, T., Raju, P., & Bawa, A. (2015). Optimization of pretreatment and evaluation of quality of jackfruit (Artocarpus heterophyllus) bulb crisps developed using combination drying. *Food and Bioproducts processing, 95*, 106-117.

Shyamalamma, S., Chandra, S., Hegde, M., & Naryanswamy, P. (2008). Evaluation of genetic diversity in jackfruit (Artocarpus heterophyllus Lam.) based on amplified fragment length polymorphism markers. *Genetics and Molecular Research, 7*(3), 645-656.

Sim, M. Y. M., Ahmad, M. N., Shakaff, A. Y. M., Ju, C. P., & Cheen, C. C. (2003). A disposable sensor for assessing Artocarpus heterophyllus L. (jackfruit) maturity. *Sensors, 3*(12), 555-564. doi:10.3390/s31200555

Spencer, S. (2016). From farm to retail–how food prices are determined in Australia. In: Canberra: Australian Government Rural Industries Research and Development ….

Srinivasan, K., & Kumaravel, S. (2016). MASS SPECTROMETRY ANALYSIS OF VOLATILE CONSTITUTENTS OF JACK FRUIT POWDER. *Indo American Journal of Pharmaceutical Sciences, 3*(4), 331-339.

Sulaiman, M. A., Yusoff, F. M., Kamarudin, M. S., Amin, S. N., & Kawata, Y. (2022). Fruit wastes improved the growth and health of hybrid red tilapia Oreochromis sp. and Malaysian mahseer, Tor tambroides (Bleeker, 1854). *Aquaculture Reports, 24*, 101177.

Swami, S. B., Thakor, N., Haldankar, P., & Kalse, S. (2012). Jackfruit and its many functional components as related to human health: a review. *Comprehensive Reviews in Food Science and Food Safety, 11*(6), 565-576.

Swami, S. B., Thakor, N., Orpe, S., & Kalse, S. (2014). Development of osmo-tray dried ripe jackfruit bulb. *Journal of Food Research and Technology, 2*(2), 77-86.

Zeng, S., Chen, Y., Wei, C., Tan, L., Li, C., Zhang, Y., . . . Cao, J. (2022). Protective effects of polysaccharide from Artocarpus heterophyllus Lam.(jackfruit) pulp on non-alcoholic fatty liver disease in high-fat diet rats via PPAR and AMPK signaling pathways. *Journal of Functional Foods, 95*, 105195.

Appendix A. Literature review on technology for fruit maturity measurement

Targeting of search

A literature search of Web of Science using search words "NON-DESTRUCTIVE" AND "FRUIT" AND ("RIPENESS" OR "MATURITY") generated 585 English language research publications, of which 416 were retained after removal of duplicates, review papers, erroneous inclusions and non-empirical conference papers. From a first paper's appearance in 1991, more than half the publications were produced since 2015.

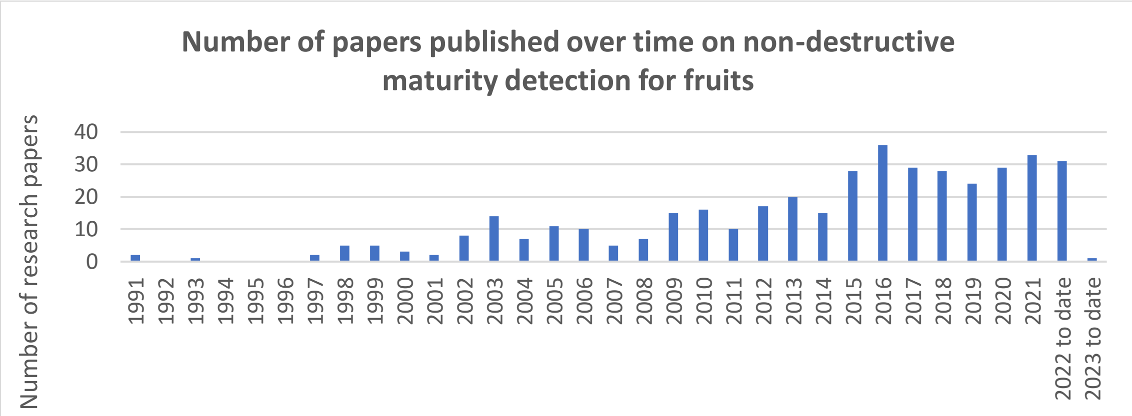


Figure A1. Numbers of papers published on non-destructive fruit maturity measurement

Purpose of research

The purpose of research into non-destructive measurement of fruit ripeness and maturity is mostly associated with quality prediction (e.g. shares of crop achieving a high quality grade) and improving supply chain performance (e.g. shelf life). A further 21% of published research papers were concerned with establishing and calibrating maturity indices. Improvement of the harvest timing decision occupied just 14% of the research papers produced since 1991.

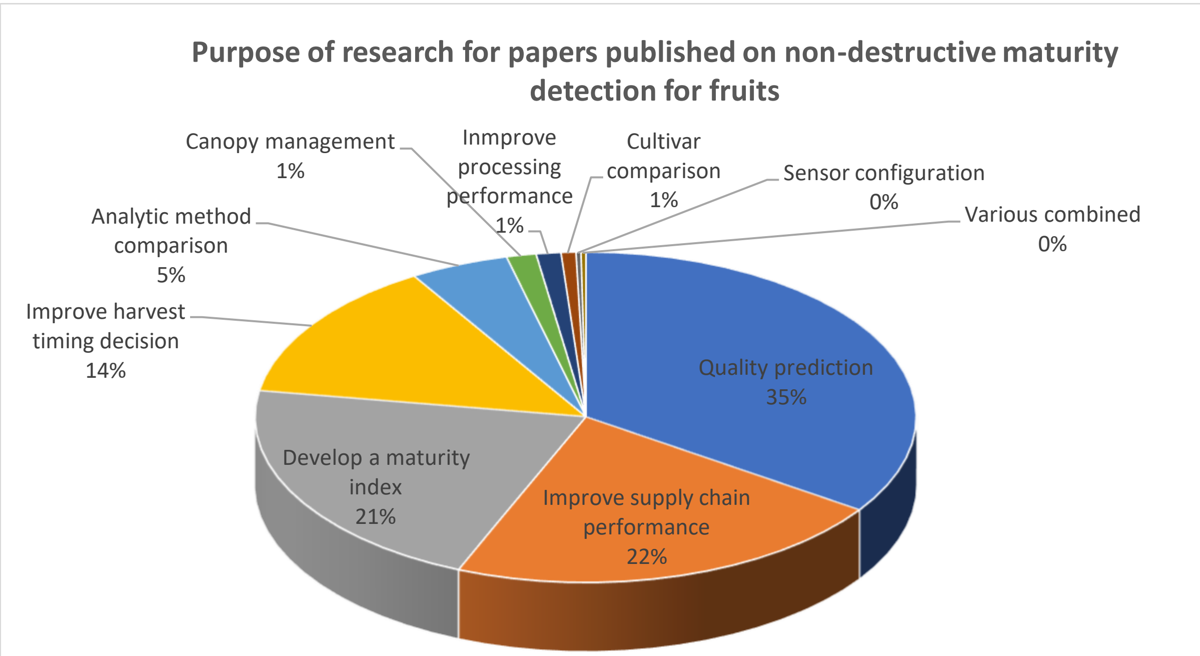


Figure A2. Purposes of published research on non-destructive fruit maturity measurement

Broad categories of technology

The broad categories of maturity-measuring technologies examined in this research include optical, mechanical, electromagnetic and ultrasound. Particularly in recent years, optical methods have predominated.

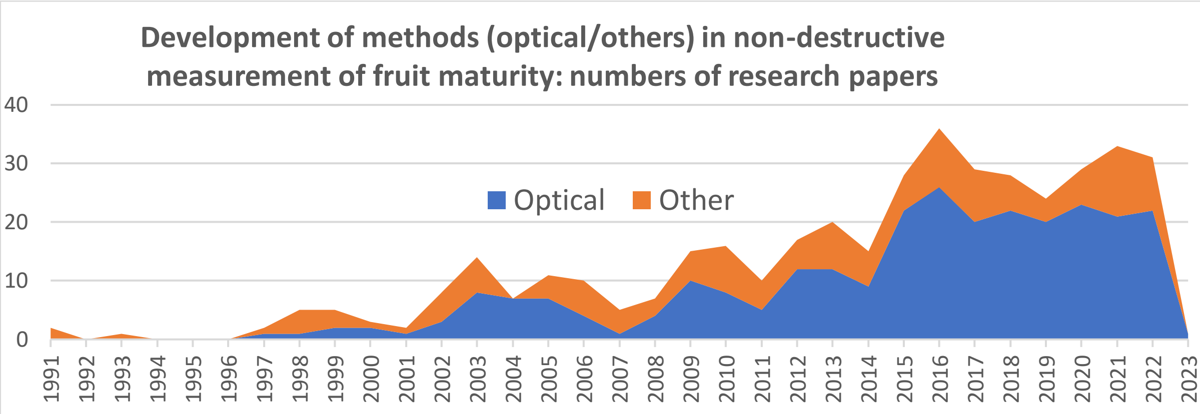


Figure A3. Optical vs other methods in non-destructive fruit maturity measurement

Fruits targeted in research

The general categories of methods directed at non-destructive fruit maturity measurement – as noted above dominated by optical technology – is NIRS (84 papers with some 10 using NIRS derivatives or refinements). This is followed by image analysis, which includes methods involving analysis of photographs, particularly relating to fruit colours' presence, intensity and distribution on the fruit or as seen within an orchard's canopy.

The fruits targeted in this body of research do not include jackfruit. Amongst tropical fruits, only mango is well represented (52 studies), as is banana. Amongst tropical fruits the presence of durian, pineapple, cantaloupe and pomegranate are of particular interest as these fruits have non-smooth skins with multiple colours and a non-uniform flesh which includes seeds and distinct seed structures.

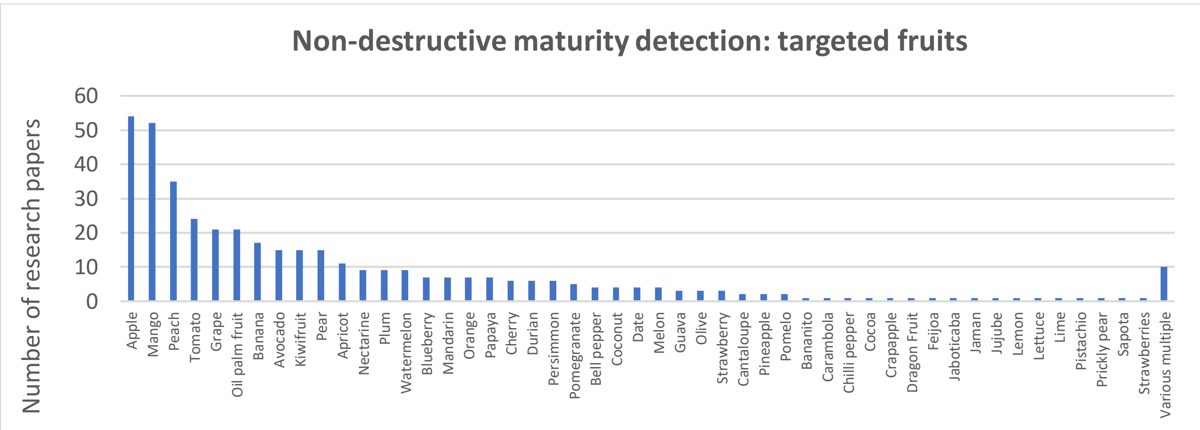


Figure A4. Fruits targeted in research on non-destructive fruit maturity measurement

Applications of optical technologies used

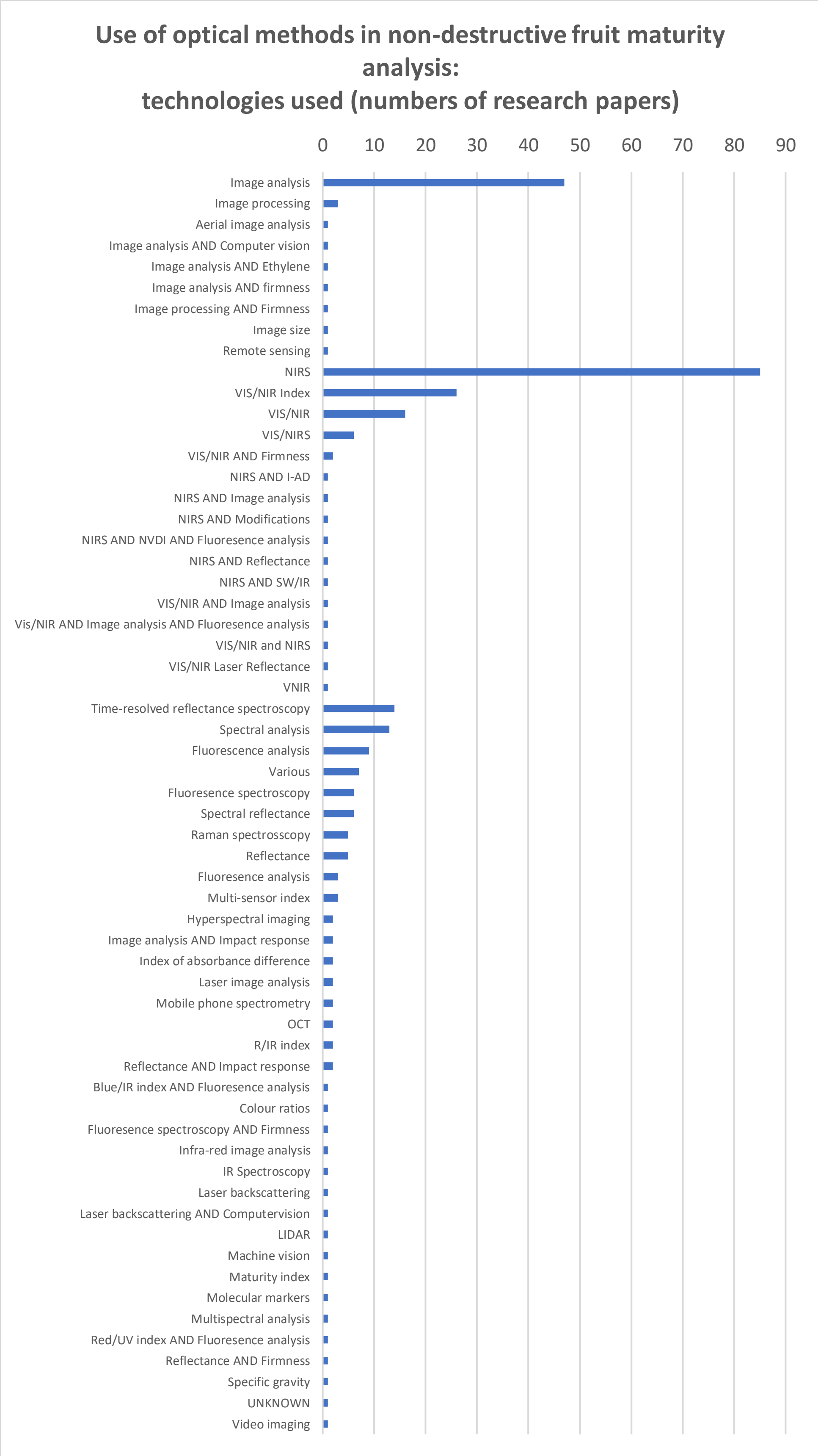


Figure A5. Detail of optically-based technologies in research on non-destructive fruit maturity measures

Detailed results for these fruits are presented below, along with classification of the research as utilising fruit pre- or post-harvest: it should be noted that this information is interpreted from the research papers and refers to suitability rather than to experimental practice as reported. Amongst these examples, and in the absence of studies of jackfruit, particular attention (shaded cells) is drawn to optical methods, both image analysis and NIRS.

Table A1. Summary of research on maturity measurement: cases of thick/irregular skinned tropical fruits

Fruit	**Pre or post-harvest measurement of maturity**	**Purpose of research**	**Method used**	**Variable measured**
Cantaloupe	Pre	Harvest decision	Optical	Reflectance
Cantaloupe	Post	Maturity index	Mechanical	Firmness
Durian	Pre	Harvest decision	Optical	NIRS
Durian	Post	Maturity index	Optical	Fluorescence spectroscopy
Durian	Post	Maturity index	Acoustic	Wave attenuation
Durian	Post	Processing performance	Optical	Video imaging
Durian	Post	Supply chain performance	Optical	Image analysis
Durian	Pre	Maturity index	Optical	Molecular markers
Pineapple	Post	Supply chain performance	Mechanical	Acoustic analysis
Pineapple	Pre	Quality prediction	Genetic	DNA analysis
Pomegranate	Post	Maturity index	Optical	Raman spectroscopy
Pomegranate	Post	Maturity index	Optical	VIS/NIR Index
Pomegranate	Pre	Harvest decision	Optical	Image processing
Pomegranate	Pre	Quality prediction	Optical	NIRS
Pomegranate	Post	Quality prediction	Magnetic	MRI

Both image analysis and NIRS analysis rely – to differing degrees – on modelling of observed information and its fitting to models developed for prediction. These modelling and calibration procedures are well developed, and even for the small number of fruits represented, they have been applied across the spectrum of the key variables (maturity measurement and indexing, quality prediction, and harvest decisions). A data collection and model training exercise is reported from 2019 (Diczbalis, 2019).

Disposable sensors have been used in post harvest and with supply chain applications to categorise and measure jackfruit ripeness, both from a chemical and consumer assessment point of view (Sim et al., 2003). Hand-held NIRS technology is readily available, and image analysis has been implemented for use in portable devices such as mobile telephones.

Appendix B. Commercial Readiness Assessment Matrix (CRAM) used in Technology Readiness Assessment

The Commercialisation Readiness Assessment Matrix (CRAM)					
TECHNOLOGY			max score = 36		
USE					
CRAM SCORE	0	0	0	0	0
Development Stage	**Score**	**Technology Readiness Level (T)**	**Market & Customer Knowledge (M)**	**Supply, Manufacturing & Distribution Knowledge (S)**	**Financial, Revenue and Cost Models (F)**
Early Stage/Research		The basic principles have been observed and reported.	The target end-user and market are clearly understood and described (including segments).	Initial manufacturing and supply chain stages to deliver the technology have been identified.	The total costs to develop and commercialise (extension) the technology have been documented.
	0				
		Competing technology and/or technology applications have been formulated or reviewed and compared.	Secondary research has been undertaken and included in the project materials.	The supply chain requirements have been identified, including the types of partners or manufacturers.	Revenues for the next 36 months have been modelled for the initiative and documented.
	0				
		Preliminary analytical, experimental, or proof-of-concept functions have been demonstrated.	Primary market research has been undertaken and insights applied.	The roles and responsibilities have been defined for the types of supply chain partners who will need to deliver the technology, products or services.	Cost of production and delivery have been validated by direct discussion with suppliers/manufacturer/ distributors.
	0				
Proof-of-Concept		The component and/or prototype approach has been validated in a laboratory or 'in-house' environment.	The value proposition has been validated against competing approaches (products/services or practices).	Specific supply chain partners have been identified, including the role/s within organisations to approach regarding the deal.	The costs of distributing and supplying the product or service have been verified.
	0				
		Validation in a relevant industry operating environment has occurred.	A prototype has been sold, or a collaborative project initiated, with a partner.	Supply chain processes have been discussed with initial customers and critical partners have demonstrated their ability to meet needs.	The revenue model has been tested with at least one customer.
	0				
Development		System/subsystem model or prototype demonstration in a relevant environment has occurred.	End-user/customer sales pitches have been developed for the technology, product or service.	All supply chain partners have been engaged. Key back-ups have been identified.	The costs of production and distribution have been validated across multiple markets and regions.
	0				
		A system prototype has been used by target end-users in an operational environment.	Marketing collateral has been developed using the results of market research for each target customer/region.	The supply chain has been trialled with at least one customer in each target market.	Revenue and cost models have been verified based on the final product or service over 6 months.
	0				
Application/Adoption		Actual system has been completed and qualified through early use with 10 end-users.	The technology has been sold to 10 unique customers (or used by 0.5% of end-users if the technology is incorporated into other products or services).	Post-sales support has been tested and verified to be effective for each target region.	Cost models have been validated across multiple batches or sales over 12 months (or multiple countries if applicable).
	0	0	0	0	0
		Actual system has been proven through successful operations. 50 end-users paying for access.	Over 50 sales have been made or demonstrated sales across multiple regions (or the technology been used by 5% of the target market).	The robustness of the supply chain has been validated across all customer types, target markets and regions.	Revenue models have been validated with a minimum of 50 sales (or 5% of a target market) over 12 months.
	0	0	0	0	0

Source: Agrifutures

Figure B1. CRAM matrix

Appendix C. List of people met

Chelsea Moore	Northern Territory DPI
Dominic Calder	Northern Territory Farmers
Warren Hunt	Charles Darwin University ,CRC for Northern Austarlia
Yan Diczbalis	QLD DAF
Massimo Bianco	QLD DAF
Mark Hoult	Northern Territory DPI, retired
Doris Marcsik	Northern Territory DPI
Greg Owens	Northern Territory Farmers
Kerry Eupine	Grower, Bees Creek, NT
Marcus Karlsson	Grower, Humpty Doo, NT
Marie Piccone	Grower, Queensland and Katherine, NT
Alan Birch	Alan Birch Transport and Fruit Packing, Humpty Doo, NT
Joe Dunham	Simon George and Sons, Fruit wholesaler, Darwin NT
John Trimboli	Romero's, Fruit Wholesaler and grower, Rockhampton, QLD
Duane Johnson	Grower and agent, Atherton, QLD
Josh Maunder	Grower, Innisfail, QLD
Ashley Flegler	Grower and agent, Atherton, QLD
Duncan Kyle	FPE Fruit processing equipment manufacturers, QLD.