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**Bridging Manual Labour and Mechanisation:
Enhancing Blueberry Harvesting Efficiency for New
Zealand's Fresh Market**



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

A thesis submitted
in fulfilment of the requirements
for the degree of
Master of Engineering
At
The University of Waikato

Sheau Lan (Alicia) Sim

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Declaration

In submitting this thesis to The University of Waikato School of Engineering, I affirm my awareness of the university's standards and honour code.

Name: _____

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Abstract

This thesis addresses the challenges of fresh market blueberry harvesting in New Zealand, where rising global demand and labour shortages put pressure on traditional hand-harvesting methods. Although hand-picking remains the industry norm, it is labour-intensive and costly. With global blueberry consumption projected to grow, developing efficient and sustainable harvesting methods is critical, particularly for local growers.

The core objective of this research was to develop a human-assisted mechanical harvesting system tailored for tunnel-grown fresh market blueberries. This system utilises lightweight, battery-powered handheld reciprocating shakers and multi-level soft surface catchers designed to reduce harvest damage, minimise ground loss, and improve fruit quality and yield. Performance assessments compared this system to traditional hand harvesting regarding post-harvest quality and harvest rate in field trials across two seasons.

The field trials yielded valuable findings. In Field Trial 1.0, the Catcher V1.0 showed promising results, achieving a harvest efficiency of up to 83.7%, slightly less than the 89.3% efficiency of hand-harvesting into buckets. In Field Trial 2.0, the optimised Shaker V2.0 had a harvest rate of 81.3 berries/min, outperforming traditional hand-harvesting into a bucket (71.8 berries/min) and hand-harvesting into Catcher V3.0 (80.3 berries/min). Notably, Catcher V3.0 caused the least berry damage (0.9%), confirming the benefits of its soft surface design.

For the Masena cultivar, optimal shaker settings were identified at 899 RPM and a shaking duration of 1.08 seconds, achieving a projected harvest performance score of 81.76%, with detachment accuracy of 93.21% and detachment efficiency of 96.53%.

Future research should focus on larger-scale trials, long-term economic analysis, and developing methods to assess bloom retention. The integration of machine vision could further enhance this system, enabling fully automated harvesting, even during nighttime operations. These innovations have the potential to improve efficiency and sustainability for New Zealand's blueberry industry.

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Chapter 1

Introduction

1.1 Overview

Food is a fundamental necessity for human survival, and its importance is magnified by a growing global population, diminishing natural resources, and an increasing demand for healthier food options. As the global population continues to rise, the demand for food increases correspondingly. Research indicates that population growth directly contributes to food insecurity, as it places massive pressure on agricultural production systems [1], [2], [3]. In addition, there is a growing demand for healthier food options as populations' dietary preferences shift away from processed foods, meat, and dairy, which not only increases the demand for fresh food but also aggravates competition for land and water resources [4], [5]. This shift highlights the need for a reevaluation of agricultural practices to ensure that food production is both sustainable and capable of meeting the nutritional needs of diverse populations [6], [7]. Moreover, the challenge of providing nutritious food is compounded by climate change and global pandemic events, which threatens agricultural productivity and food security [8], [9].

Blueberries have become one of the most sought-after fruits globally, experiencing a surge in consumption over the past five years and securing their position as the second most significant soft fruit species, trailing only strawberries [10]. The blueberry market

has grown significantly, with the industry valued at approximately USD 2.5 billion in 2021 and projected to reach USD 5.2 billion by 2027 [11]. This growth is driven by the increasing recognition of blueberries as a super-food, rich in antioxidants and associated with various health benefits. In New Zealand, the blueberry industry is also expanding, with exports increasing significantly in recent years. The land area dedicated to blueberry cultivation has steadily increased since 2011, reaching 787 hectares in 2022 [12]. The country is well-positioned to capitalise on the global demand for blueberries due to its favourable climate and growing agricultural capabilities [11]. The economic potential of the blueberry industry in New Zealand is significant, with exports contributing to the country's agricultural economy as global demand for blueberries continues to rise [13]. The blueberry industry must adapt to meet these demands in light of a growing population and changing dietary preferences. Addressing these challenges requires a well-rounded approach to improving food security on a global scale, including better automation solutions, sustainable agricultural practices and effective resource management.

1.2 New Zealand Blueberry Industry

Blueberries are increasingly recognised for their health benefits and versatility, leading to a surge in popularity, particularly in New Zealand. The primary cultivars include Northern Highbush (*Vaccinium corymbosum*) and Southern Highbush (*Vaccinium darrowii*), each exhibiting distinct characteristics that influence their marketability and cultivation practices [14]. Highbush blueberries are particularly favoured for fresh markets due to their firm texture and superior flavour profiles, essential for consumer acceptance [15], [10].

The harvesting of blueberries can be categorised into fresh market and bulk harvest. Fresh market blueberries are typically hand-harvested to ensure quality, while bulk harvest methods, including mechanical harvesting, are employed for larger-scale production [16], [17]. The growing season for blueberries varies, but in New Zealand, the harvest typically occurs from November to February, aligning with the Southern Hemisphere's summer

months [13].

Adopting poly-tunnels has become popular among New Zealand blueberry growers, as these structures enhance fruit quality and extend the growing season by protecting from adverse weather conditions [18]. This method not only improves yield but also allows for earlier market entry, catering to the increasing consumer demand for fresh blueberries year-round [18], [19]. Figure 1.1a and 1.1 show two different orchards utilising poly-tunnels to improve fruit quality and yield.



(a) *Blueberry orchard with poly-tunnel*

(b) *Another orchard*

Figure 1.1: *Poly-tunnel blueberry orchards*

1.3 Characteristic and Challenges

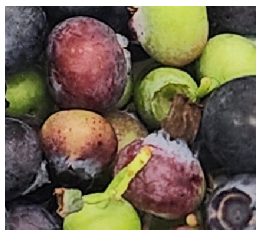
Fresh market blueberries are characterised by their vibrant colour, firmness, and flavour, critical for consumer appeal. However, these attributes also pose significant challenges during harvesting. One of the primary difficulties is the visual assessment of ripeness; blueberries can appear similar in colour regardless of their actual ripeness, as shown in figure 1.2, making it hard for harvesters to determine the optimal time for picking [20]. This challenge is compounded by stringent quality control standards that require only the highest quality fruit to be selected for the fresh market, necessitating careful handling to avoid discarding ripe berries that may not meet these standards [21].



(a) Ripe, peak sweetness, (b) Under-ripe, almost ready to harvest (c) Overripe, declining in taste and firmness

Figure 1.2: Little visual difference when comparing three distinct stages of blueberry maturity, with the latter two deemed undesirable

Moreover, blueberries are delicate and can be easily damaged during harvesting. Figure 1.3 shows the common reject attributes for fresh market blueberries. Splitting, bruising and loss of bloom can occur from mishandling, affecting the fruit’s appearance, shelf life, and marketability [22]. The high costs associated with hand harvesting, driven by labour shortages and increasing wages, further complicate the situation. As labour becomes scarcer and more expensive, the economic viability of maintaining quality through hand harvesting is increasingly questioned [23]. Consequently, the blueberry industry faces a pressing need to balance quality with the practicalities of labour availability and cost, making fresh market blueberries particularly challenging to harvest effectively.



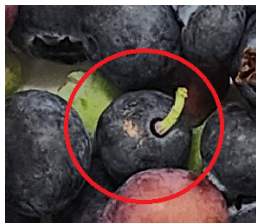
(a) Varying unripe stages



(b) Split and bruise



(c) Beard retention



(d) Pedicel retention



(e) Loss of bloom



(f) Fungal growth

Figure 1.3: Common blueberry reject attributes

While fresh market blueberries are highly valued for their quality, the challenges associated with their harvest—such as ripeness assessment, quality control, and labour costs—pose significant hurdles for producers.

1.4 Need for better harvesting method

The limited uptake of mechanised harvesting methods for fresh market blueberries, particularly among smaller producers (less than 10 hectares of crop), is primarily due to concerns regarding viability and feasibility. While mechanised harvesters can enhance efficiency and reduce labour costs, they often come with high initial investment costs that may be prohibitive for smaller operations [24]. Additionally, the quality of fruit harvested mechanically can be inconsistent, leading to increased bruising and damage, which is unacceptable for fresh market standards [23], [25]. This quality issue is particularly critical, and any compromise can result in significant economic losses [24].

Moreover, smaller producers may lack the scale necessary to justify the investment in mechanised equipment, especially when the return on investment is uncertain due to potential quality losses [24]. The labour shortage exacerbates this issue, as the reliance on manual labour remains high, and many producers are hesitant to transition fully to mechanisation without a reliable bridge solution that maintains fruit quality while reducing labour dependency [26].

To address these challenges, there is a pressing need for hybrid solutions that combine the efficiency of mechanised systems with the quality assurance of manual harvesting. Such innovations could include modified harvesters designed to minimise bruising or systems that allow for selective harvesting, thereby ensuring that only ripe fruit is picked while reducing labour costs [27]. This approach could provide a feasible pathway for smaller producers to adopt mechanisation without sacrificing the quality essential for fresh market blueberries.

1.5 Objective

The objective of this master's thesis is to develop a prototype harvesting system that enables selective harvesting of blueberries. This system aims to minimise harvest damage and ground loss, thereby improving the overall quality and yield of the produce. By streamlining the harvesting process, the project seeks to reduce the need for manual handling, making the operation more efficient and effective.

In addition to these technical improvements, the research focuses on making the harvesting process less physically and mentally demanding. This approach is designed to open up the labour market to a broader demographic, allowing more individuals, including those who may find traditional harvesting too strenuous, to engage in blueberry harvesting.

This thesis aims to provide a practical pathway for smaller producers to adopt mechanisation by bridging the gap between fully mechanised harvesters and conventional manual labour. This transition aims to enhance operational efficiency and promote sustainability within the blueberry industry, ultimately contributing to a more resilient agricultural sector in the face of growing global demands.

1.6 Co-design approach

Blueberry harvesting operation is a complex process that involves many aspects, such as orchard operation management, plant health, human resource management, tools & equipment, weather, etc. A co-design approach is applied to this research to view the complete picture of the issue itself. Co-design in horticultural solutions, particularly in the context of hand-harvesting blueberries, offers several advantages that enhance the effectiveness and practicality of the solutions developed. Engaging workers directly in the design process allows for a deeper understanding of their challenges and fosters the creation of tools and practices tailored to their needs. Many correspondents and stakeholders are involved in the investigations. This includes regular engagement with

stakeholders and voluntarily working as a blueberry picker for a day to understand the entire harvest operations. Working alongside pickers in the orchard has allowed direct observations of inefficiencies and areas needing improvement. This hands-on experience helps create solutions grounded in real-world needs [28]. Co-design also creates a feedback loop between researchers and stakeholders, allowing ongoing adjustments to practices and tools and ensuring solutions stay relevant to field conditions [28]. This leads to better acceptance and implementation of new solutions [29].

1.7 Publications

This thesis incorporates previous conference publications and videos that explore the concept of human-assist selective harvesting.

Conference Paper

- Redefining Selective Blueberry Harvesting - Localised Shaking with Minimal Damage
 - Sim A, McGuinness B, Lim SH, Williams H, Duke M
 - Australasian Conference on Robotics and Automation, ACRA
 - 2023
 - https://ssl.linklings.net/conferences/acra/acra2023_proceedings/views/includes/files/pap134s2.pdf
- Evaluation of a low-cost selective shaking device and soft surface catchment for fresh market blueberry harvesting
 - Sim A, Pearse J, McGuinness B, Williams H, Duke M
 - IEEE International Conference on Automation Science and Engineering, CASE
 - 2024
 - DOI or URL is not yet available

- Hyperspectral Imaging and Machine Learning to Identify Epicuticular Wax Loss in Masena Blueberries for Post-Harvest Freshness
 - Pearse J, Thawdar Y, Sim A, Ooi M, McGuinness B, Reutemann P, Fletcher D, Duke M
 - IEEE International Conference on Automation Science and Engineering, CASE
 - 2024
 - DOI or URL is not yet available

Video

- Human-Assisted Selective Harvesting Blueberry 2023
 - Sim A
 - Youtube (Unlisted)
 - 2023
 - <https://youtu.be/F03nWY335Sw>

1.8 Thesis Overview

This thesis addresses key labour and quality challenges in fresh-market blueberry harvesting, aiming to promote more efficient and sustainable practices. The research investigates human-assisted selective harvesting methods, focusing on improving efficiency, ergonomics, fruit quality, and developing low-cost equipment solutions. With labour shortages and rising costs affecting traditional hand-harvesting, this study explores how handheld shakers and soft surface catchment systems can optimise selective harvesting for fresh-market blueberries.

The remainder of this thesis is organised as follows:

Chapter 1: Introduction This chapter introduces the core challenges of blueberry harvesting, emphasising current inefficiencies and the need for improved harvesting methods. It discusses the research objectives and the broader context of precision agriculture and selective harvesting within the industry.

Chapter 2: Literature Review This chapter provides a detailed review of existing harvesting technologies and methods used in blueberry production. It identifies research gaps related to human-assisted selective harvesting, focusing on optimising detachment settings, efficiency, ergonomics, fruit quality, and cost-effective equipment. The chapter also examines advancements in mechanical systems and sensor technologies, as well as the hurdles smaller producers face in adopting mechanisation.

Chapter 3: Development of Shaker and Catcher This chapter explores the mechanics of blueberry detachment at different maturity stages for three fresh-market cultivars, assessing their potential for selective mechanical harvesting. Various end effector mechanisms and catchment techniques are developed and evaluated, with the most appropriate design for human-assisted harvesting systems selected based on selectivity, quality, and feasibility. The chapter also details the creation of an artificial blueberry plant to facilitate off-season testing.

Chapter 4: Field Evaluations 1.0 This chapter outlines the design and testing of the first set of prototypes, Shaker V1.0 and Catcher V1.0, and the methods used to assess their performance against current harvesting methods. The analysis includes metrics such as harvest rate, firmness, reject analysis, detachment accuracy, and efficiency. User feedback and trial results are used to guide improvements for future iterations.

Chapter 5: Field Evaluations 2.0 This chapter focuses on the improvements made in subsequent prototypes (Shaker V2.0, Shaker V2.1, and Catcher V3.0), particularly regarding usability and ergonomics. It describes the methods used to compare the three harvesting treatments and optimise the settings for Shaker V2.1. The chapter concludes with analysing the second field trials, covering metrics such as harvest rate, firmness, shelf life, grading results, and overall performance.

Chapter 6: Conclusion and Future Work The final chapter summarises the research findings, evaluates how the objectives outlined in Chapter 1 were achieved, and highlights key limitations. It offers recommendations for future research to enhance selective harvesting methods and improve the harvest system's efficiency and sustainability in the blueberry industry.

Chapter 2

Literature Review

This chapter provides an overview of manual harvesting methods, followed by an examination of mechanised and precision robotic harvesters, focusing on the blueberry industry. It also explores human-assisted harvesting solutions. The chapter concludes with a summary and presents the key research questions guiding this thesis.

2.1 Manual Harvesting of Blueberries

Hand harvesting remains the primary method for fresh market blueberries. It is labour-intensive and physically demanding. Workers must carefully select ripe berries while contending with hot and humid field conditions, making the process mentally taxing (Figure 2.1). Despite its precision in preserving fruit quality, hand harvesting presents numerous challenges beyond the immediate picking task, contributing to inefficiencies and losses in blueberry production. It is well documented that labour shortage poses the main barrier to harvesting.



Figure 2.1: Pickers working in the hot and humid field.

In addition to the labour issues, hand-harvesting practices present specific operational challenges that further complicate blueberry production. The investigations also highlighted problems not outlined initially, such as excess fruit handling, ground loss during harvest, and over-filtering fruit. These inefficiencies underline the urgent need for improved harvesting techniques that minimise waste, reduce labour demands, and maintain the high quality essential for fresh-market blueberries.

2.1.1 Labour issues

Hand-harvesting blueberries presents challenges beyond the commonly recognised labour shortages, significantly impacting operational efficiency and profitability. These include an unreliable labour force, the need for constant supervision to maintain harvest quality, the time required for training new workers, and the difficulty of retaining skilled labour. Each of these factors contributes to inefficiencies and increased costs in blueberry production.

One of the primary issues with relying on seasonal labour for hand-harvesting is the workforce's unreliability. Workers may arrive late or fail to show up, which can disrupt the harvesting schedule and lead to fruit quality losses [30]. Given the highly perishable nature of blueberries, timely harvesting is crucial; delays can cause overripening and

increased spoilage [23]. This unreliability becomes particularly problematic during peak harvest periods when the demand for labour is at its highest.

Maintaining the quality of blueberries also requires constant supervision. Workers must be trained to carefully identify and handle ripe fruit without causing damage, but inexperienced workers may struggle to meet these standards. This necessitates constant oversight by orchard managers or more experienced workers, which increases labour costs and reduces overall efficiency. Managers must divert time and resources to supervise workers rather than focusing on other essential operational tasks [31, 30, 32].

Training new workers is another time-consuming aspect of hand-harvesting. Picking blueberries requires skill, not only to avoid damaging the fruit but also to distinguish between ripe and undersized fruit. Growers often invest significant time training seasonal workers, but high turnover rates can delay harvest operations and reduce productivity. When workers leave before the harvest season ends, the time spent on training is essentially lost [32, 16, 30, 33].

Additionally, retaining skilled workers is a persistent challenge. Blueberry pickers vary in skill levels and work attitudes, as evidenced by their harvest rates. While the average picker may harvest around 5 kg/hour, skilled pickers can reach up to 9 kg/hour [30]. However, many skilled workers seek better-paying jobs or improved working conditions elsewhere, which results in a loss of experienced labour. This turnover forces growers to continuously train new workers, exacerbating labour shortages and negatively affecting the efficiency of the harvesting process [22].

The cumulative impact of these labour issues can have profound economic consequences. The need for increased supervision, lengthy training periods, and challenges in retaining skilled workers all lead to higher labour costs and decreased profitability [34]. Traditional hand-harvesting methods for blueberries are labour-intensive, often accounting for over 50% of production costs, a scenario that has become unsustainable as labour availability declines and wages rise [35]. For example, in the United States, labour costs for blueberry harvesting can reach up to \$0.70 per pound, requiring approximately 520 hours of labour per acre [36]. This situation has sparked increasing interest in mechanisation as a feasible

alternative to lessen reliance on manual labour. However, the shift to mechanical harvesting presents challenges, including the need for significant investment in equipment and the risk of increased fruit bruising, which could adversely impact marketability [20].

Many local labourers are unwilling to engage in agricultural work due to low wages and poor working conditions, leading to a labour shortage that has been exacerbated by urbanisation and the COVID-19 pandemic [37][38]. Integrating overseas workers into the blueberry harvesting workforce is increasingly seen as a viable solution to address labour shortages in the agricultural sector. For example, a survey indicated that 78.8% of employers preferred hiring foreign workers due to their willingness to accept lower wages, which can be as low as \$10 per hour compared to the \$15 average for local workers [39]. Nevertheless, the logistics of recruiting, training, and managing these workers can be complex and costly for producers, particularly smaller farms that may lack the resources to navigate the bureaucratic processes involved in hiring foreign labour [40].

2.1.2 Excess fruit handling

A major paradox in hand-harvesting blueberries is the excessive handling required to remove undesirable berries. The process starts with pickers removing unwanted berries that accidentally make it into the waist bucket during harvest. Following this, a dedicated team takes over at the weighing station, pouring harvested fruit from waist buckets into pack house trays (Figure 2.2). Additional sorting is done to remove leaves, pedicels, beards, under-ripe, and damaged berries before the fruit is transferred to cold storage, ready for transport to the pack house. This level of handling not only increases labour costs but also heightens the risk of bruising and other damage to the fruit, potentially compromising its quality [15] [22].



Figure 2.2: Blueberries being poured into the harvest tray at the weighing station.

The cumulative impact of this handling often leads to significant post-harvest losses, as bruised or punctured berries may fail to meet market standards and could either be discarded or sold at a lower price [22]. The demand for perfect fruit quality upon delivery to the pack house exacerbates this issue, forcing growers to over-handle their harvests. They are evaluated based on pack house grading results and penalised for each kilogram of rejected fruit. As grading processes move from manual to digitised methods, rejection rates have increased, placing further pressure on growers to meet these stricter standards. However, the financial impact of penalties—just \$0.25 per kilogram of rejected fruit—pales in comparison to the high labour costs, which can reach \$5 per kilogram harvested or \$25 per hour [41] [33] [30]. Consequently, the additional efforts to perfect fruit quality post-harvest often prove inefficient and financially burdensome for growers.

2.1.3 Ground loss during harvest

Ground loss refers to the fruit that falls to the ground during harvesting, which can be substantial in blueberry production. Figure 4.5 shows the berries left on the ground after the weekly harvesting rotation. Research indicates that as much as 25% of fruit can be lost to the ground during harvesting, mainly when using traditional hand-harvesting methods [27] [41]. The main contributors are fruit drops during harvest operations and accidental tipping of the waist bucket when reaching for lower-hanging fruit. This loss reduces

the overall yield and impacts the economic viability of blueberry operations. Despite this, ground loss is challenging to quantify, and growers rarely account for this loss when calculating their profits. Ground loss can be exacerbated by factors such as fruit ripeness and the physical characteristics of the blueberry plants, which can lead to premature fruit detachment during harvesting [27].



Figure 2.3: Aftermath of weekly harvesting.

2.1.4 Over-filtering of fruit

Solely relying on the tickling method when hand harvesting is insufficient to determine the harvest readiness of berries. Pickers often perform a quick visual scan on the detached berries in their palm and filter out the potential rejects before placing them into the waist bucket. However, it is almost impossible to distinguish clearly between ripe and almost-ripe berries. Over-filtering occurs when pickers excessively sort and filter out potential marketable fruit [30] [41]. While quick filtering is essential for maintaining quality, it can lead to increased harvest time and further wastage. The need for meticulous sorting can slow the overall harvesting process, leading to delays in getting the fruit to market and potentially affecting its freshness [26].

2.1.5 Ergonomic Issues

Traditional hand harvesting remains a critical component of blueberry production, particularly in regions where mechanisation is not feasible. Ergonomic improvement to the design of tools and the harvesting process can significantly reduce strain on workers [42]. For example, lightweight, ergonomically designed containers with harnesses intended to distribute the weight of the harvest container across the shoulders and back can alleviate pressure on the arms and hands (figure 2.4), allowing workers to maintain a more natural posture while harvesting [43] [44], allowing them to work more efficiently and effectively. Additionally, training workers in proper harvesting techniques can further enhance productivity and reduce the risk of injury. However, the labour-intensive nature of hand harvesting and reliance on seasonal labour still pose challenges regarding workforce availability and stability. There is a growing interest in hybrid systems combining human expertise with mechanised assistance to optimise the harvesting process [45].

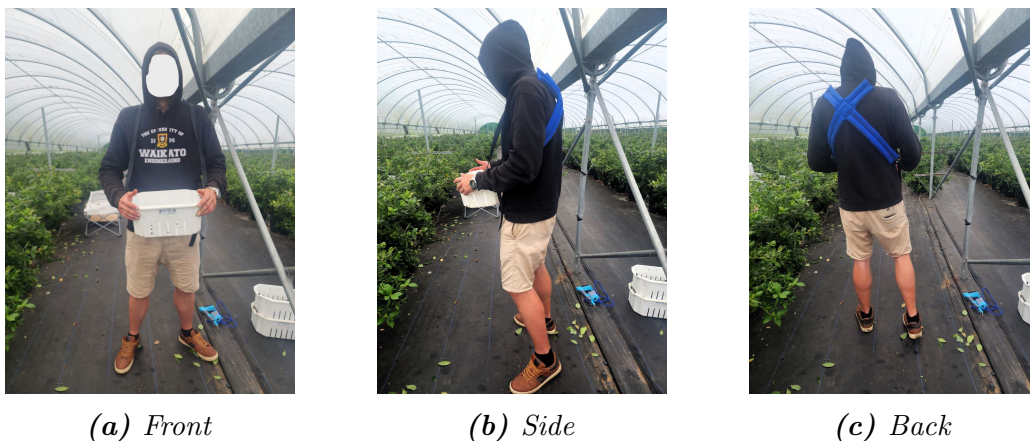


Figure 2.4: Picking container with ergonomic body harness

2.2 Mechanised Harvesting

Mechanised harvesting has shown promise in increasing efficiency and reducing labour costs, not just in the blueberry industry. For instance, studies have shown that mechanical shaking systems can increase labour productivity by 5 to 15 times compared to hand-

picking methods, resulting in reduced unit harvesting costs by over 50% [46]. This efficiency is particularly beneficial during peak harvest periods when labour shortages are common.

Canopy and trunk shaking are mechanical harvesting technologies used primarily in the agricultural sector to efficiently bulk-harvest various fruits, particularly those that grow on trees.

Canopy shaking involves the application of vibrations directly to the branches of the tree canopy. This method utilises rods or tines that penetrate the canopy and induce vibrations. The vibrations cause the fruit to detach from the branches, allowing for efficient collection. Canopy shaking systems have demonstrated high harvest efficiency, often achieving rates of 90-95% in optimal conditions [47]. This technique is commonly applied to fruits such as citrus, olives, and apples, where the fruit is located within the canopy and can be effectively dislodged without excessive damage [48][49].

Bulk harvesting of blueberries primarily involves using over-the-row (OTR) harvesters (figure 2.5). OTR harvesters have been designed to straddle rows of blueberry bushes and shake the plant canopy to mechanically detach fruit using various mechanisms, including vibrating rods, air jets, and catch surfaces [31] [23].



Figure 2.5: An OTR harvester commercialised by Finefield

Trunk shaking, on the other hand, involves applying vibrations to the tree trunk. This method typically operates at higher frequencies with lower displacements. The vibrations are transmitted from the trunk to the branches, causing the fruit to detach. Trunk shaking is widely used in the harvesting of olives and some citrus varieties, where the fruit is more easily detached due to the vibration being transmitted through the tree structure [50][51]. However, trunk shaking may not be as effective as canopy shaking for certain fruits, as it can be less efficient in reaching fruits located farther from the trunk [52].

Both methods have their advantages and limitations. Canopy shaking is generally more effective for fruits tightly clustered within the canopy, while trunk shaking may be more suitable for trees with a straight trunk and less dense foliage. The choice between these harvesting technologies often depends on the specific fruit type, tree architecture, and the desired quality of the harvested produce. This technology is suitable for harvesting fruit destined for processing but not suitable for fresh market fruit [47].

2.2.1 Struggle with selective harvesting

One of the primary barriers to the fresh market fruit crop adopting mechanised harvesting technology is achieving selective harvesting, especially for crops like blueberries and apples that ripen variably. While theoretically advantageous, selective harvesting of blueberries with mechanised harvester has not yet reached a level of practical implementation that meets industry needs. Selective harvesting requires distinguishing between ripe and unripe fruits, which is inherently complex due to the variability in fruit maturity within a single plant [53]. Research indicates that mechanical methods may inadvertently harvest immature fruit due to the ease of detachment when the abscission zone is not fully developed [16].

For instance, the V45 blueberry harvester has shown potential in harvesting highbush blueberries with quality comparable to hand-harvested fruit (bruising rates of 5% and below) [54]; however, it has very slow ground speed, and still struggles with accurately identifying and selectively harvesting ripe berries [17] [45].

The design of end effectors, which are crucial for the mechanised harvesting process, must ensure that only ripe fruits are picked while leaving the plant and remaining fruits intact. This requirement complicates the engineering of harvesting systems, as they must be precise and gentle to avoid damaging the fruit or the plant itself [53].

2.2.2 High mechanical damage rate

Another significant barrier to adopting mechanised harvesting technologies is the mechanical damage that blueberries often sustain during harvesting. Studies have shown that mechanised harvesters can cause unacceptable levels of bruising [22], with damage rates ranging from 55% to 78% for harvested fruit, compared to only 23% for hand-harvested fruit [55]. This high bruising is particularly problematic for fresh-market blueberries, which require high quality and minimal damage to compete [54].

On top of that, studies have also shown that mechanised harvesting can result in

ground losses ranging from 10% to 50% of the potential yield due to fruit falling and being damaged during the process [16]. The mechanised harvesters originally designed for processed blueberries do not adequately address the quality requirements for fresh fruit, leading to significant post-harvest losses and reduced marketability [55] [54].

Various studies have focused on integrating catchment systems for mechanised harvesting in blueberry production, highlighting their potential to enhance harvest efficiency while minimising fruit damage and subsequent disease susceptibility [22]. It is also noted that reducing the drop height and impact forces experienced by the fruit during harvesting could significantly improve the quality of mechanically harvested blueberries [27]. Furthermore, replacing the traditional hard surface in modified over-the-row mechanised harvesters with soft-catch surfaces has also resulted in lower bruising rates, thereby improving the marketability of the harvested fruit [23].

However, concerns about the potential for mechanical damage to the fruit and the plant remain a significant barrier to widespread adoption [45]. Therefore, ongoing research focuses on developing gentler harvesting mechanisms to minimise damage while maximising efficiency.

2.2.3 Not suitable for every blueberry cultivars and orchards

Specific blueberry cultivars amenable to mechanised harvesting must possess characteristics such as firm texture, easy detachment when ripe, and minimal stem retention to ensure high-quality fruit and reduce bruising during the harvesting process [23]. Research indicates that while some cultivars can achieve a pack out of 90% with mechanised harvesting, they often result in softer fruit and more attached stems compared to hand-harvested berries [23]. Cultivars unsuited for mechanised harvesting can lead to higher rejection rates due to quality degradation [17].

Moreover, mechanised harvesters' performance is heavily influenced by the architectural design of the blueberry plants and surrounding structures. For example, the V45 model, while capable of harvesting to fresh market standard, has design limitations restricting

operational efficiency that require a crown-restricted growth pattern to minimise potential damage to the plants during operation, which complicates its adoption in diverse blueberry production systems [54] [27].

2.2.4 Economic aspect

In addition, the economic aspect is also a significant barrier to adopting mechanised harvesting technology. The cost of over-the-row (OTR) mechanised harvesters can be prohibitively high for small- and medium-sized blueberry orchards, which is a significant factor contributing to the continued reliance on manual labour in many blueberry operations [42]. Additionally, concerns about the quality of the mechanically harvested blueberries mean growers hesitate to transition to mechanical systems that may not yield a sufficient return on investment due to quality losses [54].

2.3 Precision Harvesting with robotics system

Precision harvesting involves applying advanced technologies to optimise crop harvesting by ensuring fruits and vegetables are collected at their peak quality while minimising waste and reducing labour costs. This method integrates robotics, machine learning, and sensor technologies to improve the accuracy and efficiency of harvesting operations [56] [57]. As the agricultural sector faces global challenges such as labour shortages, increasing demand for high-quality produce, and the push for sustainable practices, precision harvesting has become vital in promoting food security and sustainability [58] [59].

Recent advancements in blueberry harvesting have focused on precision, mechanisation, and human-assisted technologies. Blueberries ripen progressively, with indicators such as ease of removal, consistent colour, and taste signifying harvest readiness [60]. Technologies like the YOLO-BLBE model offer high accuracy in detecting blueberries at different ripeness stages, enabling more effective selective harvesting [61]. Despite these advancements, challenges persist in integrating new technologies into existing practices,

as they require significant investments in equipment and training [45].

Convolutional neural networks (CNNs) have shown promise for tasks such as fruit detection and ripeness assessment, especially under varying lighting conditions where traditional image processing techniques often fail [62] [63]. By utilising deep learning, CNNs are revolutionising the harvesting process by enabling robust fruit detection and selective harvesting, particularly for high-value crops that do not ripen uniformly [53] [64]. For instance, the CES-YOLOv8 model for strawberry maturity detection enhances the ability to determine optimal harvest times by considering factors beyond visual cues like colour and size [65]. These data-driven approaches are poised to reduce labour costs and improve efficiency, though their commercial viability is still in its early stages due to technical and financial barriers.

Lemon harvesting has also seen interest in applying robotic systems, though challenges remain in achieving the delicate balance between precision and speed. Lemons, like strawberries, have a complex plant architecture that complicates mechanical harvesting. In recent developments, an autonomous harvesting robot for lemon orchards is combined with remote sensing and machine learning algorithms, allowing for efficient fruit detection and quality assessment, achieving an overall harvest success rate of 87.2%; although picking time was slow, with an average picking time of 10.9 s/fruit. These technologies, however, still require further refinement to enhance fruit detection accuracy, especially under different environmental conditions [59].

In addition to lemons and berries, precision harvesting technologies are applied to other high-value crops. For instance, in apple orchards, GPS and remote sensing technologies enable precise orchard mapping, allowing for targeted harvesting that maximises yield and reduces waste [64]. However, the fruit size and ripeness variability complicate the automation process, necessitating advanced algorithms to ensure only ripe fruits are picked [64].

Another notable advancement in strawberry harvesting is that robotic systems equipped with advanced sensors and artificial intelligence have been employed to detect fruit ripeness and automate the picking process [66]. While promising, they still face limitations

regarding vision accuracy and gripper dexterity, making it difficult for robots to perform efficiently when obstacles obscure fruits. Additionally, robotic harvesting systems are slower than human pickers, with one- and two-arm operations taking 6.1 and 4.6 seconds per fruit, respectively. The complex structures of strawberry plants and the delicate nature of the fruits pose challenges to ensuring robots do not damage the fruit or the plants.

The complexity of developing a system that can operate effectively in a biologically driven environment adds to the challenges researchers and developers face [67]. However, by leveraging these precision harvest technologies, growers can optimise their harvest schedules, reduce waste, and increase profitability [57] [59]. Additionally, automating labour-intensive tasks can help mitigate the impact of labour shortages in the agricultural sector [68].

2.3.1 Short Harvest Window

Despite advancements in precision harvesting technologies, several challenges impede their widespread adoption. One key issue is the short harvest windows associated with many high-value fruits, which limit the time available for effectively deploying automated systems. For instance, the blueberry harvest period is remarkably brief, and any delays can lead to rapid quality degradation [23]. Furthermore, mechanical harvesting often results in fruit damage, a problem exacerbated by the delicate nature of crops such as blueberries [69]. This highlights the need for soft robotic systems that gently handle fruit while maintaining efficiency [70]. However, integrating these advanced systems into current agricultural practices remains complex.

2.3.2 High investment cost

Another significant barrier is the high cost of adopting robotics systems with precision harvesting technologies. The initial investment required and the necessary infrastructure

can be prohibitive for many growers. Although progress has been made, such as developing robotic arms with low-cost stereo-vision cameras for fruit harvesting [71], the ongoing maintenance costs, software updates, and technical support present additional financial burdens. This can deter adoption, especially in regions where manual labour remains comparatively inexpensive [68] [64]. As a result, the economic viability of these technologies is often questioned, particularly in lower-cost labour markets [72].

2.3.3 Complex physiological traits of blueberries

Beyond economic and mechanical issues, the physiological traits of blueberries add complexity to the adoption of robotic harvesters. Blueberries exhibit considerable variability in firmness and ripeness, influenced by factors such as their location within the canopy and environmental conditions [34] [73]. Fruit on the outer canopy may ripen faster than those deeper within, leading to inconsistencies in harvest timing and quality [34]. As such, the development of sensors and algorithms that can accurately assess fruit maturity in real-time remains essential but is still an area of active research [74] [75]. The high variability in fruit ripeness and incomplete information pose significant hurdles to developing effective robotic systems, as noted by Kootstra et al. [64].

2.3.4 Limitation on current orchard structural design

The structural design of orchards presents another barrier to adopting automated systems. Many orchards are not designed for mechanised harvesting, which limits the effectiveness of robotic harvesters. The design of end effectors, which must consider the spatial arrangement of fruits, branches and trellis to ensure that the plants are not damaged during the harvest [53] [64]. Additionally, variability in tree height and fruit distribution across different orchards complicates the development of universal solutions capable of handling these challenges [76] [77].

2.3.5 Resistance to change

Moreover, adopting automated systems in traditional harvesting practices requires a cultural shift among growers. Many fear reliance on technology could displace seasonal workers, a critical issue in numerous agricultural communities [68]. Growers accustomed to manual methods may also resist new technologies due to concerns about reliability and the potential loss of traditional skills [78]. This reluctance is often compounded by the need for training and education on using these advanced systems, adding another layer of complexity to adoption.

2.3.6 Performance concerns

Finally, the performance of robotic harvesting systems has seen limited improvement in recent decades. Many platforms continue to struggle with fruit localisation and detachment success rates [79]. While certain robots have successfully localised and detached fruit, their overall efficiency in completing the harvest remains low, which has hampered the commercialisation of these systems [76] [79]. This stagnation in performance raises questions about the feasibility of current technologies in meeting the demands of high-value fruit harvesting.

2.4 Human-assist Technology

Human-assist harvesting technology is part of a broader trend toward semi-mechanical harvesting systems, which combine human labour with mechanical tools to enhance the efficiency and effectiveness of fruit harvesting. This approach bridges robotics and manual labour by combining the strengths of both approaches to enhance agricultural productivity and efficiency. Aivazidou and Tsolakis emphasised that human-robot synergy is essential for addressing the complexities of agricultural operations, as fully automated solutions may not be feasible for all tasks 10.1002/sres.2887. This collaboration allows

for a more nuanced approach to harvesting, where human intuition and robotic precision work together.

For instance, workers can focus on more complex tasks that require human judgment, such as selecting ripe fruit, while robots or semi-mechanical harvesting tools can handle repetitive actions, reducing the physical strain associated with manual labour; human assist technologies can improve worker satisfaction and retention [?] [?].

Human involvement ensures that quality control is maintained throughout the harvesting process. As noted by Casamali et al., mechanical harvesting may reduce ground losses, but it can also result in higher percentages of unripe or damaged fruit being harvested. In these instances, human workers provide the necessary oversight to ensure that only high-quality fruit is picked, which is particularly important for fresh-market produce [16].

Additionally, human-assist harvesting systems are adaptable to different conditions and crop types. Cunha et al. highlighted that semi-mechanized systems can be tailored to specific crops, enhancing operational performance while accommodating the unique challenges posed by varying agricultural environments [?]. This adaptability is critical in an industry with diverse crops and harvesting conditions.

A prominent example of human-assist harvesting technology is co-robotic platforms in apple and strawberry crops. These platforms work alongside human pickers, adjusting the platform height and position according to the fruit load and the workers' movements, optimising the harvesting process. By improving the working conditions for labourers, these platforms reduce fatigue and increase productivity [80].

Additionally, research by El-Iraqi et al. focused on designing mechanical harvesting aids for mangoes, such as mechanical disk cutters and electric scissors, to enhance manual labour productivity while minimising fruit damage. This approach highlights the collaboration between human pickers and mechanical tools, improving overall harvesting efficiency [81].

In the blueberry industry, semi-mechanical harvesting systems like the handheld pneumatic shaker (designed initially for olive harvesting), as shown in figure 2.6a, and the Starberry hook shaker (developed by Campagnola) as shown in figure 2.6b, are gaining

popularity. These devices combine the efficiency of mechanical harvesting with the selectivity of manual labour, particularly in scenarios where over-the-row (OTR) harvesters are not feasible due to orchard design or specific fruit quality requirements [27].



(a) Pneumatic hand-held shaker and catchment system (b) Starberry, battery-powered handheld shaker by Campagnola

Figure 2.6: Several semi mechanised human-assist harvesting methods for blueberries

Despite handheld shakers' potential and much lower initial investment costs compared to OTR or robotic harvesters, several research gaps remain that hinder their widespread implementation and need to be addressed to optimise their effectiveness.

2.4.1 Identify optimal shaking parameters to enhance selective harvesting

Current handheld shakers used for blueberry harvesting often display variable detachment efficiency when it comes to selectively harvesting only ripe blueberries. This efficiency can be influenced by several factors, including fruit maturity, shaking frequency, and duration [82] [83]. These shakers transmit vibrations to the blueberry bushes or individual canes, achieving a harvest efficiency of around 80-90% under optimal conditions. However, this includes both ripe and unripe berries [17] [27]. Further research is necessary to determine the optimal shaking parameters that enhance selective harvesting while minimising fruit damage. A deeper understanding of the mechanics of fruit detachment at the pedicel level is essential for improving the design and performance of these devices [83].

2.4.2 Relationship between shaking intensity and fruit damage

The impact of mechanical harvesting on fruit quality remains a significant concern. Studies have shown that mechanical harvesting can lead to bruising and quality degradation, particularly when fruit is subjected to excessive force during detachment [31] [23]. Further research is required to quantify the effects of handheld shakers on fruit quality, including firmness, appearance, and post-harvest shelf life. This includes investigating the relationship between shaking intensity and fruit bruising [20] [84].

2.4.3 Development of an effective collection device

Designing an appropriate catchment device with adequate cushioning to operate alongside handheld shakers is crucial to preserving the blueberries' quality. Research should focus on developing portable collection devices with soft catch surfaces that can effectively absorb impact forces and minimise collision between falling fruit, thereby minimising the bruising and preserving fruit quality during the harvesting process [23] [26].

2.4.4 Ergonomics considerations

The ergonomic design of handheld shakers is another critical area that requires attention. Prolonged use of vibrating handheld devices can lead to musculoskeletal disorders among workers, particularly in repetitive motions and awkward postures [42]. Research should focus on optimising the design of handheld shakers to reduce operator fatigue and improve comfort during use.

2.4.5 Economic Viability

The economic feasibility of implementing handheld shakers in blueberry production is still uncertain. Factors such as initial investment costs, maintenance, and potential cost savings

must be thoroughly evaluated to determine the overall cost-effectiveness of these devices compared to traditional hand harvesting, and OTR harvesters [54]. Economic analyses should consider the potential for increased yield, harvest rate, and reduced harvest-related costs associated with handheld shakers.

2.5 Summary

The blueberry industry continuously explores innovative methods to enhance harvesting efficiency and fruit quality, particularly by applying human-assisted selective harvesting techniques. Among these, using handheld shakers paired with soft surface catchments presents a promising avenue for improving the harvesting process. However, despite the theoretical advantages of this approach, its practical implementation remains limited. This shortfall is primarily due to several persistent research gaps that have yet to be adequately addressed. Addressing these gaps in detachment efficiency, impact on quality, ergonomics, economic viability, and soft surface catchment will be essential for optimising the use of handheld shakers in blueberry production. Continued innovation and research in these areas will be crucial for advancing the mechanisation of blueberry harvesting and ensuring the industry's sustainability.

This thesis aims to investigate these key areas, offering insights and solutions to the existing challenges in the context of human-assisted selective blueberry harvesting:

2.5.1 Optimised Detachment Settings

Limited research exists on optimising detachment settings in handheld shakers for selective harvesting. Current studies often concentrate on mechanical systems, neglecting how to fine-tune these settings for more efficient, targeted detachment of ripe blueberries while preventing damage to unripe fruit and plants. This thesis will explore the mechanics of fruit detachment at the pedicel level and methods for optimising these settings to enhance harvesting outcomes.

2.5.2 Detachment Efficiency

Although mechanical detachment has been investigated, the effectiveness of handheld shakers in selectively detaching ripe blueberries is still under-explored. Most research focuses on larger machinery, leaving a knowledge gap regarding handheld devices that could enhance accuracy in selective harvesting. This work will address these gaps and evaluate the efficiency of different handheld shaker models.

2.5.3 Ergonomics

Another area lacking sufficient investigation is the ergonomic design of handheld shakers for prolonged, repetitive use in the field. Current devices may not adequately consider user comfort, fatigue, and the risk of strain injuries during extended operation, which could hinder their practical application. This thesis will examine ergonomic factors and propose design improvements for handheld devices.

2.5.4 Fruit Quality

The balance between detachment efficiency and maintaining fruit quality has been limitedly explored. Handheld shakers and catchment surfaces may cause damage, bruising, or quality degradation, necessitating further investigation, particularly in comparison to traditional hand-picking methods. This research will focus on evaluating the impact of different harvesting techniques on fruit quality.

2.5.5 Low Cost and Simple Equipment

A thorough analysis of low-cost and straightforward equipment used in blueberry harvesting is lacking. The initial investment in complex machinery may be prohibitive for many growers. This thesis will investigate how low-cost, simpler handheld shakers can be

effective alternatives while providing labour savings and improved yield quality.

2.5.6 Soft Surface Catchment in Human-Assisted Harvesting

There is minimal research on the role of soft surface catchment systems in minimising fruit damage during harvesting. This aspect is critical for preserving fruit quality and ensuring the blueberries remain marketable after harvest. This thesis will explore the effectiveness of soft surface catchments in human-assisted harvesting to reduce bruising and improve the overall quality of harvested fruit.

2.5.7 Testing of prototypes outside of harvest window

As mentioned earlier, the limited harvest window of each blueberry cultivar has complicated the research and development of a practical harvesting solution. Although simulating a blueberry plant digitally is common for laboratory testing, it limits real-life ergonomic evaluations and user feedback. This thesis will explore the creation of an artificial blueberry plant to enable continued physical testing of the prototypes when a field trial is not possible.

In summary, this thesis addresses these critical research gaps, focusing on optimising detachment mechanisms, enhancing detachment efficiency and ergonomics, and balancing these factors with fruit quality and the practicality of low-cost equipment in real-world applications. By comprehensively analysing these issues, the research aims to contribute valuable insights to the blueberry industry and facilitate the adoption of effective harvesting technologies.

Chapter 3

Development of Shaker and Catcher

This chapter presents the investigation and design evaluation of several components that led to developing a low-cost human-assist harvesting system capable of selectively harvesting blueberries. The system also aims to minimise harvest damage and ground loss.

Firstly, Section 3.1 investigates the detachment force required to separate the blueberry from its pedicel based on its maturity level, weight, physical size, and detachment method. The most suitable blueberry cultivar for selective mechanical harvesting is identified.

Sections 3.2 and 3.3 describe the development of the harvesting and catchment devices, respectively. The chosen principle of operation of both is presented at the end of the sections.

Finally, Section 3.4 outlines the development of an artificial blueberry plant used to test prototypes outside of the harvesting season.

3.1 Blueberry Detachment Force

It is crucial to confirm whether it is possible to determine blueberry harvest readiness by detachment force without visual confirmation. The appearance between ripe and unripe blueberries is almost impossible to distinguish with human eyes. Therefore, an alternative method to determine ripeness is necessary. The traditional technique of harvesting blueberries is tickling by hand. With the palm placed underneath the berry cluster in a cup shape to collect detached berries, the picker uses their fingers to induce gentle and controlled rolling and pulling motions (tickling) on the berries. Berries that detach easily are deemed ripe, while the unripe berries will resist and remain attached. However, this method does not entirely prevent unripe berries from being harvested.

3.1.1 Method

A distinct difference in detachment force between ripe and unripe berries would be a desirable trait to exploit to enable selective mechanical harvesting, assuming the required detachment force could be applied accurately. This could remove the need for expensive, complex vision, control and manipulation systems.

Three fresh market blueberry cultivars were selected for the trial: Eureka, Eureka First Blush, and Masena. Two hundred berry samples of all ripeness stages per cultivar were collected randomly from different parts of the plant, with the pedicel still attached. The sample was split evenly between each detachment method (rolling and pulling), as illustrated in Figure 3.1. Samples were collected the same day in mid-December, seven weeks after the start of the harvest season.

Information of the individual berries was recorded: cultivar, detachment method, stage of ripeness, weight without pedicel (m_{berry}), major (ϕ_a) & minor (ϕ_b) diameter, and peak detachment force (F_{peak}).



Figure 3.1: Flow chart showing how each sets of samples are collected

3.1.1.1 Measurement of Detachment Force

The detachment force was measured using a Starr Instruments FGD-20 force gauge, with a maximum load of 20N and accuracy of $\pm 0.04N$. A piece of paper reinforced with clear tape, with three holes punched through, was used to apply an even force to the berry. The hole in the middle of the paper allows the pedicel to protrude for the pulling experiment while enabling the berry to sit centred for the rolling experiment. The other two holes are used as an attachment point for the hook on the force gauge. Figure 3.2 illustrates how the berries were held for each experiment and the location of force applied. Force is used steadily in the direction indicated until the berry is separated from its pedicel. The peak detachment force F_{peak} was recorded. Berries that failed to separate from the pedicel were discarded.

3.1.1.2 Maturity Assessment

The maturity level of the berries was classified by colour, where ‘blue’ represents ripe berries (Figure 3.3a), ‘pink’ represents partially-ripe berries (Figure 3.3b), and ‘green’ represents unripe berries (Figure 3.3c). Berries in the green and pink categories were considered unripe. Berry that showed signs of being overripe (dehydrated or soft) or damaged (bruised, split, or punctured) were discarded.

Berries with dark blue skin colour with no more than 20% red hue and no hint of any green colour were classified as blue. Berries with a majority skin colour of dark blue with

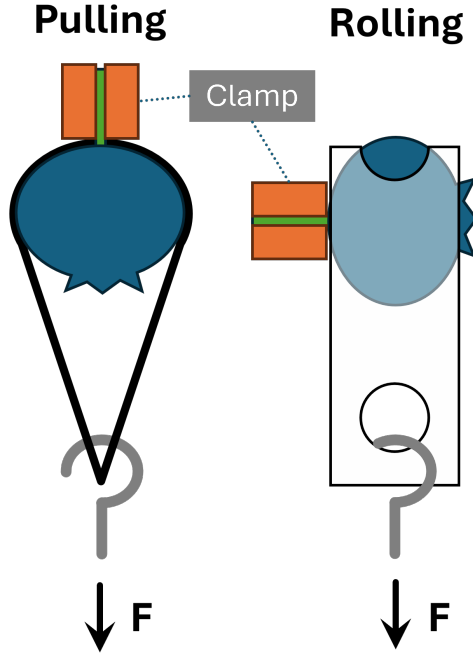


Figure 3.2: Illustrated diagram of the experiment setup for pulling and rolling

at least 20% of red hue, which may or may not have a small area of green colour, were classified as pink. Finally, berries with more than 20% of green colour were classified as green.

3.1.1.3 Approximation of Diameter

The shape of the blueberry was assumed to be ellipsoidal, with major and minor diameters ϕ_a and ϕ_b , respectively. The ellipsoidal volume of the berry ($V_{ellipsoid}$) can be calculated from 3.1. However, to simplify the size comparison, the ellipsoidal volume was equated to the volume of a sphere (V_{sphere}). Equating 3.1 and 3.2 and solving for the relative diameter of the sphere (ϕ_r) gives 3.3.

$$V_{ellipsoid} = \frac{4}{3}\pi\left(\frac{\phi_a}{2}\right)^2\frac{\phi_b}{2} \quad (3.1)$$

$$V_{sphere} = \frac{1}{6}\pi(\phi_r)^3 \quad (3.2)$$



(a) Blue represents ripe berries



(b) Pink represents partially-ripe berries



(c) Green represents unripe berries

Figure 3.3: Blueberries at different maturity levels

$$\phi_r = \sqrt[3]{\phi_a^2 \phi_b} \quad (3.3)$$

3.1.2 Results

Table 3.1 shows the total number of berries tested for each and the number of berries at various maturity levels. There were more green samples in Eureka First Blush and Masena.

Table 3.1: Maturity level distribution of tested blueberries across three cultivars

	Blue	Pink	Green	Total
Eureka	87	66	47	200
Eureka First Blush	110	72	18	200
Masena	112	61	27	200

The distributions of detachment force F_{peak} against the m_{berry} of individual berries and their maturity level are shown in a stacked plot in Figure 3.4. From the figure, F_{peak} is unaffected by its m_{berry} . While the unripe (green) berries have higher F_{peak} , there is no

clearly defined difference in F_{peak} between the partially ripe (pink) and the ripe (blue) berries.

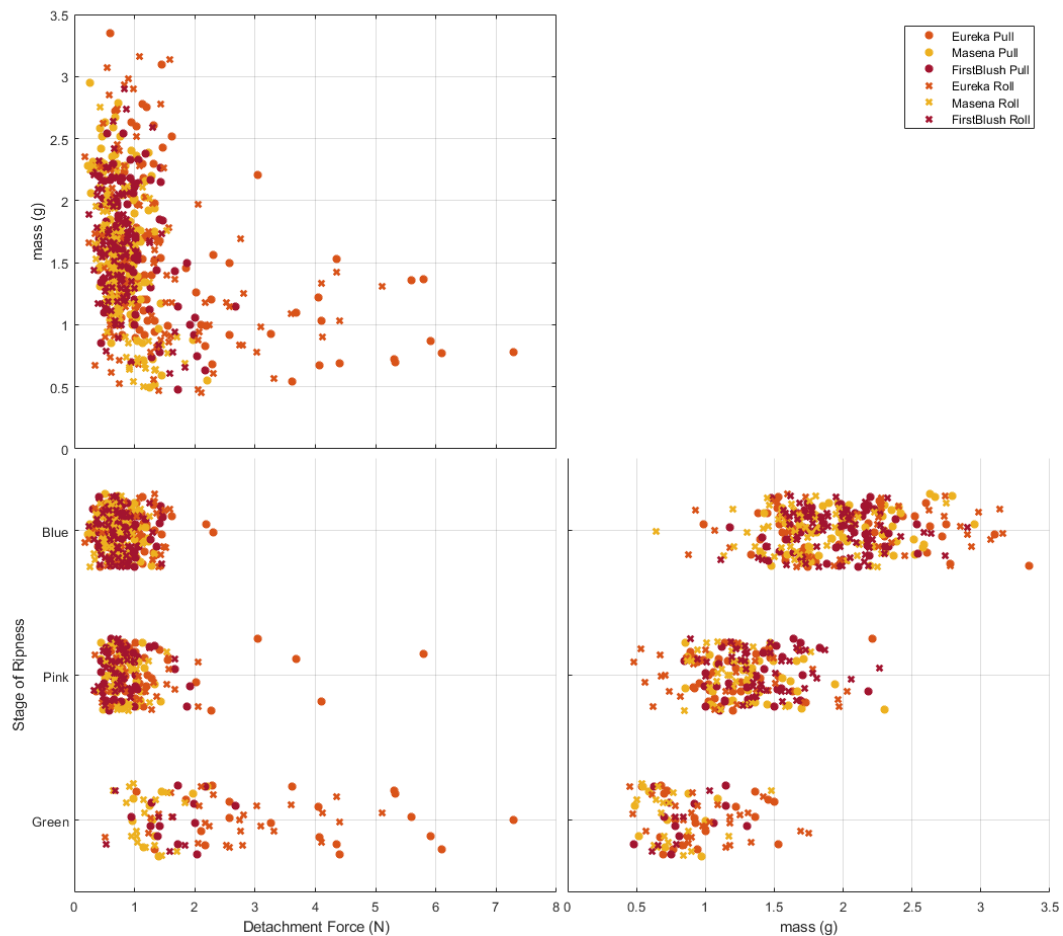


Figure 3.4: Scatter plots of detachment force F_{peak} , stage of ripeness, and mass of berries m_{berry} .

Figure 3.5 shows the average detachment force of berry of each, maturity level and detachment method. In general, across all three cultivars, the blueberries take a lower F_{peak} to detach than the pink and green berries. However, the standard deviations are significant, with a force overlap between all maturity levels. It suggests no one force magnitude separates the ripe and the unripe berries. The force magnitude will also vary between blueberry cultivars and orchard environments. However, carefully selecting the detachment force range could minimise the number of unripe berries detached while ensuring that all the ripe berries are harvested. The trend also suggests that a lower force on average is required to detach the berries with the rolling method compared to pulling.

Comparing between cultivars, detachment forces for ripe and partially ripe berries are

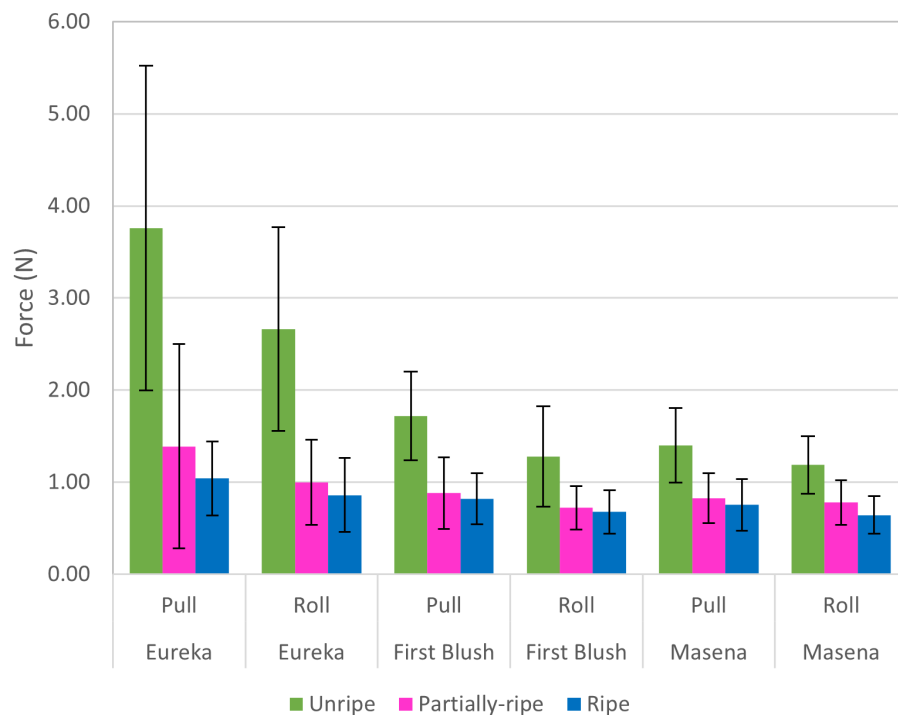


Figure 3.5: Median detachment force F_{peak} for the detachment methods by for ripe berries only, the error bars indicate the standard deviation of the samples.

similar, averaging around 1N. From both Figure 3.6 and 3.7, Masena has been shown to require the least force to achieve a high percentage of ripe berries harvested and the least percentage of unripe berries. At a detachment force of 1.2N for Masena, an estimated 37.5% of unripe and 95% of ripe berries will be harvested.

This analysis showed that the suitable approximate range of detachment force magnitudes for selectively harvesting each cultivar of blueberries are different. It also highlights the importance of applying appropriate detachment force according to cultivars, as different cultivars can have different detachment characteristics.

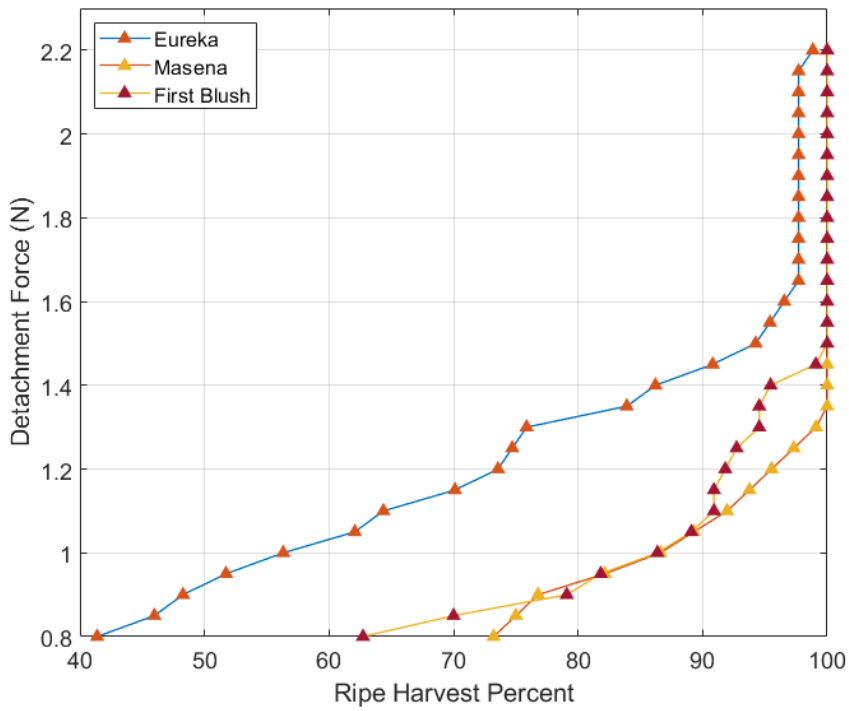


Figure 3.6: Percentage of ripe berries removal success with increasing detachment force limits

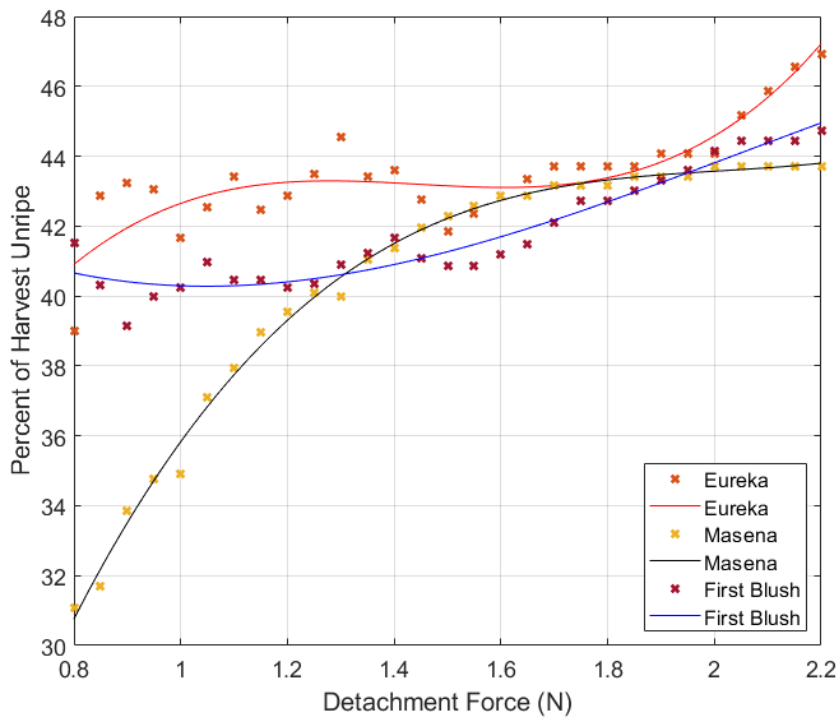


Figure 3.7: Percentage of unripe berries removal success with increasing detachment force limits

3.2 Design of the hand-held harvesting device

3.2.1 Detachment Method Exploration

There are many potential methods to detach the berries from the plant. However, it is also essential to consider the potential of the final design to adapt to future automated harvesting systems. Several harvesting methods were explored: tapping, suction with vacuum, air blowing, air pulsing and reciprocating. Important factors were compared in the selection of the most suitable detachment method:

- harvest speed
- harvest quality
- ease of use
- potential to selective harvest
- power source required
- application accuracy
- cost to implement

3.2.1.1 Tapping

A gentle tapping motion was achieved with a flat paddle, targeting the berry cluster and applying impact force on the cluster to cause vertical swaying of the branch. It is slow and challenging to perform this motion in tight spaces, especially amongst the dense foliage. The interaction of the paddle and the berries may also cause bruises or punctures. However, with this method, minimal location accuracy is required and is easy to manufacture. Some degree of selective harvesting potential is observed.

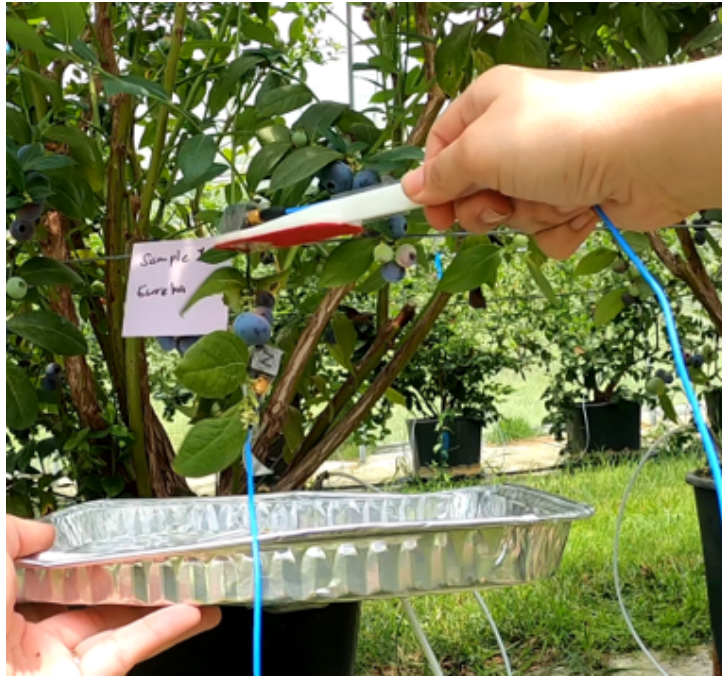


Figure 3.8: Tapping the branch to remove berries from the cluster

3.2.1.2 Suction with Vacuum

The suction method was developed using silicon cups and a small vacuum pump to form a tight seal on the berry's surface to grip and detach the berry from the pedicel. Compared to others, this method is very slow as it targets a single berry at a time and requires very accurate location and machine vision to assess harvest readiness. Harvest is likely to be unsuccessful on smaller or deformed berries due to the difficulty of forming a proper seal with a suction cup. It is observed that some berries could not handle the vacuum's suction pressure, bursting and contaminating the vacuum chamber. Fine adjustment to the suction pressure is necessary to ensure a successful harvest while not damaging the berry.



Figure 3.9: vacuum suction with silicon cup to detach berry

3.2.1.3 Air Blowing

This method blows air onto the targeted berry cluster, using wind-induced oscillation to detach them from their pedicel. It is relatively slow due to long build-up time and poor energy transfer due to canes swaying away from the air source. Although air blowing reduces contact and preserves the bloom, a wide-catching device is necessary to capture the fallen berries. Selective harvesting is somewhat achievable but requires more research.



Figure 3.10: Wind-induced oscillation similar to shaking the cane physically

3.2.1.4 Air Pulsing

This is similar to the air-blowing method but with the intermittent pulsing of air to deliver impact force onto the berry cluster. This method is also relatively inefficient, comparable to air blowing, due to poor energy transfer. Selective harvesting is also, to some extent, achievable but requires more research to identify the ideal pulsing frequency. A wide-catching device is necessary in addition to a grabbing device to reduce the swaying of branches to maximise the energy transfer.



Figure 3.11: Impart impact force with pulsing air onto berry cluster.

3.2.1.5 Shaking

This method shakes the blueberry cluster by applying reciprocating movement to the cane with a cam yoke mechanism powered by a DC motor, using a spring clip to grip the cane firmly for maximum energy transfer through reciprocation movement adjacent to a cluster of berries. The berry experienced a secondary oscillation movement and centrifugal force, which detached the berry. It is observed that the bigger berries detached relatively more straightforwardly than the smaller ones. This method targets multiple berries of one single cane, but the harvesting is still relatively slow. A simple experiment was set up to compare the effects of varying the amplitudes and shaking speeds; the results are tabulated in Table 3.2. The 15 to 20mm amplitude shows the best results, while the

combination of mid-range amplitude and medium and above RPM range shows better potential for selective harvesting. It is also observed that higher RPM causes the detached berries to launch at high speed in random directions away from the cane. A comprehensive soft catchment device is essential to minimise berry loss and damage from falls.



Figure 3.12: Reciprocating movements on berry cluster with a cam yoke shaking device.

Table 3.2: Comparing different amplitude, RPM, Harvest speed and potential for selective harvesting. Note: The percentage harvested includes both ripe and unripe berries.

Test	A (mm)	RPM	Harvest Speed	% harvested	Selective H.
1	10	235	N/A	0.0%	N/A
2	15	235	fast	45.0%	high
3	20	235	fast	36.4%	high
4	25	235	slow	100.0%	low
5	30	235	very slow	100.0%	low
6	10	300	slow	100.0%	low
7	15	300	med	72.7%	high
8	20	300	fast	66.7%	high
9	25	300	med	60.0%	low
10	30	300	very slow	100.0%	low
11	30	176	very slow	100.0%	low
12	35	176	very slow	100.0%	low

From the observation, the vigorous shaking motion on the cane can deliver the ac-

celeration required to detach the berry swiftly. The end effector and the cane need physical contact for maximum energy transfer. Selective harvesting is achievable with fine adjustment of RPM and amplitude of oscillation. The higher the RPM, the faster the harvest speed and the more unripe fruit is harvested.

3.2.1.6 Decision Matrix and Summary

The weighting factor of 1-3 is applied to each critical attribute listed previously, with weighting of 1 being less critical and 3 being very critical. The performance of each attribute is given a score of 1-3, with a score of 1 being not ideal and 3 being ideal. The final decision matrix score is the sum of each attribute score multiplied by their weighting. Respectively, they are tabulated in Table 3.3. The shaking method accumulated a score of 43, followed by air blowing at a score of 39. Shaking will be the method to move forward to the prototyping stage.

The combined operation of the shaking harvest tool and soft surface catchment devices is critical to verify the effectiveness of the shaking harvest method.

Table 3.3: Decision Matrix for harvesting methods

Attributes	Factor	Tap	Vacuum	Blow	Pulse	Shake
harvest speed	3	2 6	1 3	3 9	2 6	2 6
harvest quality	3	2 6	1 3	2 6	2 6	3 9
ease of use	2	1 2	1 2	3 6	3 6	3 6
selective harvest	3	2 6	3 9	2 6	2 6	3 9
power source	2	3 6	1 2	2 4	2 4	3 6
accuracy	2	3 6	1 2	3 6	3 6	3 6
cost to implement	1	2 2	1 1	2 2	2 2	1 1
Selection Score:		34	22	39	36	43

3.2.2 The End Effector

The end effector is the section of the harvesting tool that contacts the plant and transfers the movement and energy for the harvesting process. However, each blueberry has its

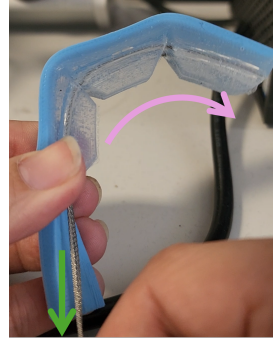
own distinctive growing habits that affect the end effector requirement. For example, Masena berries grow in dense clusters, covering the whole cane, while the Eureka First Blush berries form a much smaller cluster with upright canes. The essential attributes of the end effector are:

- low cost to implement
- easy to use and attach to the harvesting tool
- robust and easy to fix
- effective in transferring energy and movement
- does not induce damage to plant
- requires low positioning accuracy

Identifying a suitable location to grasp the cane without contacting the berry cluster can be difficult. Several gripping methods were tested to determine the most effective solution.

3.2.2.1 Soft Silicone Fingers

The soft gripper consists of three gripper fingers cast with two different hardness of silicone with a 3D-printed mould in Figure 3.13a. The fishing wire threaded through the centre controls the finger's folding and unfolding motion and is actuated with a DC motor. Figure 3.13b shows the fingers folding by pulling the wire. [85] published the details of silicone finger manufacturing. This method was not ideal as the gripper could not deliver maximum energy transfer to the berries. Due to the requirement to be in contact with the berry cluster, the fingers also cause unripe berries to detach. Furthermore, the manufacturing complexity and cost of the end effector was significantly higher than the rest.



(a) 3D-printed mould for casting the silicone fingers

(b) Silicone fingers fold by pulling the wire threaded through the finger

Figure 3.13: Soft silicone gripper fingers

3.2.2.2 Spring-loaded clips

An ordinary clothes peg was used to verify this idea quickly. The clip was securely attached to the end of the shaker rod, and a motor will actuate the clip's opening and closing, but it is actuated manually at this stage. Although the clip can grip onto the cane firmly, shaking the cane with this method requires significant torque. Besides that, the end effector requires accurate orientation and positioning to grip successfully.

3.2.2.3 C-shaped hook

The C-shaped hook was 3D-printed in PLA, with a prong to guide the cane towards the hook, as shown in Figure 3.14. The cane can sway freely between the hook and the prong, allowing occasional constructive interference to produce a more significant force on the berries. The C-shaped hook allows for higher positioning errors, while the shape also helps keep the cane in line with the shaking direction. However, the shape also increases the difficulty releasing the cane after harvesting.

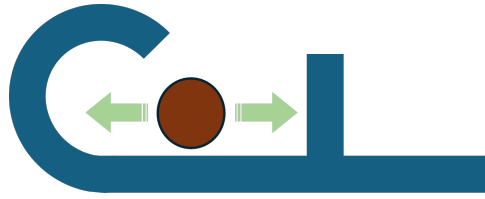


Figure 3.14: C-shaped hook end effector

3.2.2.4 Two-prong hook

To reduce the difficulty of releasing the cane after harvest, the C-shape hook method is modified into two simple prongs as shown in Figure 3.15. Similarly to the C-shaped hook method, the cane can sway freely in between, and the two-prong end effector provides for even higher positioning error and makes it easier to release the cane after harvest. Moreover, the fabrication of this end effector has a negligible cost and is simple, requiring no extra actuator installed. The distance between the prongs was decided to be 25mm, as larger spacing increases the harvest time.

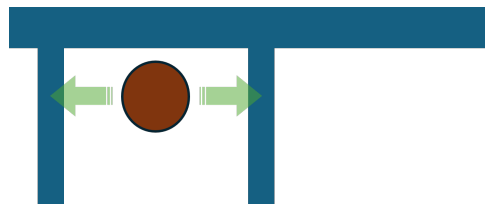


Figure 3.15: Two-prong end effector

3.2.2.5 Decision Matrix and Summary

Equal weighting is applied across all attributes critical for selecting the end effector. For each approach, a score of 1-3 is given for each attribute, where 1 is the least ideal and 3 is the most ideal. As seen in Table 3.4, the two-prong hook is the highest performer, scoring 18 out of 18, followed by a C-shaped hook.

Table 3.4: Decision Matrix for end effector

Attributes	Silicon Fingers	Spring Clips	C-Hook	Two-Prong
Cost	1	1	3	3
Ease of use	1	2	2	3
Robustness	2	2	3	3
Effectiveness	1	1	2	3
Damage to plant	1	2	3	3
Positioning accuracy	3	2	3	3
Selection Score:	9	10	16	18

3.2.3 Principle behind shaking

During shaking, the berry will likely experience forces comparable to the rolling method. When a reciprocating movement at the maximum velocity, v_{max} is applied to the cane, causing the berry to oscillate in the opposite direction of the movement, at $-v_{max}$, as shown in Figure 3.16. To detach successfully, the centrifugal force must overcome the attachment force F_d between the pedicel and the berry.

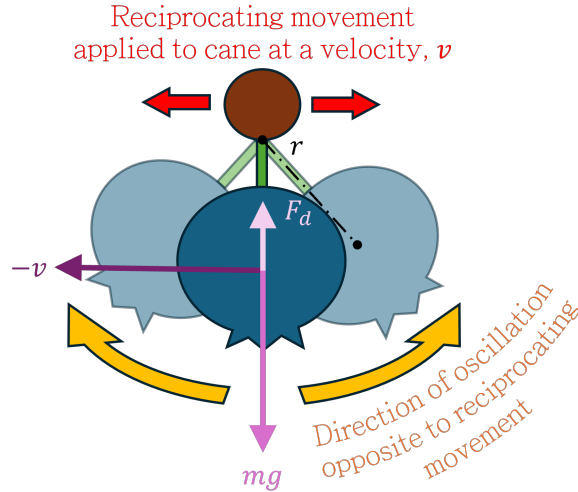


Figure 3.16: Force diagram of a berry experiencing shaking movements

When the berry detaches, the centrifugal force is equal to the detachment force, F_d , which can be described by equation 3.4, where m_{berry} is the mass of the berry, v_{max} is the maximum velocity experienced by the berry, and r is the distance from the attachment

point of the cane and pedicel to the centre of gravity of the berry.

$$F_d = \frac{-m_{berry}v_{max}^2}{r} \quad (3.4)$$

Since $v_{max} = A\omega$, where A represents the amplitude, and ω represents the radial velocity of the reciprocation movement. Therefore, the minimum RPM of the reciprocating movement applied to the cane required to match or overcome F_d can be estimated by the equation 3.5. To simplify the calculation, r is given a constant value of 0.010 metres as the variation between values is minimal.

$$RPM = \frac{60}{2\pi} \sqrt{\frac{F_d r}{m_{berry} A^2}} \quad (3.5)$$

With the derived equation of RPM, applied to the detachment force and weight of the ripe berries data from the detachment force evaluation, the theoretical mean RPM for Eureka Original, Eureka First Blush and Masena are calculated and plotted in Figure 3.17, where the error bar represents the standard deviation. Masena has a mean RPM of approximately 950 rpm and an approximate range of 750 to 1150 rpm. These values will aid the decision on the RPM test range of the ideal detachment settings of the shaker prototype V2.1 in Field Trial 2.0.

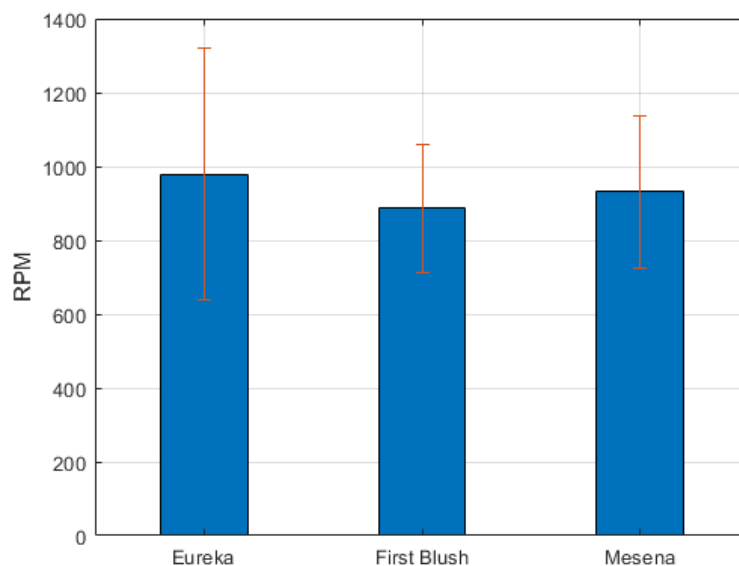


Figure 3.17: Mean RPM for each with error bar represents the standard deviation

3.3 Design of the catchment device

An effective catchment device is a critical part of the harvesting system. Its primary purpose is to collect and transfer the detached berries into the standard pack house trays without introducing further damage. To create an effective harvesting system, the catchment device must complement the harvesting tool rather than hinder the harvest process. The shaking harvest method introduced new challenges to gather the berries undamaged. The main design objectives of the catchment device are:

- minimal damage
- minimal ground loss
- made with food-safe contact surface
- easy to maintain - contact surface can be removed and cleaned easily
- easy to use - can be carried and setup by one person
- low cost to implement - parts are readily available
- low positioning accuracy required

Blueberries sustain bruising with fall height as little as 150mm, according to [86]. However, the bruising rate varies depending on the acceleration of the fall, the blueberry and the impact surface. A few catchment approaches suitable for the hand-held harvesting tool are considered.

3.3.1 Funnel attached to the shaking device

This method consists of a funnel-shaped frame lined with a stretched woven fabric bag where the berry is collected at the bottom. The frame is attached to the shaking device and placed directly under the cluster, as illustrated in Figure 3.18. This device reduces the

berry's fall height but adds extra weight to the handheld device, making the whole shaking tool unnecessarily bulky and challenging to reach tight spaces. It was also observed that the berry bounced off the stretched fabric, suggesting it did not absorb the impact force effectively.

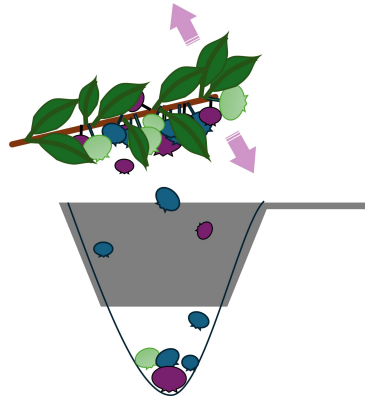
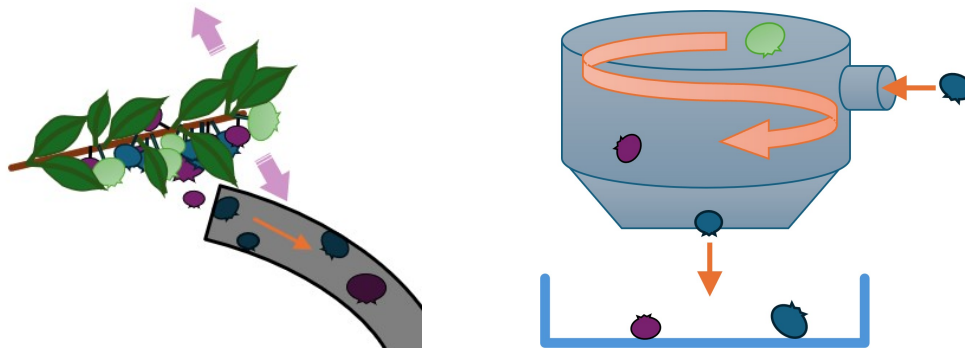


Figure 3.18: Illustration of the funnel-shaped frame collecting berries

3.3.2 Vacuum collection

Figure 3.19 shows another method that collects the berries directly under the cluster. A vacuum tube is attached below the shaking device, and the other end of the tube is a vacuum collection chamber powered by a vacuum pump with enough suction force to collect detached berries (Figure 3.19a). The berry then follows the contour of the vacuum tube into a collection chamber that allows the berry to roll slowly into the standard pack house tray (Figure 3.19b). It is much less bulky than a funnel container but still not ideal for the handheld device. Nevertheless, the initial impact and the berry rolling in the vacuum tube were enough to cause bruising, plus the constant operation of the vacuum pump, which means it requires a reliable power source in the form of a battery. This method was discarded due to the high implementation cost and complications involved in fabrication.



(a) Detached berries pull towards the vacuum inlet (b) Berries enter the chamber and eventually exit into the tray below

Figure 3.19: Illustration of Vacuum collection chamber collecting berries

3.3.3 Single-layered catch net

The final method tested was a sturdy, portable wide frame that provided full coverage under a single blueberry plant footprint. The frame is no taller than the top of the planting container. It is lined with a relaxed woven fabric that absorbs impact force from falling berries, allowing them to roll gently on the fabric surface towards the bottom of the catchment area, the concept can be seen in Figure 3.20. Although this catchment method does not prevent berries from falling at great heights (up to 1500mm from top of the plant), the relaxed fabric was able to slow down the speed of the drop effectively. However, bruising can still occur when berries land directly on top of another berry pooled in the catchment area's centre.

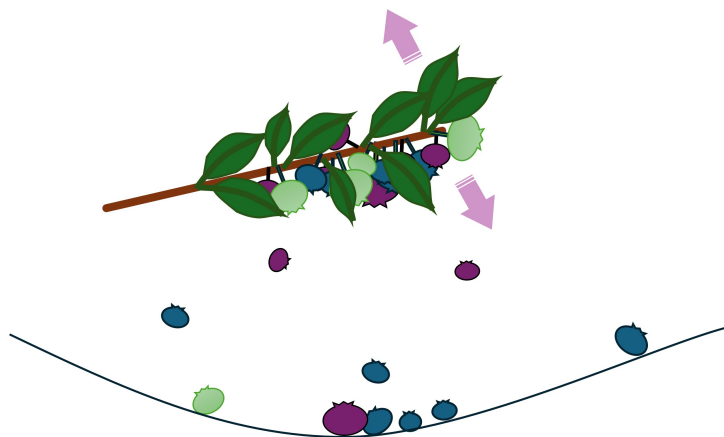


Figure 3.20: Illustration of collecting the berries with a single layer of fabric

3.3.4 Multi-layered catch net

It is critical to prevent the berries from pooling in the high-impact area. Below the first fabric layer, another layer with a slightly steeper slope is added to swiftly guide the berries from the impact zone into the standard pack house tray placed below. A third layer is introduced to slow the rolling again before the berries fall onto the hard plastic surface of the tray. The configuration is illustrated in Figure 3.21. This catchment method has shown promise and meets most of the design objectives.

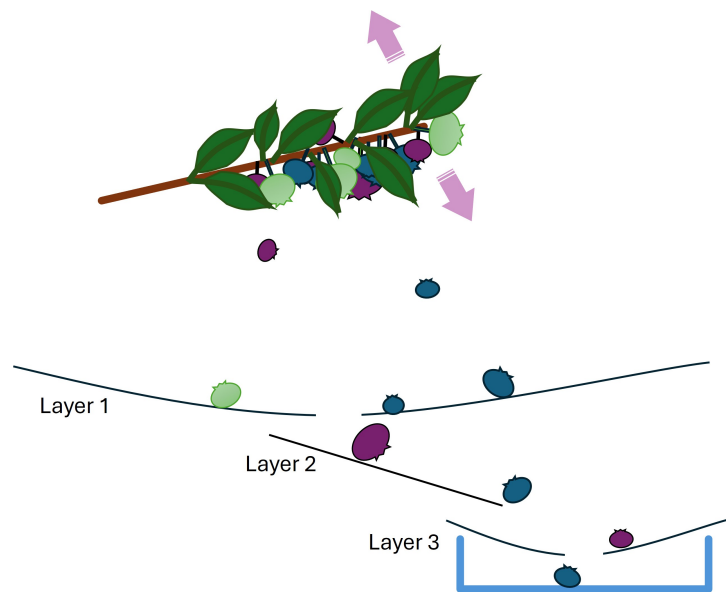


Figure 3.21: Illustration of collecting the berries with triple layers of fabric

3.3.5 Decision Matrix and Summary

The weighting factor of 1-3 is applied to each critical attribute listed previously, with weighting of 1 being less critical and 3 being very critical. The performance of each attribute is given a score of 1-3, with a score of 1 being not ideal and 3 being ideal. The final decision matrix score is the sum of each attribute score multiplied by their weighting. The scores of each catchment approach are tabulated in Table 3.5. The multi-layered catch net scored the highest of 45, with the single-layered catch net following behind at 41. Therefore, the multi-layered catch net approach was chosen for further development.

Table 3.5: Decision Matrix for catchment device

Attributes	Factor	Funnel	Vacuum	Single-layer	Multi-layer				
Min. damage	3	2	6	1	3	2	6	3	9
Min. ground loss	2	1	2	1	2	3	6	3	6
Food safe	3	3	9	1	3	3	9	3	9
Maintenance	1	3	3	1	1	3	3	2	2
Easy to use	3	1	3	1	3	3	9	3	9
Low cost	2	3	6	1	2	1	2	2	4
Positioning accuracy	2	2	4	2	4	3	6	3	6
Selection Score:			33		18		41		45

3.4 Artificial Blueberry Plant for Testing Purpose

Like many seasonal crops such as apples, grapes, and rock melons, blueberries are only available at certain times of the year, with each typically having a harvest window of approximately three months. The design and validation of the prototype must be completed before the start of the harvest season. Many researchers opt for virtual simulation of the crop to validate their design. However, it is challenging and time-consuming to simulate the physics describing the removal of blueberries from their branches. There are many advantages of an artificial plant with properties similar to real ones, especially for the physical trial of an end effector and training for fruit detection with deep learning. It also allows for repeated testing of the same setup in a controlled environment.

Hence, an artificial blueberry plant was created. Producing an artificial plant has multiple challenges, for example, the berries should show a similar detachment force that can be detached and reattached repeatedly, and the canes need to have the correct stiffness to be reasonably solid, yet still flexible. The detachment forces of blueberries of various cultivars have already been quantified in Section 3.1 which can be used in the development of the artificial plant. The completed artificial plant is expected to behave similarly to an actual plant.

For the shaking experiment, it is crucial to have these physical attributes as accurate

as possible. Masena is chosen as the to replicate.

- weight and size of berries
- detachment force of pedicel
- hardness of berries
- cane diameter
- berries distribution
- leaves distributions
- cane flexibility and strength
- dense foliage to recreate occlusion of berries

The creation of the artificial plant is divided into two sections: the support structures and the berries. The properties of the artificial plant are modelled against the blueberry cultivar Masena.

3.4.1 Support structures

Masena is a high bush with dense clusters of berries and leaves along the cane. The cane is flexible and robust enough to support at least 30 berries. The weight of the berries can sometimes weigh down the cane such that the cane reaches the ground.

To achieve similar flexibility and strength, a flexible 4 mm rattan cane is reinforced with an 18 gauge florist wire and twisted around to provide extra strength and stiffness. The cane is then wrapped in green heat shrink. A small cutout is made in the heat shrink on the cane to insert the peduncle, which is made of 18 gauge florist wire, with branches of plastic leaves disassembled from another store-bought artificial plant attached with a small bit of heat shrink. Two small twisted loops are added to each of the peduncles, one at the tip of the peduncle and one at the middle, to attach a few pedicel wire loops made

of 22 gauge florist wire, as seen in Figure 3.22. Each pedicel wire end can support up to two berries. Users can decide the size of the berry cluster by adding or removing pedicel wire to each peduncle loop.

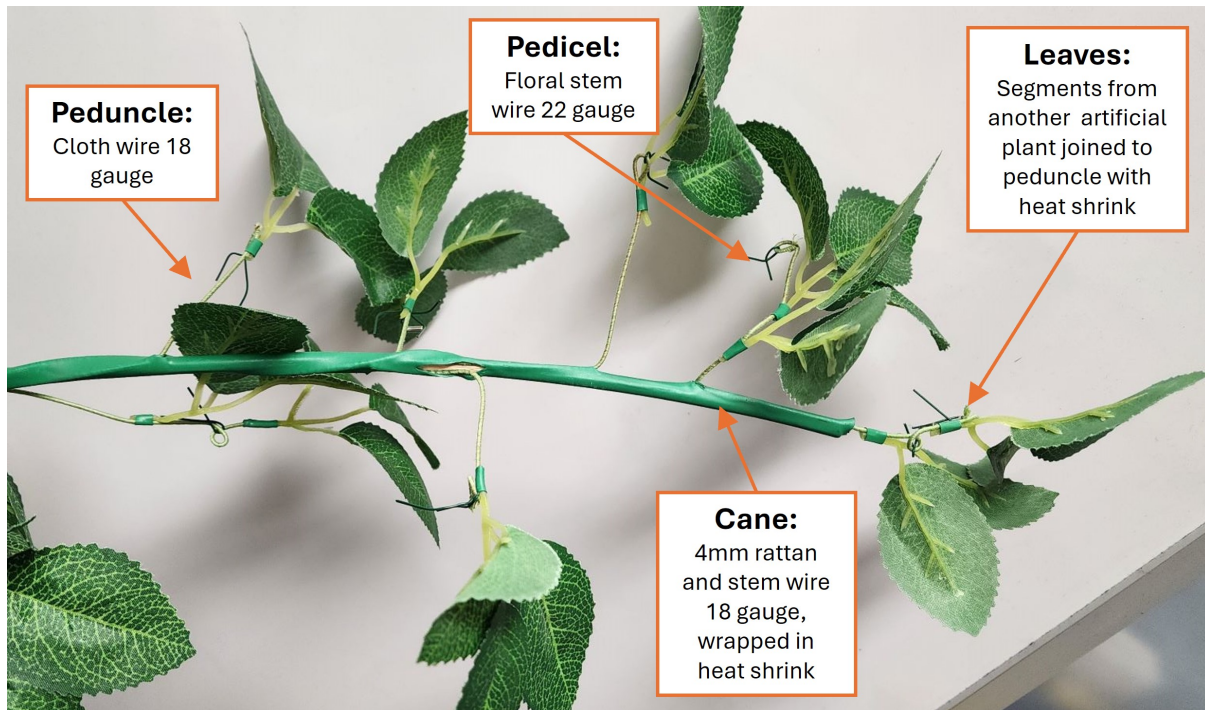


Figure 3.22: The construction of each cane including pedicel, peduncle and leaves

Ten individual canes were made. Two to three canes were wrapped in a heat shrink to form thicker branches. Then, all ten canes were combined at the lower end and wrapped with a brown-coloured heat shrink to form the trunk, as shown in Figure 3.23. The lower part of the trunk is secured and set in a potting pot with a concrete mixture.

3.4.2 Artificial blueberries

Properties of ripe berries were considered only to simplify the fabrication process. The berry was modelled using Solidworks 3D CAD software. Several methods were investigated to create the most realistic berries, including FDM printing with PLA. The final design of the berry is cast with Smooth-Sil Pourable Platinum Cure Silicone 960 (Figure 3.24a), with a nominal shore hardness of 60A which is similar to the hardness of a Masena

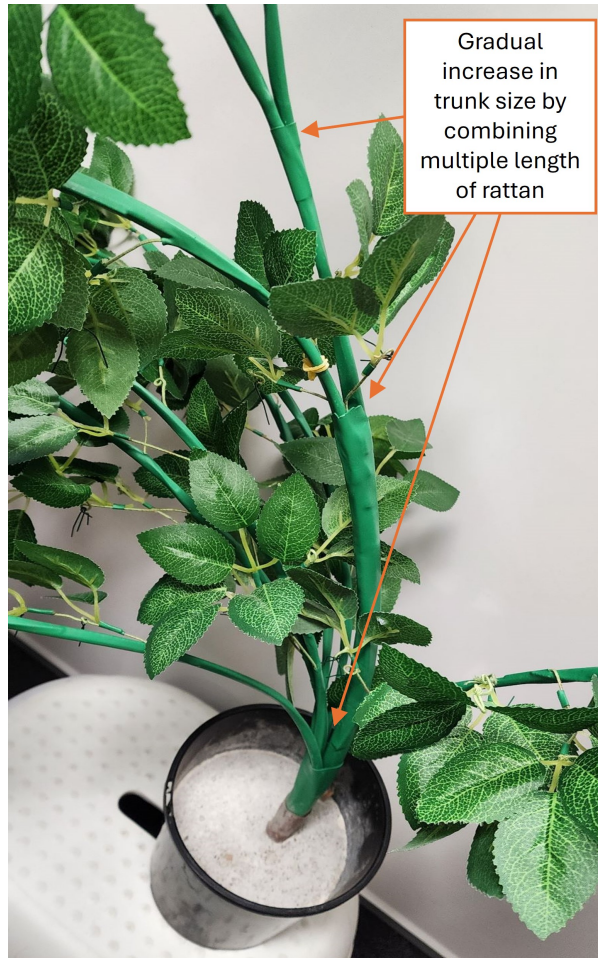


Figure 3.23: Combining multiple canes into trunk and setting the base with concrete

blueberry, at 57A ([87]. The silicone is dyed with one part Silc Pig Red and two parts Silc Pig Blue to achieve a similar colour to a ripe blueberry.



(a) Smooth-SIL Pourable **(b)** Silicone Dye - **(c)** Silicone Dye -
Platinum Cure Silicone 960 Silc Pig Blue Silc Pig Red

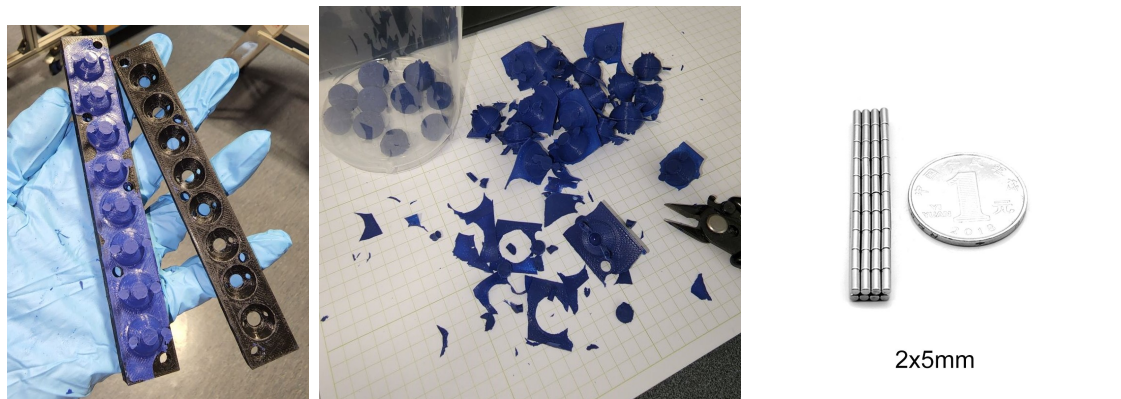
Figure 3.24: Silicone used for casting

The step-by-step process of fabricating the silicone blueberries is shown in Figure 3.25. The mould was designed and 3D printed in two parts for ease of removal (Figure

3.25a). Five sizes of berries (major diameter of 13mm, 14mm, 15mm, 16mm and 17mm) were selected to be cast. Sizes were determined by applying normal distribution to the diameters of the ripe Masena berries collected from the detachment force evaluation in Section 3.1.



(a) 3D printed blueberry mould in various sizes (b) After pouring silicone mixtures into the moulds (c) Trim the overflow from the mould after curing



(d) Removing from the mould (e) Trimming the excess skirt and breather hole trunks (f) Neodymium N50 $\phi 2 \times 5\text{mm}$

Figure 3.25: Process of making the silicone blueberries

Magnets act as the attachment point between the berry and pedicel which gives a repeatable mechanism of detachment. A cylindrical Neodymium N50 magnet with a diameter of 2 mm and length of 5 mm was used, as pictured in Figure 3.25f. The magnet is rated at 1.55 N of pull force when removing the magnet from a 10 mm mild steel opposite to the direction of pull, similar to the measured detachment forces found in Section 3.1. A hole was punctured into the top of the cast silicone blueberry and the cylindrical magnet was inserted.

The final assembly of the artificial blueberry plant, including berries, is shown in Figure 3.26.



Figure 3.26: Silicone blueberries attached on the artificial cane

Chapter 4

Field Evaluations 1.0

This chapter outlines the initial field evaluation of the Shaker and Catcher V1.0 prototypes. Section 4.1 describes the prototype development, Section 4.2 describes the method of evaluation, Section 4.3 presents the results and discussion, and finally, Section 4.4 provides a summary of field trials, and presents the plan for the next field trials and improvements to be made to the next iterations of the prototypes.

The field evaluation 1.0 took place in a commercial blueberry orchard near the town of Aongatete in the Bay of Plenty region of New Zealand. This orchard has one hectare of blueberries planted on a hillside with a gentle slope under poly-tunnel structures.

4.1 Shaker and Catcher V1.0 Prototypes

4.1.1 Shaker Prototype V1.0

From the findings of the harvest method evaluation in the previous chapter, a set of requirements for the Shaker V1.0 prototype are:

- capable of output shaking speed of up to 1500 rpm while under load

- portable, in the form of a handheld device
- reciprocating amplitude of 15 to 20 mm

The general arrangement of the Shaker V1.0 prototype is shown in Figure 4.1. As a proof of concept, a Makita XPH12/DHP484 18V Brushless Hammer Drill/Driver was selected to drive the shaking mechanism with a no-load speed of 2000 rpm. The drill was coupled to a modified reciprocating saw attachment, with a 20 mm stroke, to hold a set of prongs for shaking the canes. A tube 300 mm long was used to reach the blueberry bush's centre

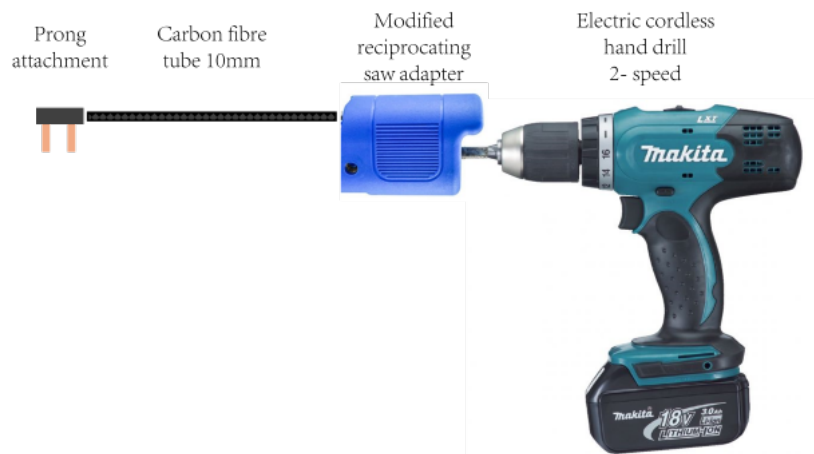


Figure 4.1: *Reciprocating prong end-effector attached to battery drill*

The reciprocating movement is created by rotating a barrel cam, pushing and pulling a roller attached to a sliding beam as shown in fig.4.2. This prototype requires two hands to operate, one holding the hand drill and the other holding the reciprocating saw adaptor to prevent backlash.

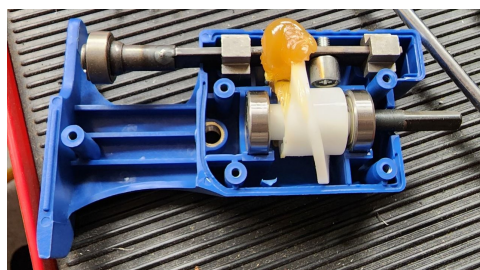


Figure 4.2: *Barrel cam inside the reciprocating saw adaptor unit*

4.1.2 Catcher V1.0 Prototype

The soft surface catchment consists of three layers of food-safe polyester Ezi-Flow netting. The layers progressively absorb kinetic energy from the falling berries and gently convey them to a removable collection tray. The overall principle of operation is shown in 4.3.

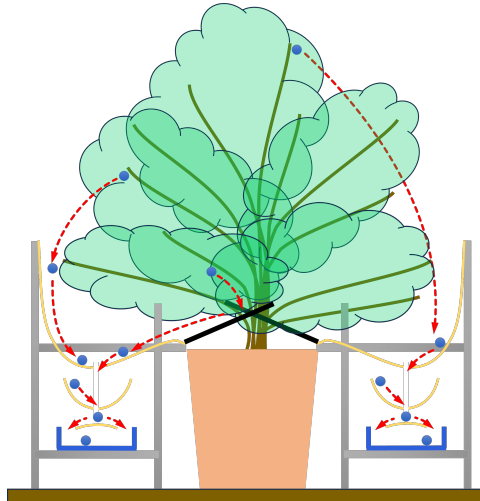
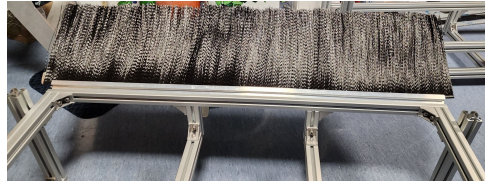


Figure 4.3: Layout of the catchment system

The Catcher V1.0 comprises a frame assembled with a V-slot aluminium extrusion with a cross-sectional area of 40x40 mm on four 160 mm castor wheels. The collection tray is installed in the middle of the frame, with stopping tabs at the end of the holder rail to stop the tray from sliding off easily. The wide opening at the rear also allows the operator to change the tray easily. In Figure 4.4c, the netting is shown draping over the frame before being customised to fit the frame with the desired slack and contour. The netting was cut and sewn with a sewing machine to achieve the contour and curves using standard sewing techniques used in garment sewing. At the lowest level of the top layer netting, two holes were cut on the sides, while the middle part of the netting was pinched and sewn to create a higher contour, allowing the berries to roll towards the holes. Below the holes, another layer of netting is formed into two channels using metal wire inserts. This layer guides the berries towards the tray. Finally, the last layer of netting sits slightly above the tray. This layer absorbs the final kinetic energy from the berry. A slit was cut into the middle of the netting to allow the berry to roll into the tray only when it had slowed down.



(a) The bare frame



(b) Mounting position of the brush strip



(c) Customizing the netting to the frame



(d) Assembly of Catcher V1.0 without brush strip



(e) Top view of the first and second layers of netting



(f) Rear view shows the tray holder and third layer of netting

Figure 4.4: Catcher V1.0

The device is designed to cover one-half of an entire blueberry plant, with a catchment area 1200 mm wide and 500 mm deep (Figure 4.4d). The front edge of the device was placed right up against the pot. A second catchment device is mirrored on the other side of the plant for complete coverage. A 230 mm broad strip brush was attached at the front edge of each catchment device (Figure 4.4b). The bristles overlap to close most of the gap between the blueberry trunk and the catchers. Two angle brackets were installed as adjustable hinges for the strip brush, which allowed the operator to adjust the brush angle to suit the brush while enabling the brush to be folded away during transportation. The slight angle on the brush strips enables berries to roll gently towards the netting. Two 3D-printed handles are installed on each side of the frame to aid handling.

The berries fall onto the first layer and roll off onto the second layer through a cut-out at the lowest point (figure 4.4e). They are then guided towards the final layer before rolling into the pack house tray below. The pack house tray moves along the row with the catcher, and the user can easily swap for an empty tray from behind when it is filled, as shown in Figure 4.4f. Figure 4.5 shows the Catcher V1.0 aligned to blueberry bushes in an orchard.



Figure 4.5: Catcher V1.0 in the orchard

4.2 Method

In field trial 1.0, both prototypes were assessed separately. This section describes the methods used to determine the performance of the Shaker and Catcher V1.0. Figure 4.6 outlines the field trial overview and how each sample is evaluated. The first part of the evaluation focuses on the performance of the Catcher V1.0 by comparing hand harvesting

methods in both the traditional bucket and Catcher V1.0. The metrics of interest include number of rejects, harvesting rate, and firmness, which is a measure of berry quality. The second part focuses on the performance of Shaker V1.0 to determine the accuracy of selectively harvesting ripe berries, and the most effective speeds for the mechanism.

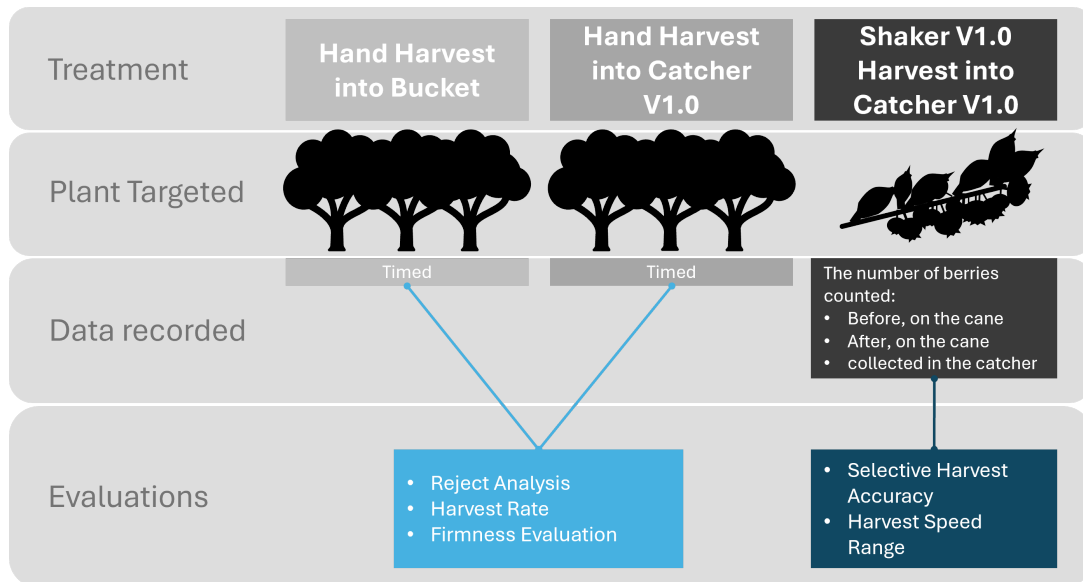


Figure 4.6: Flow chart of Field Trial 1.0

The field trial took place on a commercial blueberry orchard in Aongatete, Bay of Plenty, New Zealand. Three cultivars, Eureka Original, Eureka First Blush and Masena, were selected for the evaluations. However, depending on which cultivar was harvested in the recent cycle, not all three cultivars were available at the same time of the experiment.

4.2.1 Catcher V1.0 Evaluation

This evaluation aims to determine the effectiveness of Catcher V1.0 at reducing harvest damage and increasing harvest speed, compared to the traditional method of hand harvesting into a bucket. The harvest rates are compared, while the quality of the harvested berries is compared through reject analysis and firmness evaluation.

Two harvest treatments were compared on the Eureka and Eureka First Blush. Masena was excluded as it was not available during the trial.

- Hand harvest into a bucket attached to a waist belt (HB) (Figure 4.7a)
- Hand harvest into Catcher V1.0 (HC) (Figure 4.7b)



(a) Hand harvest into bucket

(b) Hand harvest into Catcher 1.0

Figure 4.7: Two treatments for Catcher V1.0 performance evaluations

Two experienced pickers were selected for the trial on the eighth week of the harvest season. Two sets of three plants were selected for each cultivar, with one picker on each side of the row, harvesting on the same plant at any time. The time taken to harvest three consecutive plants was recorded, t_{pick} , along with the mass (m_{pick}) of each sample harvested.

The harvest rate of each experiment, \dot{m}_{pick} , was calculated with Equation 4.1.

$$\dot{m}_{pick} = \frac{m_{pick}}{t_{pick}} \quad (4.1)$$

In the reject analysis, the number of berries N_{total} of each sample was counted, and samples were inspected manually and sorted into two groups: marketable, $N_{marketable}$, and rejects, N_{reject} .

Blueberries were classified as rejects if they showed at least one of the following attributes: splits, bruises, softness, pedicel retention, beard retention, dehydration or under-ripe. The remaining berries were classed as marketable. This evaluation did not consider the berry's overall size and bloom retention. The harvest efficiency, HE , indicates the ratio of marketable berries present in the total harvested and can be determined by equation 4.2.

$$HE = \frac{N_{marketable}}{N_{total}} \quad (4.2)$$

Condition of blueberries, such as puncture, bruises, dehydration, over-hydration, and overripeness, result in lower average firmness of the berries. These defects are significant contributors to post-harvest premature decay, and early detection is critical. However, some defects are undetectable with human vision, and most are not detectable until further down the supply chain. Firmness measurement can detect the first sign of these defects and is one of the properties used to predict blueberries' quality and shelf life.

The instrument used to measure the berry firmness is the Firmtech FT7 (figure 4.8a), a desktop non-destructive small fruit firmness tester. The berry is gently squeezed by the instrument's load cell with increasing force. The rate of force in grams increases per millimetre of deformation is defined as firmness, f in g/mm . Twenty-five marketable berries were randomly selected from the sample from each harvest treatment, as shown in figure 4.8b and figure 4.8c. Each was placed in the groove on the prepared aluminium disc on its side to measure its equatorial firmness. The force was increased until the berry skin ruptured from the applied pressure. The firmness of each berry, f , was recorded.

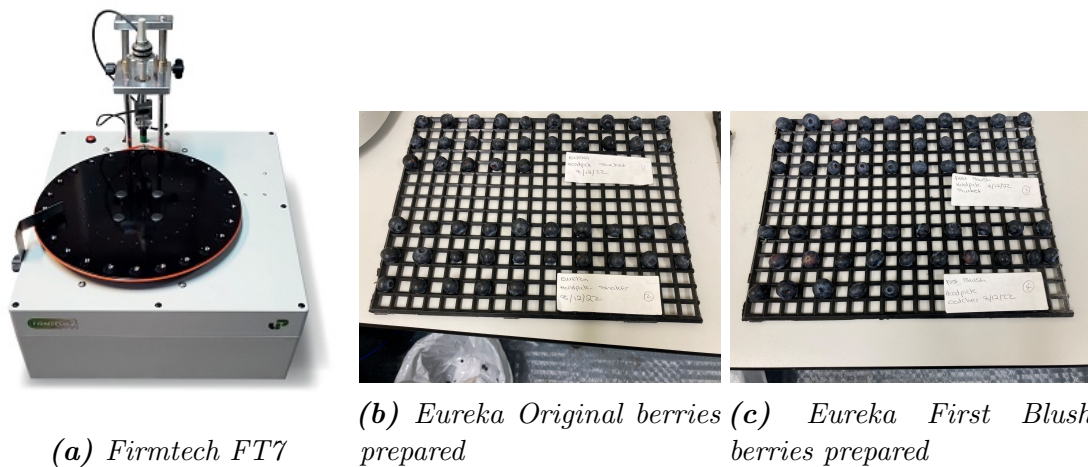


Figure 4.8: Device used for firmness evaluations and berries samples prepared for the test

4.2.2 Shaker V1.0 Evaluation

This evaluation assesses the shaker's ability to harvest selectively (Detachment Accuracy, DA , and Harvest Efficiency, HE), ground loss ratio (G_{loss}) and the most effective shaking

frequency for each cultivar. An ideal selective harvesting device would harvest all the ripe berries, leaving the unripe behind on the plant. Detachment accuracy, DA , defines the ability of the shaker to detach only ripe berries. DA can be evaluated by comparing the number of unripe berries on the cane before and after harvest, as shown in equation 4.3.

$$DA = \frac{G_f}{G_i} \quad (4.3)$$

In contrast, harvest efficiency, HE , similar to the metric in the previous evaluation, measures the ratio of marketable berries to total harvested berries. HE can be calculated by finding the ratio of ripe berries within the total harvested amount, as shown in Equation 4.4.

$$HE = \frac{(B_h)}{B_h + G_h} \quad (4.4)$$

Ground loss can happen due to the rigorous shaking motion applied, causing detached berries to take off in a random direction. The ground loss ratio, G_{loss} , was calculated by Equation 4.5.

$$G_{loss} = \frac{B_i + G_i - B_f - G_f - B_h - G_h}{B_i + G_i - B_f - G_f}. \quad (4.5)$$

Catcher V1.0 was used in this evaluation to help capture the detached berries. The trial was performed on eight randomly selected canes from Eureka Original and Masena cultivars with at least one intact cluster of berries.

The end effector prongs were positioned over the cane, close to the berry cluster. A shaking motion was applied by holding the trigger on Shaker V1.0 until visual confirmation of all ripe berries was detached. The motor's speed in RPM for each test, RPM , was

recorded with a hand-held digital tachometer. As shown in Figure 4.9, before applying the shaker, the number of visually ripe berries, B_i , and unripe G_i on each cane were recorded. After using Shaker V1.0 to harvest the berries, the number of ripe and unripe berries left on the cane, B_f and G_f , and the number of ripe and unripe berries captured in the catcher, B_h and G_h , were also recorded.

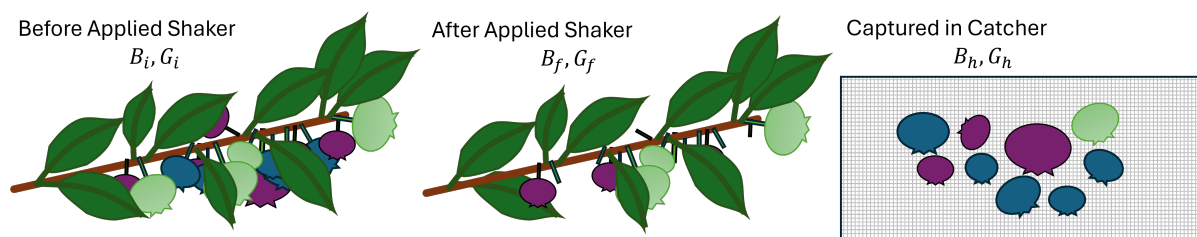


Figure 4.9: Number of berries recorded at each point of the experiment

4.3 Results and Discussion

4.3.1 Catcher V1.0

The harvest rate of all four tests is tabulated in Table 4.1. Harvesting into the catcher was slower for Eureka Original but faster for Eureka First Blush. Harvest rates of either treatment are almost doubled for Eureka First Blush compared to Eureka Original.

Table 4.1: Harvest rate by blueberry cultivar and harvest treatment

Cultivar	Treatment	Time (s)	Mass (g)	Rate (g/s)
Eureka Original	HB	343	1163	3.39
Eureka Original	HC	247	690	2.79
Eureka First Blush	HB	265	1363	5.14
Eureka First Blush	HC	361	2193	6.07

A total of 2689 berries were harvested across all four samples. The number of $N_{marketable}$, N_{reject} and N_{total} is summarised in Table 4.2. More berries were harvested from the Eureka First Blush than Eureka Original, but also more rejects. The harvest efficiency is higher for the hand harvest into the bucket (89.3% and 82.7%) in contrast to hand harvest

into the catcher (83.7% and 71.4%). It is important to note that the pickers have been harvesting into a bucket almost daily for at least eight weeks prior versus seeing and using the catcher for the first time during the tests. However, the lack of a large difference in the harvest efficiency between the two treatments has indicated that the catcher is easy to use and requires little experience. It is also expected that the harvest efficiency of hand harvesting into a catcher will improve over time.

Table 4.2: Number of berries and harvest efficiency by blueberry cultivar and harvest treatment

Cultivar	Treatment	Total	Marketable	Reject	HE
Eureka Original	HB	661	590	71	89.3%
Eureka Original	HC	435	364	71	83.7%
Eureka First Blush	HB	740	612	128	82.7%
Eureka First Blush	HC	853	609	244	71.4%

According to the reject analysis performed on the samples, as shown in Table 4.3, most reject numbers are attributed to unripe berries and a small portion of damaged berries. The number of unripe berries harvested into catcher 1.0 is 16% higher in Eureka Original and 48% higher in Eureka First Blush. During the hand harvest into a bucket treatment, it was noticed that the berry pickers spent a moment filtering out the rejects from the detached berries collected in their hand each time before placing the berries into the buckets. Berries that have been rejected are tossed on the ground. The same behaviour was observed on the pickers when hand-harvesting into Catcher V1.0, except that the rejected berries did not end up on the ground but cycled back into the catcher. This suggested harvesting by hand did not prevent unripe berries from being harvested; they were filtered out to improve the overall harvest result, while the ground loss was ignored. Pickers are pressured to deliver good harvest results. It is common to observe pickers going back through their waist bucket to remove any visible rejects accidentally made into the bucket.

Table 4.3: Reject Analysis from Field Trial 1.0

Cultivar	Treatment	Reject			Total
		Damage	Pedicel	Unripe	
Eureka Original	HB	9	7	55	71
Eureka Original	HC	5	2	64	71
Eureka First Blush	HB	0	0	128	128
Eureka First Blush	HC	35	20	189	244

Figure 4.10 shows the mean firmness of the berries harvested by each treatment and cultivar. The error bar indicates the standard deviation of each sample. Tests were done on the same day of harvest. Overall, Eureka Original has a higher average firmness than Eureka First Blush. There is no clear indication of which treatment produces the lesser firmness result. However, some harvest damage is only visible a few days after harvest. For future testing, the samples should be subjected to standard post-harvest treatment, i.e. transfer into commercial cold storage for up to three days after harvesting, before being subjected to firmness testing.

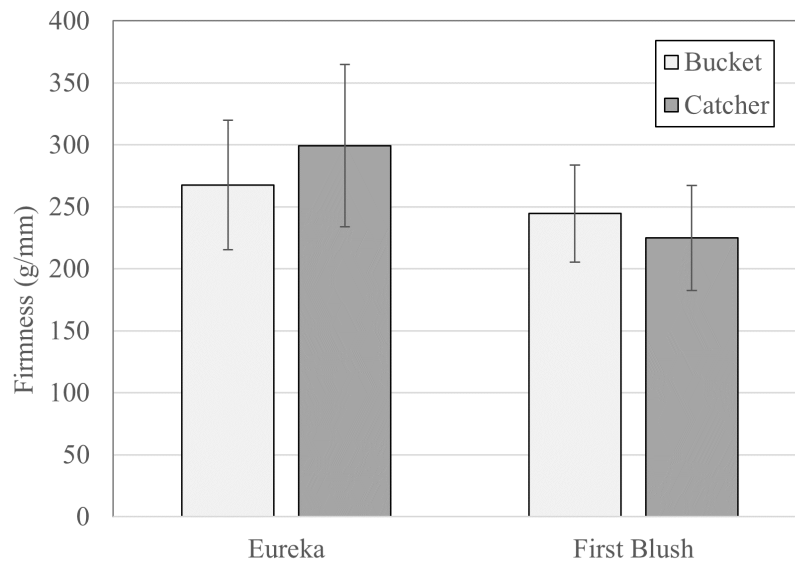


Figure 4.10: Firmness of harvested berries

4.3.2 Shaker V1.0

The concept of selective harvesting of blueberries by shaking targeted cane has shown promise. From 16 canes, 167 berries were harvested with Shaker V1.0: 71 from Eureka and 96 from Masena. Table 4.4 shows the shaking speed range applied to detach the berries from the plant for both cultivars.

Table 4.4: Blueberry harvesting efficiency using the shaking device

	Eureka Original	Masena
Min. Shaking Speed (rpm)	804	521
Max. Shaking Speed (rpm)	1284	1176
Avg. Shaking Speed (rpm)	1049	939
Avg. Detachment Accuracy	71.2%	86.4%
Avg. Harvest Efficiency	58.7%	62.6%
Ground Loss	5.2%	3.3%

All the ripe berries are detached using the shaking device, with a detachment accuracy of 71.2% for Eureka Original and 86.4% for Masena. Masena began to detach at a much lower shaking speed than Eureka, at approximately 520 rpm. Masena also shows better average harvest efficiency (62.6%) than Eureka Original (58.7%). Overall, the shaking speed range for Eureka Original is higher than that for Masena, which suggests that Eureka Original has a higher mean detachment force than Masena. This finding aligns with the detachment force results presented in Figure 3.4 of Section 3. The higher the shaking speed, the further away the detached berry lands from its origin. This can be seen from the higher ground loss percentage of Eureka Original (5.2%) compared to Masena (3.3%). This further strengthened the necessity of the developed wide footprint catcher to reduce berry loss with this harvesting method. It was also noticed that the larger berries were faster to dislodge from the branch.

According to the pack house data from 2022 provided by the orchard owner [30], the average harvest efficiency was lower for the shaker harvest than hand harvesting (89.4%). The shaking speed range must still be refined to achieve maximum harvest efficiency. Shaker V1.0 relies on the operator's vision to provide feedback for shaking speed change

and the duration applied. The berry may not separate instantly from its pedicel at a lower shaking speed. Still, it will eventually separate due to cumulative fatigue if the shaking cycle continues. It is also anticipated that the harvest efficiency may increase by minimising the applied shaking speed at the expense of not removing all the ripe berries.

Furthermore, this trial's sample size was relatively small. Hence, more extensive testing with a larger sample size is recommended to determine the range of optimal harvest settings. Additionally, the improvement in the harvest rate of the shaking selective harvest system has yet to be defined as it has not been compared to hand harvest methods.

As the introduction mentions, it is difficult to differentiate the fine visual cue between ripe, almost ripe, and overripe berries. It could take weeks or even months to refine this ability. At times, over-filtering while harvesting may cause less experienced eyes to unknowingly discard a significant amount of marketable berries. It is better to under-filter and not discard those potentially marketable berries but to include them in the harvest.

Leaving ripe berries on the plant increases the instances of soft-overripe berries that are prone to post-harvest premature decay in the next harvest cycle, which compounds to more fruit loss due to liquid contamination onto adjacent berries. The loss of profit from the contamination is far greater than the penalty incurred from unripe berries rejected in the pack-house. In contrast, removing the unripe berries also means reducing the yield of the future harvest cycle, which is also devastating for growers. Harvesting as many ripe berries as possible while avoiding the unripe berries as much as possible is recommended. The detachment force evaluation has shown that it is impractical to differentiate the ripe from the unripe by controlling detachment speed alone. Therefore, future prototypes and trials should also consider the shaking duration.

4.4 Prototype design review

After the field trial, it was clear that the shaker assembly was too heavy to be operated for an extended period. The bulky shape of the hand drill and longer pole hinder the

flexibility of the human wrist movement to achieve specific orientations for the end effector to harvest hard-to-reach berries. The hand drill motor is too powerful as it often detaches all of the berries, including those not ready to be harvested. The vibration of the shaker assembly also causes minor fatigue to the user's wrist and arm after an hour of usage.

The current Shaker V1.0 prototype is adapted to a high-torque industrial battery drill; the assembly is heavy, and the vibration causes discomfort when operating over extended periods. In its current form, the shaker is still too cumbersome to manipulate. A much lighter and more compact handheld device is preferred. Additionally, the power source could be separated from the hand-held assembly to reduce the weight further.

The Catcher V1.0, in its current form, is awkward to move around. The castor wheels were supposed to improve the manoeuvrability of the catcher unit. Still, they were not effective on uneven ground and required to be choked to stop them from rolling away, all while adding extra weight to the catcher unit. The next iteration of the catcher prototype should be much lighter, replacing the heavy aluminium extrusion frame with one made with lighter PVC tubing since the catcher is only subjected to self-weight and minimal impact during harvest operation. The time taken to recreate the netting for the second mirror image catcher was longer than anticipated. For future iteration, the cut patterns of the netting should be recorded to eliminate guesswork when duplicating.

The shaker is only functional with the catcher. In contrast, the catcher can be operated independently, without or without the shaker. Combining the shaker and catchment as a harvest system is expected to have further benefits in terms of ergonomics and decision-making. The catcher could reduce the uncomfortable postures required to harvest the hard-to-reach berries. For example, crouching and bending to reach those below waist-level berries could be minimised. Furthermore, the precision and dexterity needed for the blueberry pickers to perform selective harvesting and prevent berries from falling off their palms are also significantly reduced.

This trial was only a preliminary evaluation of the functionality of the first version of the prototypes, and the breakdown cost of material and fabrication is not included. The cost of the final prototypes will be included in the next chapter.

4.5 Summary

The field trial results for Catcher V1.0 show that it performed better with the Eureka First Blush variety, almost doubling the harvest rate compared to Eureka Original. Although pickers had been accustomed to harvesting with buckets, the catcher still achieved reasonable efficiency, with only a slight difference in results. Harvest efficiency was higher for hand-harvesting into buckets (up to 89.3%) than into the catcher (up to 83.7%). The pickers filtered out unripe berries before placing them in buckets, while the unripe berries in the catcher were recycled back into it. Most rejects were attributed to unripe berries, and the firmness of the harvested fruit did not show significant differences between treatments. It was noted that further testing with post-harvest storage conditions is necessary.

The selective harvesting of blueberries using Shaker V1.0 also showed promise, particularly with the Masena variety, which had a better detachment rate than Eureka. Masena required lower shaking speeds and demonstrated higher harvest efficiency (up to 62.6%) compared to Eureka (58.7%). However, the ground loss was higher for Eureka, reinforcing the need for a wide-footprint catcher. The harvesting efficiency of Shaker V1.0 is still no match to hand harvesting; however, findings suggest further refinement of shaking speeds could improve results.

While functional, both prototypes had ergonomic and design issues. The shaker was too heavy and caused user fatigue, while the catcher was challenging to manoeuvre due to its weight. The subsequent iterations of both prototypes should be lighter and easier to handle. Combining the shaker and catcher is expected to improve overall harvesting efficiency and ergonomics by reducing the need for uncomfortable postures during picking.

Chapter 5

Field Evaluations 2.0

This chapter describes the second iteration of the harvest system prototypes and the following field trials. This field trial was conducted at an orchard in Pukehina, Bay of Plenty, New Zealand. This blueberry orchard has approximately two hectares of blueberries planted under poly-tunnel structures. The land contour was relatively flat, with weed mat covering the ground under the poly-tunnels. Masena was selected as the cultivar for this trial, as the last evaluation has indicated that Masena is the most suitable cultivar for mechanical selective harvesting. Three harvest treatments were tested in this trial:

- Hand harvest into a bucket attached to the waistband (HB)
- Hand harvest into Catcher V2.0 (HC)
- Shaker V2.0 harvest into Catcher V2.0 (SC)

Section 5.1 presents the shaker prototypes (V2.0 and V2.1) and the catcher prototype (V2.0) which are used in the field trials. Section 5.2 divides the field trials into two parts: part one compares each treatment's harvest rates and quality, and part two compares the Shaker V2.1 harvest results of different harvest speed and timing combinations. Section 5.3 displays the results from the field trials and discussions.

5.1 Shaker and Catcher Prototypes

5.1.1 Shaker V2.0

Several improvement points were noted during field trial 1.0 and implemented in the next iteration of the prototypes. On top of being functional as a blueberry harvesting tool, the additional design objectives for the next iteration of the shaker were to:

- reduce size and weight
- improve ergonomics
- improve energy efficiency
- incorporate speed sensing capabilities
- reduce vibration

Shaker V2.0 has been redesigned in every component except for the end effector. As a human-assist tool, the ergonomic aspect of the handheld shaker has influenced many design decisions. The type of hand grip method that is most commonly utilised in powered hand tools is the power grip, which can be further broken down into a transverse volar grip (5.1a) or diagonal volar grip (5.1b). According to [88], the object is held with the thumb against the four fingers for a transverse volar grip. It has contact with the palm, and its axis is transverse to the hand. For a diagonal volar grip, the object is held with the thumb against the four fingers. It has contact with the palm, and its axis is diagonal to that of the hand. Shaker V1.0 employs the transverse volar grip. While it provides a higher grip strength than the diagonal volar grip, the wrist range of motion is also limited. On the contrary, the diagonal volar grip allows for a more relaxed grip and a better range of motion for the wrist, making operating more comfortable for extended periods.



(a) Transverse volar grip is commonly used (b) Diagonal volar grip is commonly used to grasp hand tools that require good grip to grasp smaller and lighter precision hand tools

Figure 5.1: Type of power grips

Several mechanisms to translate rotational to linear motion were explored, as seen in Figure 5.2. The ideal handle diameter for a hand-held tool that utilises power grips should be around 30-50mm, depending on the size of the operator's hand [89]. As the majority of the workforce in the orchard is female, the smaller diameter is preferred. The slider-crank mechanism is favoured for its compact footprint and its simplicity.

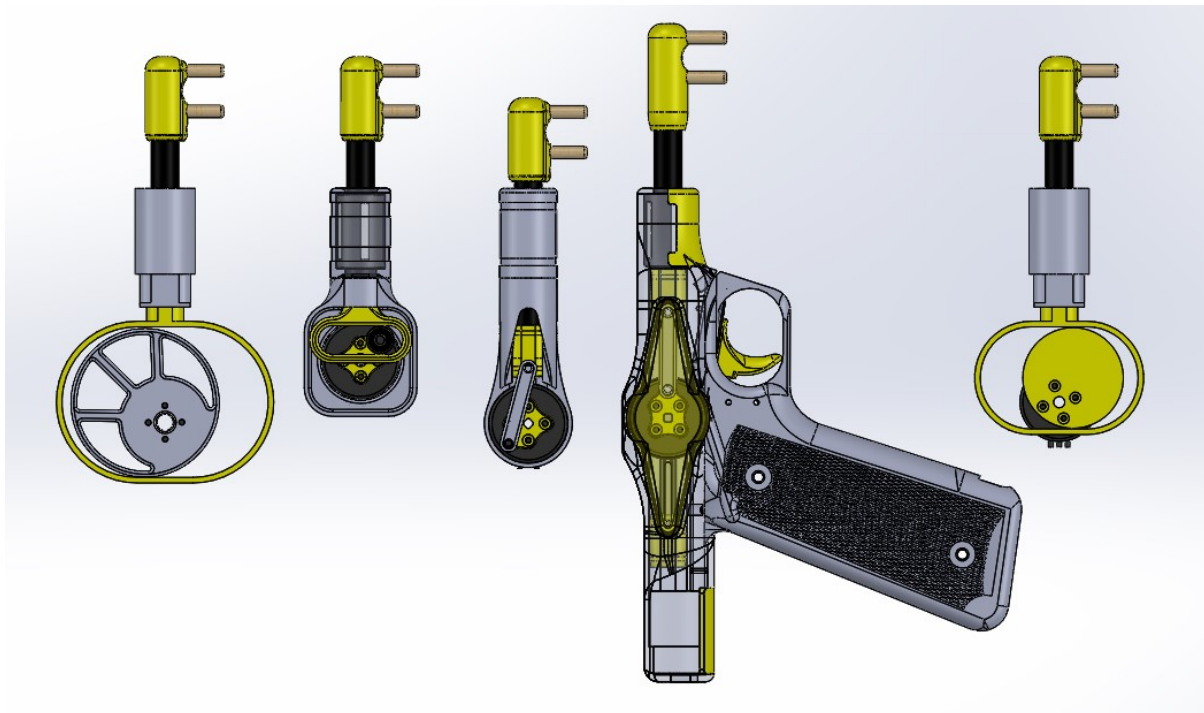


Figure 5.2: Multiple types of cam and slider-crank mechanism

Hand-arm vibration syndrome (HAVS), or carpal tunnel syndrome (CTS), can develop

if operators are exposed to vibration from tools that are transmitted to hands and arms regularly for an extended period [90]. In the previous trial with Shaker V1.0, vibration from the tool was reported to cause some discomfort in the operator’s hands. Vibration occurs when the centre of mass differs from the centre of rotation. A counterweight is added to parallel axis but in the opposite direction of the movement to reduce vibration. The overall length of the device is further shortened in the final version of Shaker V2.0.

The general arrangement of Shaker V2.0 is shown in Figure 5.3. A gimbal motor is integrated with a slider-crank mechanism and counterweight to reduce vibration. A linear bearing is installed to minimise friction on the carbon fibre tube to which the end effector is attached. A 3D-printed gearbox transmits the trigger movement to a rotary sensor. The potentiometer provides an input signal for the PWM speed controller to control the speed of the motor. The 3d printed outer casing is contoured to provide a comfortable grip. The carbon fibre tube used in Shaker V2.0 is much shorter than that used in Shaker V1, to provide better manoeuvrability in compact spaces.

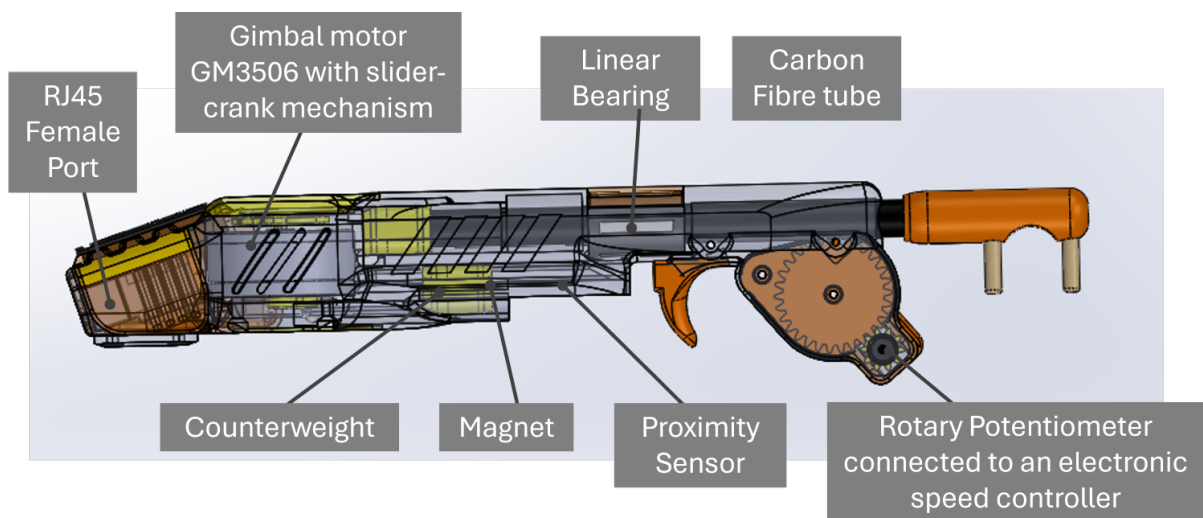


Figure 5.3: Final 3D CAD assembly of Shaker V2.0

The torque output from Shaker V1.0 was proven too powerful, therefore a much smaller motor/gearbox can be selected to reduce the size and weight of the device. A brushless DC motor typically used for drones or gimbals was selected because it is small, lightweight, and capable of high-speed rotation with moderate torque. However, it is difficult to determine

the required motor characteristics, therefore two motors were investigated and tested were performed on the artificial blueberry plant, as shown in Figure 5.4. The first motor was 2204-260KV, 27.5mm in diameter and 22 g. The motor could not output sufficient torque to reach the required shaking speed when tested on the artificial blueberry plant. The second more powerful motor, GM3506, with 1.5kg.cm of torque and a no-load speed of 2375 rpm was tested, and was capable of dislodging the berries from the artificial plant. However, this motor is slightly larger and heavier, with a diameter of 40mm and mass of 64g. The GM3506 was therefore selected for the final prototype.



Figure 5.4: Prototype 2.0 on the fake blueberry plant

Shaker V2.0 weighs 175g, which is far less than V1.0, with an extended length of 300mm, a handle diameter of 32mm, 20mm stroke, with the battery relocated to the belt for improved ergonomics and reduced weight for the operator. It has a no-load speed of approximately 1400 rpm when fully charged. Shaker V2.0 operates under open-loop speed control. Several operators reported improved vibration reduction with the counterweight mechanism. For the purpose of field-trials, a display is integrated into the shaker as shown in Figure 5.5.



Figure 5.5: A special version of Shaker 2.0 with independent speed detection and display was created just for the trial

The shaker is powered by a 12V Li-ion 2.0Ah battery made by Nordic, as shown in figure 5.6a. A battery case was designed and 3D-printed to attach to the operator’s belt, with an on-off switch and female RJ-45 Ethernet port, connecting from the battery pack to the handheld device with a CAT6A Ethernet cable. Two compression springs provide the contact points for the battery inside the battery holder (figure 5.6b). The battery provides sufficient power for the shaker to operate for at least 8 hours at regular use. The final look for the battery pack is shown in Figure 5.6.

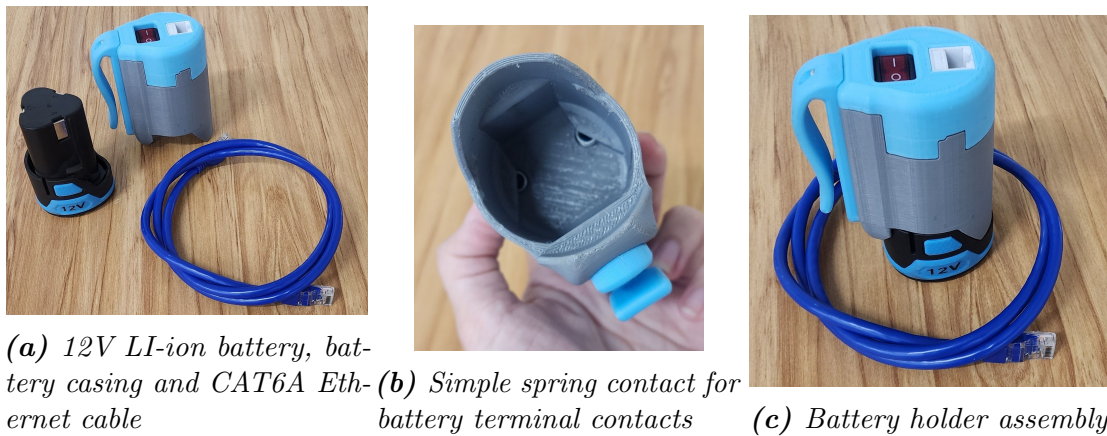


Figure 5.6: Power supply unit for Shaker V2.0 and V2.1

5.1.2 Shaker V2.1

A modified version of the shaker (V2.1) was created to integrate speed and duration control. For the purpose of ease of adjustment in the field, dials to adjust speed and duration of shaking were added. Figure 5.7 shows the components which enable closed-loop speed control, and data acquisition via an SD card. These components include:

- Arduino Pro Micro with an ATmega32U4 microcontroller for speed control and data recording
- AMT103 incremental encoder attached to the motor shaft
- DS3231 real-time clock module
- SD card reader module
- Momentary microswitch
- Two Rotary switches to select preset speed and duration profiles

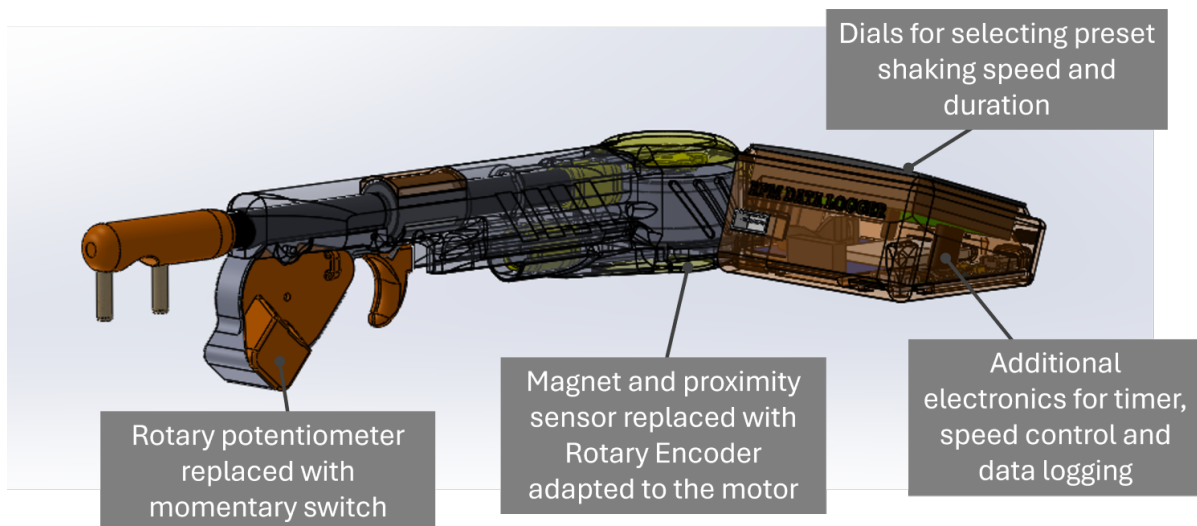


Figure 5.7: Changes made to Shaker V2.1

The PI constants were tuned such that the target shaking speed was reached as fast as possible while minimising overshoot. Data recorded and output from the SD card to

analyse the response of the closed-loop speed control system. The final 3D CAD rendered version of Shaker V2.0 can be seen in Figure 5.8. The total weight of Shaker V2.1 is 304g without the battery unit.



Figure 5.8: Rendered CAD model of Shaker V2.1

5.1.3 Catcher Prototype V2.0

Building a metal frame from scratch can be costly and time-consuming. Coincidentally, the dimensions of a 2-seater camping chair match the catcher's requirement: a minimum span of 1200mm and approximately 600mm deep. The frame is made of a thin-walled mild steel tube, lightweight yet durable. Hence, the frame of the catcher 3.0 utilised a modified 2-seater camping chair, with the chassis height lowered to 330mm. The final dimension of the frame is measuring at 1560mm in span and 580mm in depth.

The seat cover is removed and replaced with the same food-safe polyester netting used on Catcher V1.0. The netting is tailored to fit the frame's shape while retaining the essential slopes and curves. The polyester netting is cut and sewn with a sewing machine, with pockets to fit over the tubing of the frame and KAM plastic snaps for easy removal and cleaning. Catcher V2.0 only has one hole cut in the first layer of netting. The second layer of netting is sewn onto the first layer, reducing the complexity of the netting assembly. The third layer of netting construction is similar to Catcher 1.0, except it is wider in coverage area.

Two lengths of 600mm long, 275mm extruded flexible back strip brushes are each attached to a 600mm aluminium flat bar, attached to the front of the frame with four 60mm butt hinges, to form a foldable brush strip of 1200mm long. An additional angle bracket supports the brush strip at a fixed angle. A shelf is added to place the blueberry collection tray below the third layer of netting, retaining the exchangeable tray features from Catcher 1.0.

Catcher V2.0 weighs 5.6kg, including an empty tray. The final assembly of Catcher V2.0 is shown in figure 5.9.



(a) Front View



(b) Rear view with tray holder



(c) Side view

Figure 5.9: *Catcher 3.0 Assembly*

A complete human-assist harvest system consists of two units of Shaker V2.0 and two units of Catcher V2.0. The cost of material to produce a harvest system is NZD\$1,078,

excluding labour costs. The cost to produce a single unit of the harvest system commercially by an industrial design company, is approximately US\$5,100 [91].

5.2 Method

Field trial 2.0, which is divided into two parts, evaluates the performance of the improved shaker and catcher prototypes. Masena is selected as the only cultivar tested in this field trial. Part one compares three harvest treatments applied on six Masena plants regarding harvest rates, firmness, shelf-life and harvest quality:

- Hand harvest into a bucket attached to the waistband (HB)
- Hand harvest into catcher V3.0 (HC)
- Shaker V2.0 harvest into catcher V3.0 (SC)

This evaluation is repeated three times on the same six plants in the early, mid, and late seasons for nine data sets. Two inexperienced blueberry pickers were reserved for part one of the field trial to eliminate potential habits and biases from previous harvest experiences.

Part two compares different combinations of shaking speed and duration on randomly selected blueberry canes with Shaker V2.1 regarding harvest results and predicts the best harvest setting for Masena.

Figure 5.10 outlines data recorded, post-harvest treatment and evaluations subjected to each sample.

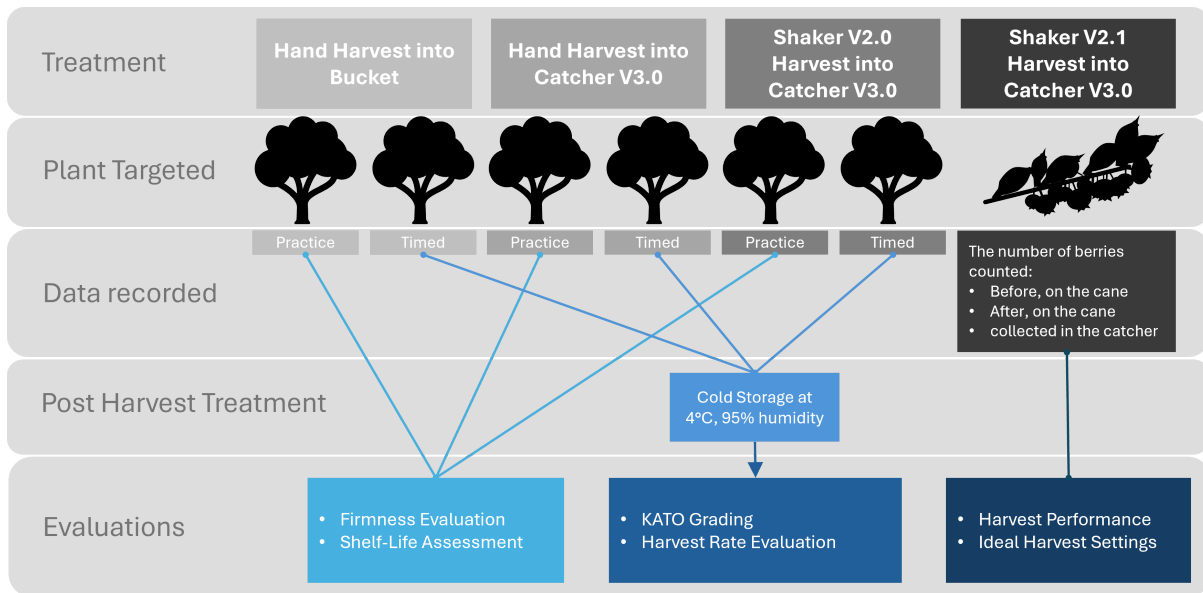


Figure 5.10: Field Trial 2.0 Evaluation Flow Chart

5.2.1 Part One: Comparing three harvest treatments

Six Masena plants are reserved for this part of the field trial for consistency, two plants per treatment. For every harvest treatment, operators are instructed to practice to get familiarised with the first plant. The berries harvested are labelled sample A. Then, the harvest on the second plant is timed, $T_{Harvest}$ is recorded. The berries harvested are labelled sample B. Berries harvested in the buckets are poured gently into the standard blue pack house tray, while berries collected in the catcher 3.0 are funnelled straight into the pack house tray. No post-harvest filtering is performed on any of the samples. This trial is repeated three times across three harvest times: early-season (third week), mid-season (sixth week), and late-season (ninth week).

Eighteen samples are collected in this trial, three of each sample A and B from each harvest timing.

Sample A is graded manually, with the rejects being discarded. A total of 180 berries were randomly selected from each harvest treatment. Half were subjected to firmness evaluation, while the others were subjected to shelf life assessment. Sample B is first stored at commercial cold storage (4°C and 95% humidity) for three days, then graded

with a commercial blueberry sorting machine. The setup time for all harvest treatments is not incorporated in this evaluation.

5.2.1.1 Firmness Evaluation

From sample A, ninety marketable quality berries from each treatment of each harvest timing are randomly selected. The equatorial firmness on each berry was measured three times at different locations, using a non-destructive hand-held Durometer, Turoi 53215BE, on the Shore A hardness scale, as shown in Figure 5.11. This device has a spherical tip diameter of 2.38mm that is pressed perpendicular to the outer skin of the blueberry, with a measuring range between 10-90A and a resolution of 0.1A. The average of the three firmness readings is recorded. Data from any berry that was punctured during the test are not included.



Figure 5.11: Turoi 53215BE, Non-destructive measurement of the firmness of soft fruit

5.2.1.2 Shelf Life Assessment

Another ninety randomly selected, marketable berries of sample A from each treatment were divided equally and stored in three 125g clamshell punnets, a total of 810 berries across all three harvest timings. The punnets were stored at 12°C with high humidity of 80-90% to replicate the same conditions of a supermarket fresh produce cooler. Samples

were inspected every few days; berries with signs of mould or breakdown were removed, and the numbers were recorded from each inspection.

5.2.1.3 Post-Harvest Grading

Sample B was removed from the commercial cold store three days after harvest. Each sample's quality was evaluated using a commercial blueberry grader, KATO260 (5.12), developed by TOMRA and BBC Technology, to eliminate subjectivity associated with manual grading and maintain data consistency. The special conveyor chain belt on KATO260 places individual berries on an indexed chain link with rollers that keep the berry rotating. The berries are shuttled into a lighting-controlled chamber at a speed of 1200mm/s, where multiple RGB and IR image data are collected. The image data is processed using the grading algorithms developed by TOMRA to extract the quality and conditions of each berry into an array of data. Usually, berries are appraised and sorted into different categories by filtering the output data using user-defined metrics entered by the operator. However, this experiment does not appraise and sort the samples. Only the data of each sample are extracted and filtered with calibrated metrics derived from the pre-trial data calibration to sort the sample results into marketable, unripe, and damaged.



Figure 5.12: KATO260 and LUCAi™, developed by BBC Technology, a popular blueberry grading machine utilised by pack houses worldwide

5.2.1.4 KATO260 Pre-trial Data Calibration

The data output from KATO260 consists of 42 columns of parameters that need interpreting to provide information such as colour, firmness, size, stem protrusion, dehydration, damage, split, blemish, etc. Unfortunately, grading metrics applied by each pack house vary and are subject to the operator, cultivars, market demand, and timing of the harvest season [92]. Therefore, it is crucial to understand how each berry condition affects the data to determine the criterion that defines whether it is marketable or rejected. Before the trial, 78 blueberries were selected for data calibration. Only the berry quality and conditions influenced by the harvest treatment are focused on in this evaluation. They are sorted into ten groups comprising six to fourteen berries with one common quality and condition. The berries are evaluated with KATO260, and the data is extracted. Data from each group were compared to determine the correlation between each column of parameters and their common condition. KATO260 parameters concerned are red(R), blue(B), green(G), white(W), infrared(IR), brown(Br), bruise(Bs), split(Sp), stem(St), blemish(Bl),

dehydration(Dh) and firmness(Fm). Table 5.1 summarised the ten conditions of blueberry selected and which KATO260 parameters are correlated. At least two parameters are associated with each blueberry condition. Moreover, each blueberry most likely has more than one condition.

Table 5.1: Blueberry conditions and which KATO260 parameters are affected

condition	Qty	Parameters correlated											
		R	B	G	W	IR	Br	Bs	Sp	St	Bl	Dh	Fm
ripe	6	X	X										
unripe	14	X		X	X								
dehydrated	7				X	X						X	X
softness	6					X							X
split	10					X			X				X
bruise	6					X		X					X
pedicel	6			X						X			
beard	9						X					X	
deformed	6				X	X							
brown spot	8						X				X		

Similar parameters are grouped to simplify the data, while those not critical, such as lane errors, are ignored. After further investigation on commercial grading standards and consulting with blueberry experts [92][33] [41], the estimated range of parameters that dictates a blueberry is marketable are summarised in table 5.2. These values are applied to grade the quality of the samples from the trial. Although bloom retention is a vital quality influenced by the harvest treatment, it is left out of this evaluation due to the white colour measurement of KATO260's being indifferent between matte white and reflection from a glossy surface [93]. The firmness data output from KATO260 is also unitless.

Table 5.2: Minimum metrics of Marketable Berries

Marketable Quality Metrics	Parameter range
Red Spot & Red Coverage	less than 25%
Green Spot & Green Coverage	less than 20%
Brown Spot & Beard	less than 5%
Stem Protruding	less than 40%
Bruise Size & Bruise Coverage	less than 20%
Split Size & Coverage	less than 45%
Dehydration	more than 95%
Firmness (0-75)	more than 30

5.2.1.5 Harvest Rate

Additional metrics derived from the output data of sample B from KATO260 include the number of berries harvested ($N_{overall}$), marketable berries ($N_{marketable}$), unripe berries (N_{unripe}), damaged berries (N_{damage}) for each treatment.

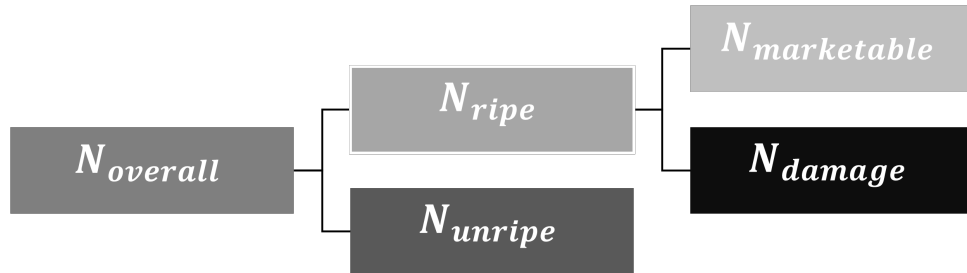


Figure 5.13: The hierarchy of the derived metrics

Each treatment's overall harvest rate ($\dot{H}_{overall}$) is a crucial metric to gauge the harvest performance, which can be calculated by equation 5.1.

$$\dot{H}_{overall} = \frac{N_{overall}}{T_{harvest}} \quad (5.1)$$

5.2.2 Part Two: Comparing Shaker 2.1 harvest settings

Removing unripe blueberries from the bush can significantly impact future harvest yields. In contrast, failure to harvest all ripe berries may result in overripe, dehydrated, or soft berries being left for future harvests [30][32]. This evaluation aims to minimise both instances by optimising the shaker 2.1 harvest settings. Field trial 1.0 has provided insight into the operators' inability to control the shaking duration effectively due to delays in visual reaction and motor deceleration. Over-shaking is the leading cause of the high percentage of unripe blueberries in the harvest. Part two of field trial 2.0 focused on the functionality of the harvest system.

5.2.2.1 Shaker Settings Combination Evaluation

Shaker V2.1 was specially designed for this evaluation. The two rotary switches added allow the operator to select the predefined shaking speed in rpm (RPM_{shake}) and shaking duration in seconds (T_{shake}). Previous findings in Chapter 3 (3.2.3 Principle behind shaking) estimated the shaking speed for Masena is between 750 to 1150 rpm, and Chapter 4 (4.3.2 Shaker V1) field trial 1.0 results indicated the average shaking speed for Masena is 939 rpm. Therefore, four predefined shaking speeds of 800, 900, 1000 and 1100 rpm are selected for the evaluation, combined with three shaking durations of 1.0s, 1.5s and 2.0s, resulting in twelve unique combinations of shaker settings. Catcher V3.0 is utilised in this evaluation to capture detached berries.

The evaluation method is similar to the Shaker V1.0 evaluation from field trial 1.0. Each harvest setting combination was repeated on four randomly selected canes with clusters of blueberry of the Masena cultivar. A total of 48 canes were tested on the ninth week of the harvest window. For each test, the number of ripe (blue) and unripe (green) berries on the cluster was noted visually before harvest (B_i, G_i), after harvest (B_f, G_f), and the number of berries collected in the catcher (B_h, G_h).

5.2.2.2 Harvest Performance

The performance of the harvest system as a whole is assessed through three calculated metrics from the results of the shaker settings combination evaluation: Detach Accuracy (DA), Detach Efficiency (DE), Catcher Efficiency (CE) and Harvest Performance (HP). DA measures the shaker's ability to detach only ripe berries (equation 5.2), DE measures the shaker's ability to detach all ripe berries (equation 5.3), CE measures the ability of Catcher V3.0 to capture all detached berries (equation 5.4), and harvest performance (HP), combines all three previous metrics, DA, DE, and CE by multiplying them with equal factor to identify the optimal shaker settings for the best possible harvest results (equation 5.5).

$$DA = \frac{(G_f)}{(G_i)} \quad (5.2)$$

$$DE = \frac{(B_i - B_f)}{B_i} \quad (5.3)$$

$$CE = \frac{B_h + G_h}{(B_i + G_i) - (B_f + G_f)} \quad (5.4)$$

$$HP = DA \cdot DE \cdot CE \quad (5.5)$$

5.3 Results and Discussion

5.3.1 Firmness results of sample A and sample B

Blueberries with a firmness below 45A are classed as soft, 65A and above as firm [41]. However, the firmness parameters for rejects are much lower than 45A. Only 30 firmness measurements for each harvest treatment from the late-season harvest trial were recorded

as the durometer probe punctured the berry skin on many occasions, rendering the measurement unusable; it appears that Masena blueberries may have thinner skin than other cultivars. The firmness results of sample A were summarised in table 5.3.

Table 5.3: Firmness Results of Sample A

Trt Code	Timing	Sample Sz	Range (A)	<45A	% soft
HB	Early	90	25.8 - 68.8	39	43
HC	Early	90	26.1 - 65.0	27	30
SC	Early	90	23.5 - 72.3	32	36
HB	Mid	90	18.2 - 70.4	32	36
HC	Mid	79	17.7 - 63.9	42	53
SC	Mid	90	17.7 - 66.8	54	60
HB	Late	30	23.0 - 67.3	13	43
HC	Late	30	26.9 - 65.2	7	23
SC	Late	30	20.1 - 66.4	10	33

There was a wide range in firmness within each sample. Slightly firmer fruit was produced with hand harvest into catcher V3.0 compared to hand harvest into a bucket, but the results were quite variable, and the contrast was insignificant. The percentage of soft fruit is alarmingly high across all treatments, even before subjecting to post-harvest cold storage. Despite this, the treatment and timing of harvest did not appear to affect berry firmness significantly.

Sample B's firmness results were unitless. Table 5.4 summarises sample B's firmness results. Similar to the firmness results of sample A, a wide range of firmness is presented within each sample. Slightly firmer fruit with hand harvesting into a bucket, but results remain variable, and the contrast was also insignificant. The difference between samples A and B is that sample B was subjected to three days of cold storage. The results suggested that the firmness of both sample A and sample B was unaffected by harvest treatment.

Table 5.4: Firmness Results of Sample B

Trt Code	Timing	Sample Sz	Range	Count <50	% soft
HB	Early	253	26.2 - 61.2	41	16
HC	Early	305	23.5 - 61.5	19	6
SC	Early	387	18.4 - 63.3	20	5
HB	Mid	520	37.1 - 63.0	9	2
HC	Mid	382	45.6 - 63.1	14	4
SC	Mid	272	44.6 - 61.7	12	4
HB	Late	433	41.3 - 61.9	133	31
HC	Late	311	34.1 - 56.9	153	49
SC	Late	250	24.3 - 55.6	107	43

5.3.2 Sample A Shelf Life Assessment

The results of the shelf life assessment on sample A are tabulated in table 5.5. Out of the 270 berries from each treatment, only one was removed from the sample of hand harvest into bucket treatment and hand harvest into catcher V3.0 treatment due to mould and breakdown over 20 days. Four berries were removed from the sample of shaker V2.0 harvest into catcher V3.0 treatment. The number of mouldy and rotten berries was surprisingly lower than usual, which is typically around 20% removed at the end of the 20 days [41]. Despite the alarmingly low firmness measurement, these findings suggested that Masena is much less susceptible to post-harvest breakdown and mould. Overall, the total number of berries removed is insufficient to suggest which harvest treatment is better.

Table 5.5: Sample A Shelf Life Assessment Result

Trt Code	Sample Sz	Days after Harvest						Total
		3d	6d	10d	14d	17d	20d	
HB	270	0	0	1	0	0	0	1 (0.4%)
HC	270	0	0	0	0	0	1	1 (0.4%)
SC	270	0	1	1	1	0	1	4 (1.5%)

5.3.3 Sample B Reject Analysis

Due to an unforeseen orchard management error, the reserved Masena plants were harvested three instead of seven days before the day of the planned early-season trial, resulting

in an unusually high percentage of unripe fruit in all three treatments. Therefore, the early-season harvest timing results are omitted from this evaluation. The outcomes from the mid and late seasons are combined and filtered with the parameters outlined in table 5.2, summarised in table 5.6.

Table 5.6: Harvest Results of Sample B

	HB	HC	SC
Sample Size	1128	910	782
Marketable	952 (84.4%)	703 (77.3%)	532 (68.0%)
Rejects	176 (15.6%)	207 (22.7%)	250 (32.0%)

The size of the sample harvested by Shaker V2.0 into catcher 3.0 is significantly less than the other two treatments despite the same trial condition of removing all ripe berries from the plant. The total berry harvested for each treatment was greatly affected by the number of berries on the bush before harvest, as there appeared to be significantly more berries in some plants than in others. Hand harvest into a bucket has the highest percentage of marketable berries (84.4%) compared to the other two treatments (HC at 77.3% and SC at 68%). Although the operators selected for this trial had never done any blueberry picking before the trial, the behaviour of filtering undesired fruit before placing the detached berries into the bucket was observed. This is depicted in the visible difference of 7.1% in the marketable ratio between hand harvest into a bucket and hand harvest into catcher V3.0, albeit the same skill level and hand harvesting technique were applied. This indicated that catcher V3.0 captured most of the detached berries and prevented accidental ground loss. Shaker V2.0 harvest into catcher V3.0 treatment's lower marketable ratio was due to over-shaking, caused by delayed operator's visual feedback, reaction timing and time required to decelerate the motor, emphasising the importance of controlling the shaker's shaking durations.

The number of berries classified as rejects and instances of every reject attribute present in each sample are listed in table 5.7. Some may have more than one faulty property. The majority of the rejected berries were unripe.

Table 5.7: Rejects Analysis on Sample B

	HB	HC	SC
Unripe	156 (13.8%)	199 (21.9%)	239 (30.6%)
Brown/Beard	4	1	1
Pedicel	1	1	5
Bruise	2	3	2
Split	13	3	2
Dehydration	0	0	1
Soft	0	0	2

Interestingly, the hand harvest and bucket treatment had a significantly higher count of splits and brown spot or beard retention. The higher count of splits or punctures may have been due to increased interaction between the operator’s hand and the berries in the hand harvesting treatment. The shaker V2.0 harvest into catcher V3.0 treatment had more instances of pedicel retention, dehydration, and softness, but not significant. Overall, hand harvest into catcher V3.0 had the least count of damages among the three. This suggests that the catcher V3.0 was gentle to the fruit, thus improving the post-harvest quality of blueberries. Operators preferred hand harvest into catcher V3.0 treatment as they were not required to squat or kneel on the ground to reach the lower-hanging berries, and also less effort to prevent ground loss.

5.3.4 Sample B Harvest Rate

$\dot{H}_{overall}$ of shaker V2.0 harvest into catcher V3.0 treatment is the highest at an average of 103 berries/min, followed by hand harvest into catcher V3.0 treatment, 84 berries/min and then the hand harvest into bucket treatment, 70 berries/min, as shown in Table 5.8. However, the percentage of unripe berries is also the highest at 30.6% for shaker V2.0 harvest into catcher V3.0 treatment (table 5.7).

Table 5.8: Harvest Rate of Sample B

Trt Code	Timing	$T_{harvest}$ (s)	$N_{overall}$	$\dot{H}_{overall}$ (/min)
HB	Early	410	461	67
HC	Early	378	577	92
SC	Early	450	1098	146
HB	Mid	520	659	76
HC	Mid	414	571	83
SC	Mid	270	455	101
HB	Late	416	469	68
HC	Late	258	339	79
SC	Late	319	327	62

5.3.5 Shaker V2.1 Optimum Shaker Settings and Harvest Performance

All four metrics, detachment accuracy (DA), detachment efficiency (DE), catcher efficiency (CE), and harvest performance (HP), were calculated and averaged. The results were summarised in table 5.9. The detachment efficiency is optimised with moderate RPM_{shake} and lower T_{shake} . The catcher efficiency is optimised lower RPM_{shake} and lower T_{shake} . The catcher efficiency performs better with lower RPM_{shake} and moderate T_{shake} . As for harvest performance, which combines the abovementioned metrics, peaks at moderate RPM_{shake} and low to moderate T_{shake} .

Table 5.9: Average harvest system performance metrics for each harvest setting combination

RPM_{shake}	T_{shake} (ms)	DE	DA	CE	HP
800	1000	0.85	0.94	0.97	0.77
	1500	0.78	0.92	0.90	0.68
	2000	1.00	0.57	0.87	0.48
900	1000	1.00	0.90	0.91	0.83
	1500	1.00	0.90	0.83	0.77
	2000	0.84	0.81	0.81	0.59
1000	1000	0.92	0.82	0.89	0.68
	1500	1.00	0.92	0.94	0.88
	2000	0.83	0.92	0.83	0.66
1100	1000	0.94	0.71	0.86	0.57
	1500	0.88	0.58	0.94	0.44
	2000	0.91	0.65	0.81	0.47

It is difficult to narrow down the optimal shaking speed and duration combination with multiple variables, particularly with limited data points. Therefore, multiple linear regression was applied to predict the combination of the optimal shaker settings and the response. Assuming the relationship between shaker speed or duration and harvest performance metrics is linear. The predicted responses (DA, DE, CE and HP) with the common x-axis (RPM_{shake}) and y-axis (T_{shake}) were plotted separately in four contour plots shown in figure 5.14. The peak response of each harvest performance metric was annotated in each plot. Across all four predicted metrics response, a preference for lower T_{shake} was evident, and both DA and DE perform best at lower T_{shake} , while CE peaks at the lowest RPM_{shake} . HP shows the optimal shaker settings that combine the preferences of DA, DE and CE at 899rpm for shaker speed and 1.08s, resulting in an HP score of 81.76%, with DA, DE and CE at 93.21%, 96.53% and 90.87%. With optimised harvest settings and improved operator experience, the harvest performance of shaker V2.1 harvest into catcher V3.0 is expected to boost nearing human levels.

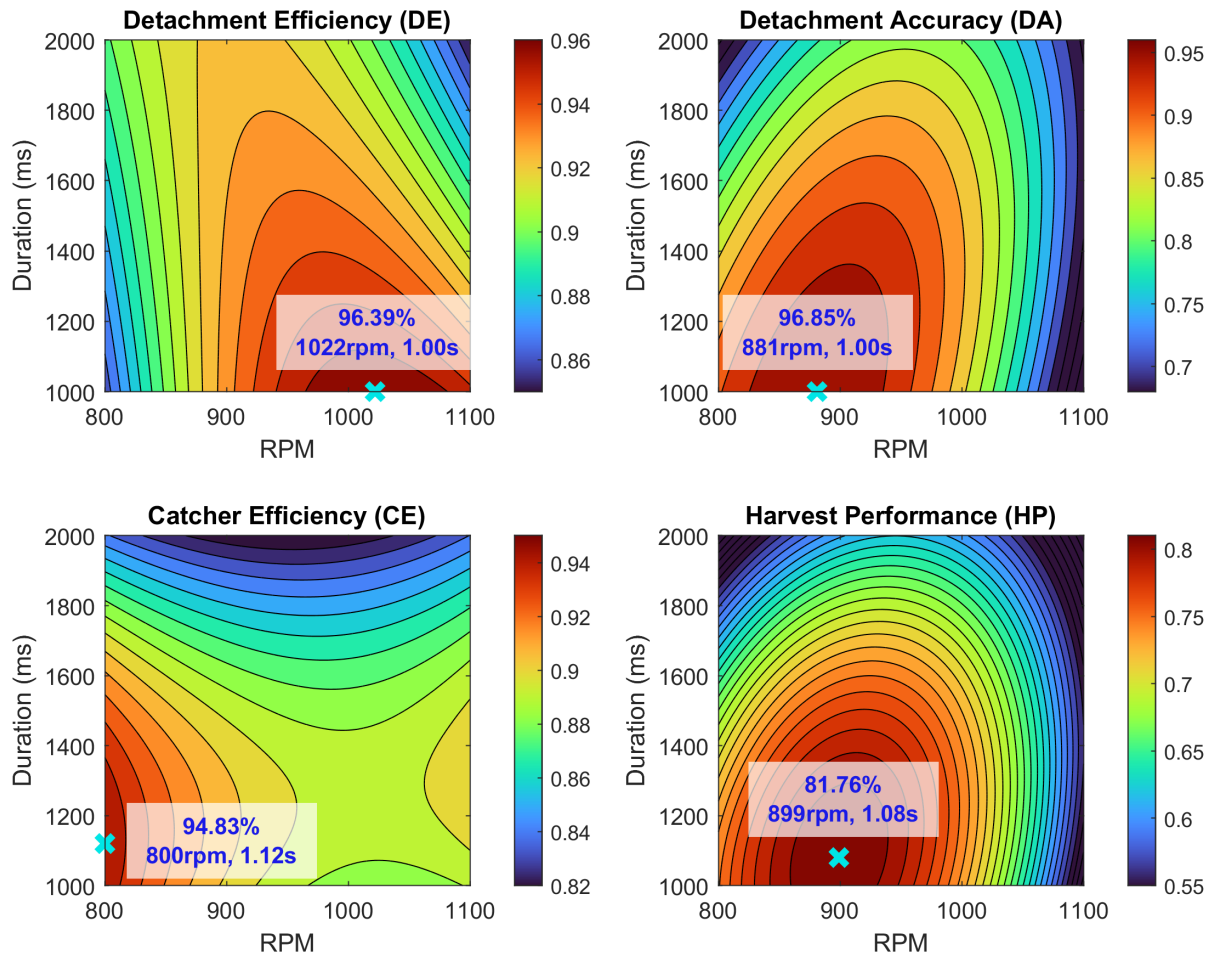


Figure 5.14: Contour plots to identify the optimum harvest settings based on the harvest performance metric

5.4 Summary

The firmness assessment revealed that neither the harvest treatment nor timing significantly affected berry firmness, indicating minimal impact damage across all three harvest methods. A notably higher proportion of unripe berries was observed in the hand harvest into catcher V3.0 treatments, attributed to the soft surface catchers capturing nearly every detached berry, including unripe ones. The lower marketable yield in shaker V2.0 was due to delayed operator feedback and reaction timing, emphasising the need for more optimised shaking speed and duration, as well as better operator experience for improved results.

Interestingly, even though operators had limited experience, they still performed unconscious filtering of undesirable berries during hand harvesting into both the bucket and catcher V3.0. Total berry yield was significantly influenced by the number of berries on the bushes before harvest, with shaker V2.0 yielding fewer berries than the other two treatments. However, the harvest rate for shaker V2.0 (81.3 berries/min) surpassed both hand harvest into a bucket (71.8 berries/min) and hand harvest into catcher V3.0 (80.3 berries/min). Shaker V2.0 did, however, result in 13.8% more unripe berries and 0.4% fewer damaged berries compared to hand harvesting into the bucket. Hand harvest into catcher V3.0 caused the least damage overall (0.9%), suggesting that the soft surface catchment effectively improves the post-harvest quality of blueberries.

Operators strongly preferred hand harvesting into catcher V3.0 due to its ergonomic benefits. It eliminated the need to squat or kneel when reaching for lower-hanging berries. Additionally, the catcher V3.0 reduced the risk of berries falling to the ground, making it a practical and efficient method for minimising fruit loss during harvest. Notably, the performance of shaker V2.1, with optimised settings, is expected to enhance harvest outcomes further, nearing human performance levels. Multiple linear regression predicted that the optimal settings for shaker V2.1 were a speed of 899 RPM and a shaking duration of 1.08 seconds. These settings are projected to result in a harvest performance (HP) score of 81.76%, with detachment accuracy (DA) of 93.21%, detachment efficiency (DE) of 96.53%, and catcher efficiency (CE) of 90.87%. With these adjustments, shaker V2.1's harvest performance should improve significantly, approaching the efficiency of manual harvesting.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The primary aim of this thesis was to develop a human-assisted prototype harvesting system that enables selective harvesting of blueberries, focusing on reducing harvest damage and ground loss while improving both fruit quality and yield. The overarching goal was to streamline the harvesting process, reduce manual handling, and make the operation more efficient by integrating human assistance with mechanisation, providing a solution that complements the strengths of manual labour while reducing its burdens.

To achieve these objectives, several key tasks were undertaken. First, the thesis identified research gaps through a comprehensive literature review and regular engagement with industry stakeholders. The detachment mechanics of three blueberry cultivars were examined to determine which were most suitable for human-assisted mechanical harvesting. Several end-effector mechanisms and catchment techniques were developed and tested, creating the first version of the handheld shaker prototype and portable catchment device. An artificial blueberry plant was also designed to allow testing outside harvest season.

These human-assisted prototypes were then tested in the first set of field trials (Field Trial 1.0), and the findings were used to refine the designs, focusing on improving usability

and ergonomics and keeping costs low with simple mechanisms and readily available components. After implementing these improvements, the second round of field trials (Field Trial 2.0) was conducted. The performance of the prototypes was assessed, and optimal harvest settings for the cultivar Masena were identified.

To meet the original objectives, the thesis successfully developed and tested a human-assisted harvesting system that enables selective harvesting while reducing workers' physical and mental strain. By enhancing the process's efficiency and ergonomics, the project made significant progress toward offering a mechanised solution that integrates human expertise. This approach is practical for smaller blueberry producers and addresses labour shortages. Thus, improving operational efficiency and promoting sustainability in the blueberry industry were largely achieved, providing a viable pathway toward a more resilient and adaptable agricultural sector.

Field trials 1.0 and 2.0 offered valuable insights into blueberry harvesting in New Zealand, focusing on improving the harvest process through prototypes like the Catcher and Shaker.

Field Trial 1.0 Catcher V1.0 showed strong performance, particularly with the Eureka First Blush cultivar, doubling the harvest rate compared to Eureka Original. Hand-harvesting into buckets yielded a higher efficiency (up to 89.3%) compared to the catcher (up to 83.7%), though the difference was minimal. Pickers filtered and discarded unripe berries when harvesting into buckets, while in the catcher, discarded unripe berries were recycled back into the catcher. Most rejects were unripe berries; no significant differences in berry firmness were found across harvest methods.

Shaker V1.0 was more efficient with the Masena cultivar, which had a better detachment rate than Eureka. However, Eureka's ground loss was higher, suggesting the need for design improvements like a wide-footprint catcher. While promising, Shaker V1.0 was still less efficient than manual harvesting, and further refinement of shaking speeds was recommended. Both prototypes had ergonomic issues—the shaker was heavy and caused fatigue, while the catcher was difficult to manoeuvre, prompting calls for lighter, more user-friendly designs.

Field Trial 2.0 Field trial 2.0 emphasised improvements in both harvesting efficiency and berry quality. A key finding was that berry firmness was largely unaffected by harvest method or timing, indicating minimal impact damage. Catcher V3.0 captured nearly all detached berries, including unripe ones, resulting in a higher proportion of unripe fruit. Shaker V2.0 yielded fewer berries overall but had a faster harvest rate (81.3 berries/min) compared to both hand-harvesting into a bucket (71.8 berries/min) and hand-harvesting into Catcher V3.0 (80.3 berries/min). However, Shaker V2.0 resulted in more unripe berries (13.8% higher) and slightly fewer damaged ones compared to hand-harvesting.

Catcher V3.0 caused the least berry damage (0.9%), showing that the soft surface of the catcher helped maintain post-harvest quality. Operators favoured the ergonomic benefits of Catcher V3.0, as it reduced the need to squat or kneel and minimised fruit loss.

Shaker V2.1, with optimised settings (899 RPM and 1.08 seconds shaking duration), is expected to significantly improve harvest performance, nearly matching manual harvesting in efficiency. Predictions suggest this setup could achieve a harvest performance (HP) score of 81.76%, detachment accuracy of 93.21%, detachment efficiency of 96.53%, and catcher efficiency of 90.87%.

In summary, field trial 2.0 highlighted that while manual harvesting still results in higher berry quality, the performance of the shaker and catcher systems is rapidly improving. Future iterations are expected to close the gap in efficiency and quality.

It's important to note that human-assisted harvest systems may not completely replace experienced labour at this stage. Nevertheless, they hold promise in expanding the labour force demographic by reducing the physical and mental demands of the task. Furthermore, integrating the mechanical shaker-catcher system with machine vision technology and controlled lighting could lead to fully automated harvesting systems operating beyond conventional hours, such as at night.

6.2 Future Work

Future research should expand the evaluation of the harvest system to include setup time and operator ergonomic assessments compared to current harvesting methods. Future trials should also involve a larger sample size, with increased trial duration and frequency, for more comprehensive data.

A long-term economic analysis is necessary to understand the system's impact in an orchard environment. Additionally, this study did not address bloom retention due to the absence of a reliable evaluation method. Future work should focus on developing a technique for assessing bloom retention and comparing different soft surface catcher materials to determine the optimal catchment surface.

While randomised controlled trials confirmed the effectiveness of the soft surface catcher, a systematic review of its design parameters is needed to improve efficiency and quality further. This will contribute to advancements in blueberry harvesting technology.

Preset detachment settings based on cultivars are ideal for human-assisted systems. However, a closed-loop feedback system with machine vision could be integrated for future autonomous applications to adjust shaking durations by monitoring the detachment of ripe and unripe berries. Such integration could pave the way for fully automated harvesting systems capable of operating beyond conventional hours, including nighttime.

Berry Co., one of the blueberry industrial stakeholders, will continue using the shaker and catcher prototypes through extended trials to evaluate their economic impact and overall harvest performance.

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