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Imaging based measurement of density for the
determination of dry matter and brix for ‘Hayward’,
‘SunGold’ and ‘RubyRed’.

A thesis presentation in partial fulfilment of the requirements of the
degree of

Masters
In
Food Technology and Post-Harvest

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Abstract

This research was conducted at both Massey University and Massey AgriFood Digital Foods, Manawatu, New Zealand. Three-dimensional scanning, volume submergence alongside the destructive experiments were conducted on more than 900 kiwifruit. Approximately 312 kiwifruits (RubyRed, SunGold and Hayward) for each cultivar from three different grower lines were tested and examined. The kiwifruits were all picked at harvest maturity, commercially graded, and placed in 0°C refrigerator storage to maintain the harvest maturity. With advances in imaging technologies, it is now feasible to measure volume accurately and non-destructively and therefore density. The aim of this project is to revisit the relationship between density, DM, SSC for all three cultivars (RubyRed, SunGold and Hayward).

This project will be determining the accuracy to which these can be estimated using imaging-based volume measurement. The results from this research will be able to assess the industrial opportunity for the exploitation of imaging technologies as a means of determining the important parameters of DM and SSC. The objectives of this work include: To see if this relationship exists in the three cultivars and to see if dry matter can be estimated non-destructively through this relationship combined with digital density determination.

The literature review explored existing destructive and non-destructive methods for measuring the kiwifruit volume and therefore density. Non-destructive fruit volume estimation can be used as a ripeness index to predict optimum harvest time, yield or to study the relationship between fruit expansion rate and susceptibility to physiological disorders such as fruit softening. In a paper by Jordan, R. B. et. al (2000), the volume was measured through the determination of buoyant force and water being displaced where volume is calculated from the object weight and the force.

The results across the three cultivars showed strong correlations between the digital volume and the submerged volume. For RubyRed and SunGold it was observed that volume, DM and density had good correlations with 72% for RubyRed and 77% for SunGold. In comparison Hayward had the weakest correlation with an R value of 42%. This was due to experimental conduct during covid-19, where lab time was limited thus influencing the timetable of experiments for Hayward. For all cultivars, the relationship between density and SSC was weak with R values of 45% (RubyRed), 20% (Hayward) and no correlation for SunGold.

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List of Abbreviations

DM	dry matter
SSC	soluble solids content
°C	Degrees Celsius
g	gram
h	hour
kg	kilogram
min	minute
mm	millimetre
mL	millilitre
NZ	New Zealand
%	Percentage
FOB	Free on Board
CP	Central Placenta
PP	Peripheral Placenta
OP	Outer Pericarp
DS	Dielectric Power Spectroscopy
HIS	Hyperspectral Imaging

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Chapter 1: Introduction and Thesis Overview

1.1 Introduction

Initially the New Zealand kiwifruit industry was a price taker rather than a price maker to export markets. Kiwifruit New Zealand responded to this through development of a new structure and brand strategy - *ZESPRITM*. New Zealand is one of the leading exporters of kiwifruit with more than 90% of production being sold internationally (*Freshfacts.*, 2021). The kiwifruit industry is the biggest sector in New Zealand horticulture. With exports exceeding \$2.5 billion in 2020 a 36% increase from 2018. New Zealand kiwifruit's three largest export markets include Japan, European Union and China (*Freshfacts.*, 2021).

An integral aspect of Zespri kiwifruit is the premium quality it provides consumers. The quality of the kiwifruit for export and international markets is an essential part in maintaining and growing consumer markets. To provide premium quality produce, many quality control tests are put in place to track maturity indicators such as soluble solids content (SSC) and dry matter (DM). These are all parameters that influence the eating-ripe quality of kiwifruit and consequently the consumer liking.

According to Crocombe et al. (1991), before Zespri clearance protocols were developed, growers were exposed to high risk, heavy fixed and variable costs. During this period Zespri was also dependent on consumer demand and climatic conditions while receiving relatively low returns. The clearance protocol ensures that fruit maturity at harvest is optimised to maintain fruit quality after harvest. Ensuring optimal fruit maturity and thus the quality of the kiwifruit allows for higher market value and consistency for target consumers. In the 1980's New Zealand Zespri regulations (NZKGI., 2019) prohibited the export of Hayward kiwifruit with a maturity index (i.e., SCC) of < 6.2 %, with the recommended range being between 7 and 10 % (Hopkirk et al., 1986). According to Trimble, S. (2022), the acceptable DM range is around 16%. Consequently, having this index in place ensured that no immature fruit were marketed overseas and helped to maintain high quality standards.

Dry matter of plant material includes all its constituents except water. This may include carbohydrates, fats, proteins, vitamins, minerals and antioxidants. Due to DM's relationship with ripe fruit SSC, it is a key parameter for measuring quality index of kiwifruit at harvest (Trimble, S., 2022). This is due to DM's

ability to include both soluble solids and insoluble solids. During fruit development, the DM changes during the different stages.

The DM correlation is a good indicator for assessing the maturity of the fruit (Jordan, R. B. et al., 2000). Traditionally the SSC is measured as the key parameter for assessing kiwifruit maturity. Ensuring a minimum consumer acceptance and adequate storability life (Trimble, S., 2022). According to Huang, W., et al. (2022), kiwifruit is commonly harvested when mature but unripe. It is then stored for up to 6 months. Ripening then begins in the duration of the distribution chain. To deliver premium kiwifruit to consumers, DM has been proposed as an additional key parameter for the quality index. Measuring maturity is an essential guideline for harvesting decisions. If the fruit is not harvested at the optimal maturity, there is an impact on delivering high quality fruit to the consumers and may be a major impediment to the success of marketing the fruit and the brand. Anderson, N. T., et al., (2017), identified that the DM content of mango fruit is correlated to the starch and sugars. The starch (and sugars to a lesser extent) accumulate as the fruit matures. DM can be measured as an indicator of mango fruit maturity.

The industry faces outgoing challenges, especially highlighting the importance of sustainability, reducing food waste and quality provided to consumers. One area of focus is reducing waste during post-harvest, which will lead to important sustainable changes that fit with the Zespri brand. There are many factors contributing to postharvest loss, including handling when the fruit is being picked to the variability between the different growers and batches of kiwifruit. These challenges create opportunities for further improvement of fruit quality. The ability to non-destructively determine density to help in predicting the DM and fruit maturity can help growers know the optimal time for the kiwifruit to be harvested and to assure prolonged storage life and eating-ripe taste. This is integral to providing consumers with premium kiwifruit to meet their demands.

Density is measured to estimate key parameters like DM, SSC and fruit maturity. Density at harvest is highly correlated with both DM and SSC of ripe fruit. The accuracy for measuring density to determine SSC will be influenced by variation in the insoluble solids fraction of the DM. Particularly, the unripe fruit containing predominantly starch in the insoluble solids fraction. These can be large and variable between 10 – 40% according to Jordan, R. B. et al., (2000).

The submergence method which can also be referred to as the xylometric method. This involves measuring the volume of fruit being submerged in a jug/beaker of water and measuring the displacement of the water. Due to water being incompressible and with negligible amount of water being absorbed by the fruit, the displaced water should provide a good estimation of the volume (G.P.Moredaa., 2008). The volume measured can be used to estimate the density of the fruit. Jordan, R. B. et al., (2000) has previous literature estimating the relationship between DM and density using the submergence method, refer to Figure 1 below. The data shows a strong correlation between the two important quality parameters, DM and density with an R^2 value of 85.1%. This is a good basis to take further, to identify whether the same correlation will appear for the SunGold and RubyRed cultivars. This positive correlation indicates potential further correlations between other quality parameters, specifically digital density for this project.

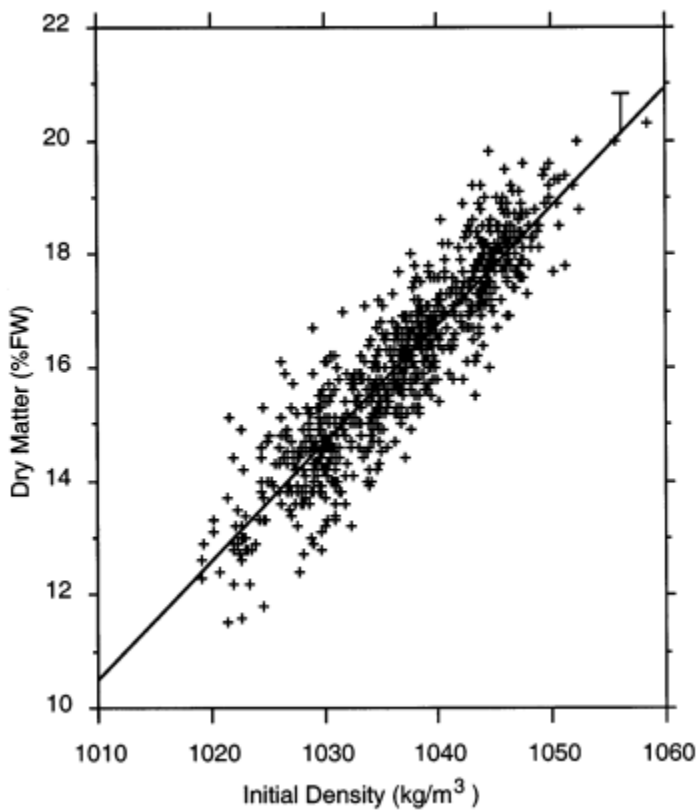


Figure 1. Graph from (Jordan, R. B. et al., 2000) representing the relationship between DM and initial density for Hayward.

A novel non-destructive method was used to estimate the density of fruit. With current advances in technology, three-dimensional scanning has ample opportunity to provide an efficient digital volume estimate. Therefore, being able to determine the fruits digital density based on the digital volume and measured fruit mass.

1.2 Aim

The aim of this work is to investigate a novel non-destructive method for determination of kiwifruit density to consequently estimate DM.

This project was conducted to revisit the relationship between density, DM, Soluble Solids Content for all three cultivars ('RubyRed', 'SunGold' and 'Hayward') using an additional novel digital technique. Determining the accuracy to which these can be estimated using imaging-based volume measurement. This project will be able to assess the industrial opportunity for the exploitation of imaging technologies as a means of determining the important parameters of DM and SSC. There is a strong correlation between density and dry matter in many types of produce.

Objectives of this work include:

- To determine the statistical relationship between digital density using novel 3-D scanning and the traditional measured density using the volume-based submergence method.
- To determine the strength of the relationship between DM and both the digital and traditional density for 'RubyRed', 'SunGold' and 'Hayward' kiwifruit cultivars.
- To determine if DM can be estimated non-destructively with digital density being used as an estimator.
- To determine the digital density efficiency and investigate its industrial implementation opportunity.

This project will be determining the accuracy to which the kiwifruit density can be estimated using imaging-based volume measurement. The results from this research will be able to assess the industrial

opportunity for the exploitation of imaging technologies as a means of determining the important parameters of DM and SSC.

1.2 Thesis Overview

The following research was carried out at both Massey University and Massey AgriFood Digital Foods, Palmerston North, New Zealand. 3D scanning, volume submergence alongside the destructive experiments were conducted on more than 900 kiwifruits. Approximately 312 kiwifruits ('RubyRed', 'SunGold' and 'Hayward') for each cultivar were tested and examined. The kiwifruits were all picked at harvest maturity, commercially graded, and selected based on a pre-selected count size range and placed in 0 °C refrigerator storage to delay the maturity process.

The literature review explores existing knowledge surrounding the kiwifruit industry, consumers perception and existing methods for kiwifruit quality used in industry. It also details information around kiwifruit physiology, the influence of the maturity process. This chapter has a predominant focus on existing destructive and non-destructive methods used within the industry, exploring the importance of non-destructive methods and potential implementation into the industry.

The third chapter of the thesis explores the multiple methods used during the experimental lab work. With a key focus on the novel non-destructive technique, 3D scanning. Preliminary trials were conducted before starting experiments. To gain the appropriate settings and to get the best scans of the kiwifruit possible. Alongside this, traditional methods are used to compare and investigate the other important parameters of each kiwifruit (DM and SSC).

In the fourth chapter, it details the results from the experiments. The graphs show the different relationships and correlations between the different parameters, which were then analysed and discussed. This chapter also includes the validation method conducted and preliminary trials. These provided valuable insights to then build recommendations for future work and the industry, which leads into the next chapter.

The fifth chapter details conclusions and recommendations from the literature, experiments conducted and results that were obtained during the work of this project.

Chapter 2: Literature Review

2.0 Overview

Zespri International Limited is the largest marketer of kiwifruit in the world, distributing in over 50 countries. To source the best quality kiwifruit, Zespri works with approximately 2,800 NZ and 1,500 international postharvest companies and growers. With a mission to create sustainable long-term value for kiwifruit growers. Currently, the industry utilises many destructive methods to help determine fruit quality and consumer acceptability.

It is suggested in previous studies that the estimation of important parameters like dry matter (DM), soluble solids (SSC), maturity, quality of the fruit have utilised the measurement of density (Jordan, R. B. et al., 2000). Consequently, density can be used to grade fruit and vegetables (Abbott et al., 1997). Jordan, et al. (2000) determined that kiwifruit density measured at harvest may be positively correlated with DM at harvest and soluble solids concentration (SSC) of ripe fruit. It is further suggested that measuring the DM at any time after harvest enables a reliable predictor of ripe fruit SSC and therefore the fruit quality (Crisosto, 1992).

Previous studies have identified the relationships between the consumer acceptability and both the DM (Scott et al., 1986) and the ripe SSC (MacRae et al., 1989; Mitchell et al., 1992) of kiwifruit. Currently in industry, DM, is used as a prime parameter for near infrared (NIR) grading equipment which is under development and refinement processes. NIR analysis has accuracy advantages for measuring ripe fruit but has small accuracy advantage with unripe fruit. This is important because kiwifruit grading occurs at harvest, when unripe. NIR in comparison to three-dimensional scanning, is more susceptible to increased error. It has higher instrument sophistication, with the method relying on fine-tuned

calibrations. According to McGlone & Kawano (1998) the success of the NIR method depends on the accurate modelling of the spectra patterns. The ability to use density measurements as an alternative for NIR to assess kiwifruit DM non-destructively in the laboratory and in commercial grading operations provides more efficiency and novel opportunities for growers and fruit quality. Using density-based measurements helps to prevent waste, fruit that would normally be damaged in the process for determining quality parameters, will remain un-damaged. This is positive on a large scale within the fruit industry.

Due to the relationship between DM and ripe fruit SSC, it is used as a target parameter in near infrared (NIR) grading. Density offers an alternative to NIR for assessing kiwifruit DM non-destructively in the laboratory, and in commercial grading operations.

A non-destructive technique being analysed is 3D scanning to determine the digital density, to then estimate the dry matter which is an important parameter for consumer acceptability. Estimation of dry matter, soluble solids, maturity and quality has long been done through the determination of density (Jordan, et al., 2000).

2.1 Project Aim

With recent advances in imaging technologies, it is now feasible to accurately and non-destructively measure volume and therefore density. The aim of this project is to revisit the relationship between density, DM, SSC for all three cultivars (RubyRed, SunGold and Hayward).

Objectives of the literature review include:

- To obtain existing literature relevant to Zespri and kiwifruit. To understand the kiwifruit maturity, morphology, and ripening process.
- To find existing literature encompassing both destructive and non-destructive methods used in the industry. To comprehend and compare what is currently used and identify future steps and industrial opportunities for this project.
- To obtain relevant literature identifying correlations between key parameters like DM, density and SSC.

- To evaluate relevant literature and compare from various sources to validate findings and obtain an extensive understanding of the existing research in correlation to this project and the current industry
- To explore the influence of the technology adoption shift in the industry. With quality driven produce for consumers, there are shifts from traditional methods to higher efficiency technology driven methods. In this case, traditional volume-based submergence method compared to novel 3-D scanning of volume.

2.2 Kiwifruit Industry

New Zealand is the world leading exporter of Kiwifruit (*Actinidia deliciosa*), with more than 90 % of production being exported (Burdon & Lallu, 2011). The fruit was first introduced in 1906 (Schroeder & Fletcher, 1965), first known as the Chinese gooseberry due to its Chinese origin. With selective breeding, three main varieties are grown today – ‘Hayward’, ‘SunGold’ and ‘RubyRed’. ‘Hayward’ being the first established variety, was grown commercially around 1930 (Schroeder & Fletcher, 1965). During the 1990’s Zespri invested in research and development of a new cultivar – SunGold. This cultivar was in development for over 10 years and proved to be a successful cultivar, meeting consumer demand (Zespri, 2022). RubyRed cultivar has been the most recent cultivar to be developed and was officially launched in 2022.

Currently, kiwifruit from New Zealand is being traded internationally around the world. With all the marketing operations being organised by Zespri International Ltd. Zespri being purely grower owned, exporting premium quality kiwifruit. As the international demand continues to increase, there is an increased emphasis on post-harvest performance and fruit quality.

2.2.1 Production and Exportation

The New Zealand horticulture industry has increased exports from approximately \$120 million in the 1980’s to more than \$2 billion today. In 2021 the fresh and processed export fruit in New Zealand was estimated to be worth \$5.9 billion (freshfacts, 2021). With predominantly kiwifruit, grape wine, apples and avocado’s being the highest in demand for export. In 2021, kiwifruit had the highest export value by

40%, valued at \$2.71b FOB (freshfacts, 2021). According to freshfacts (2021) as seen in the figure 2 below, kiwifruit was exported to Europe (\$796m), China (\$648m), Japan (\$559m), Korea (\$189m) and Taiwan (\$130m). This industry is technology intensive so growers can efficiently maintain sustainable production of high quality and value produce. According to Kilgour, M., et al. (2007) the New Zealand kiwifruit industry led in developing systems to track fruit from orchard to market. Enabling buyers to find out the orchard that produced the fruit, packhouse, packing date and history of the fruit.

With kiwifruit being consumed globally, the import demand remains strong in the EU (freshfacts, 2021). While in Asia, the sales of kiwifruit have grown significantly. Kiwifruit production is concentrated in a few countries, traditionally being China, New Zealand, Chile and Italy. These countries, especially China and New Zealand are the largest exporters of kiwifruit across the world. Between 1984 and 2009, the demand for kiwifruit significantly grew.

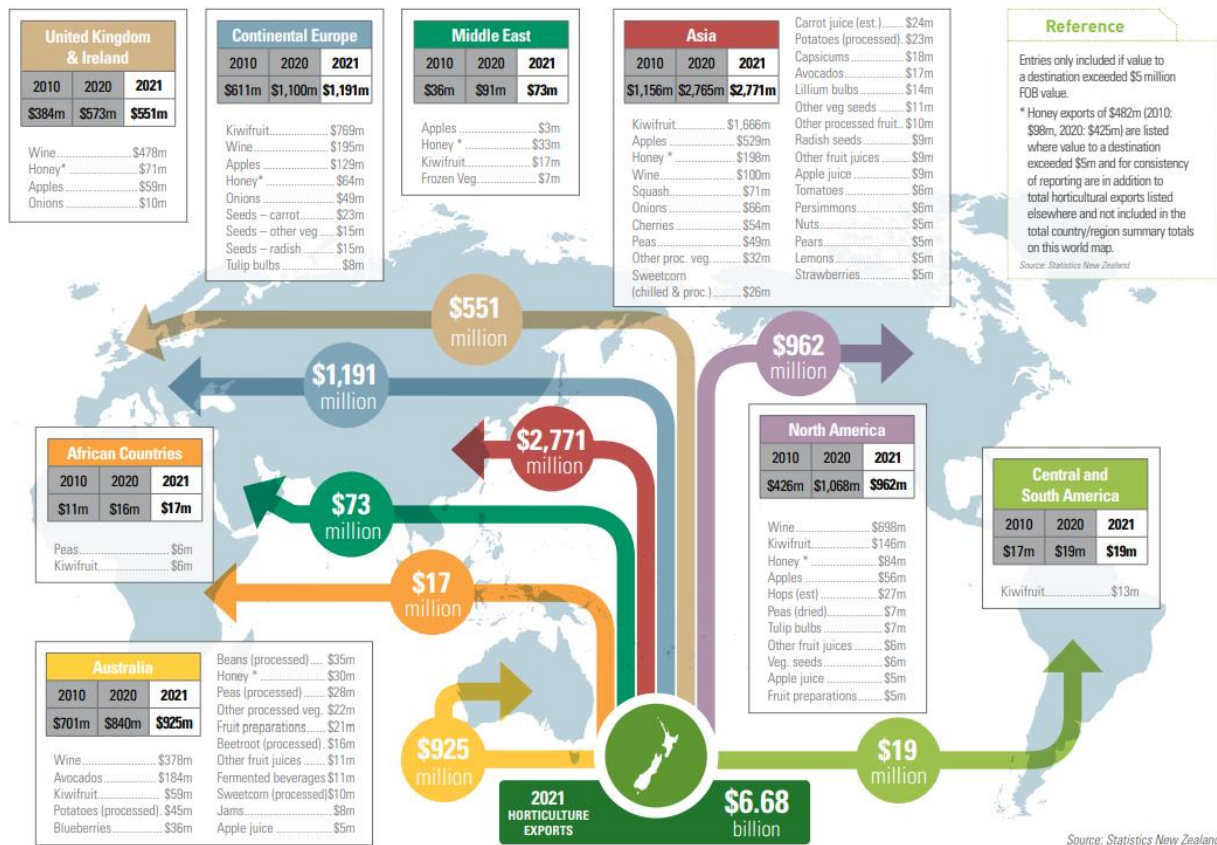


Figure 2. New Zealand's Horticultural Export Destinations (freshfacts, 2021).

At present in New Zealand, there are an estimated 2,800 kiwifruit growers and 2,900 registered orchards (NZKGI, 2021). With approximately 12,185 hectares of kiwifruit in production. At the end of 2021, statistics revealed that gold kiwifruit accumulated 47% of the total fruit export value, with green ('Hayward') accumulating only 23% of the total fruit export value (freshfacts, 2021). The majority of these kiwifruit (81%) are grown in the Bay of Plenty area.

In 2016 which can be observed in the graph (Figure 3) below, the kiwifruit season indicated SunGold value rising higher than Hayward and, in the season of 2020, SunGold volume increased higher than that of Hayward (Fruit Export Stats). SunGold has a higher unit price in comparison to Hayward. This is highly associated with increasing consumer demand for SunGold, driving a higher need for the product.

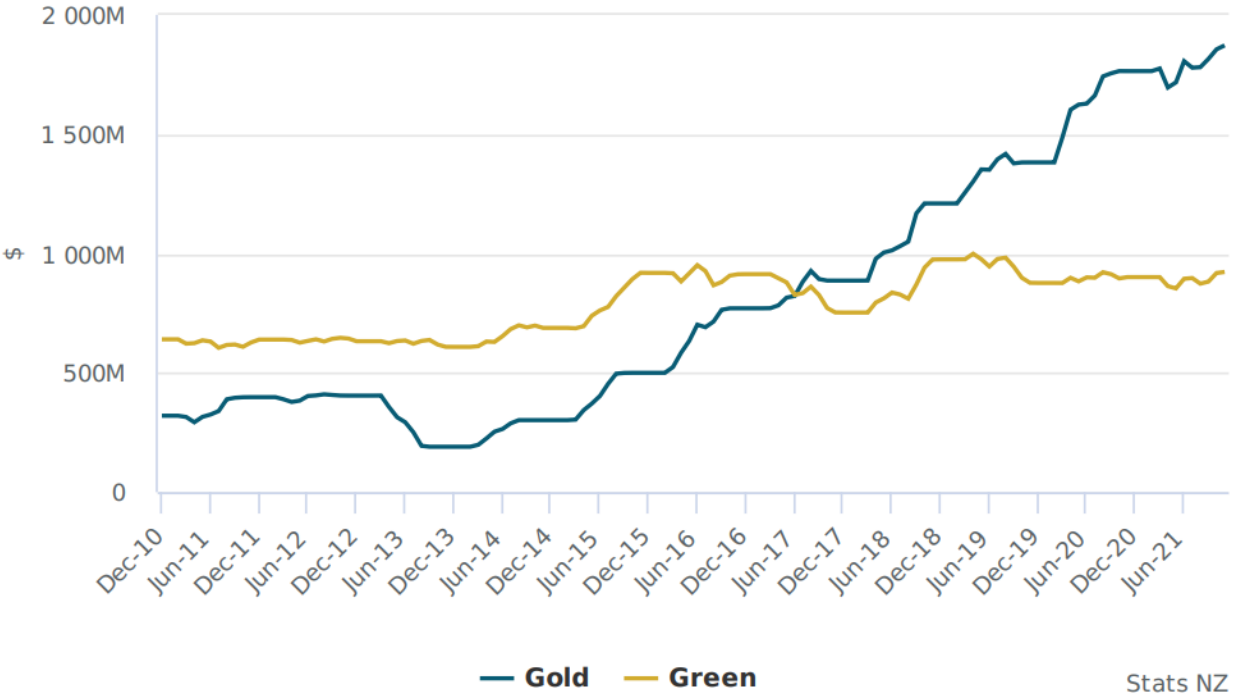


Figure 3. Annual gold and green kiwifruit export values from 2010 to 2021 from Stats NZ (2021).

New Zealand has a dominant market position. Over the years New Zealand’s kiwifruit sales have varied. More recently according to Stats NZ (2021) the gold kiwifruit exports at the end of 2021 earned \$1.9 billion, making up a large portion of the total fruit export value compared to green kiwifruit exports having earned \$923 million at the end of 2021. The observed market growth (Figure 4) and demand for kiwifruit is not common for horticultural products where there is significant competition amongst other fruits and alternative suppliers of the same fruit. Kilgour, M., et al. (2007) clearly identifies that the EU

and Asia markets have been key to the growth of the kiwifruit demand. Key Asia markets include Japan, China, Hong Kong, South Korea, and Taiwan. The United States shows minimal growth in kiwifruit demand.

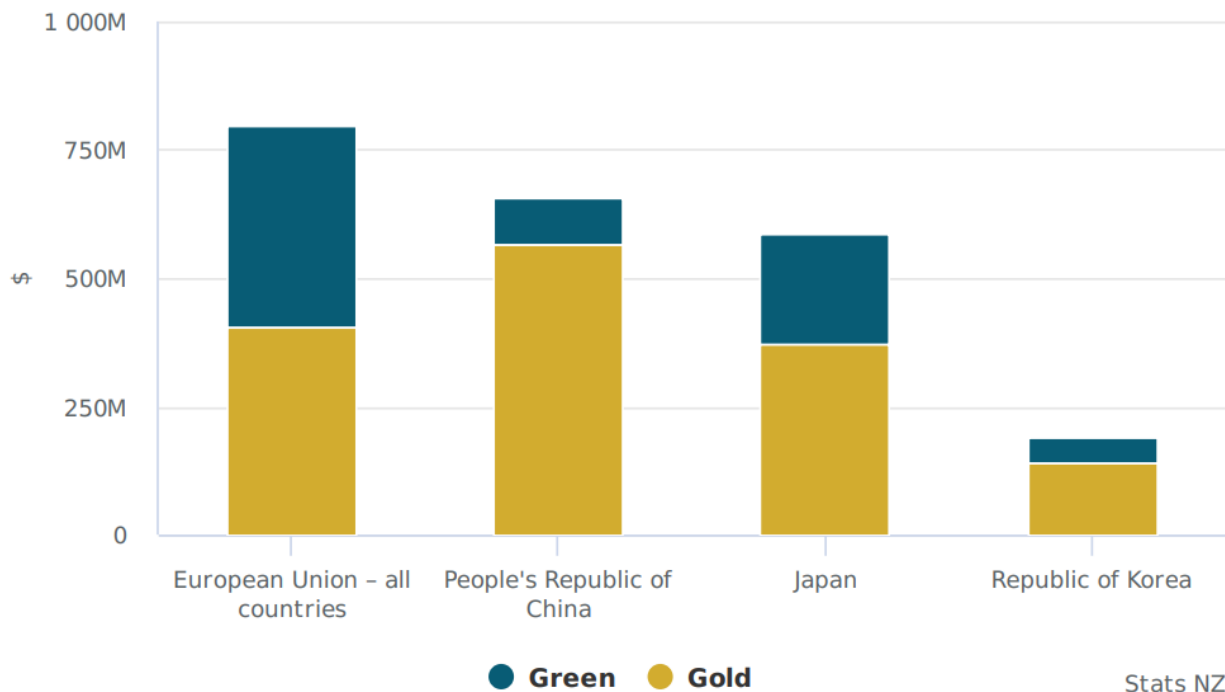


Figure 4. Annual green and gold kiwifruit export values to top four international markets (Stats NZ, 2021).

Exporting kiwifruit from New Zealand has many obstacles and challenges. Being able to meet consumer demand all year round is a continual challenge due to the different seasons and weather conditions in the two different hemispheres. New Zealand's key advantage is quality, which competes against Chile's cheaper kiwifruit. Disruption has occurred with China growing their own kiwifruit, becoming a competitor within the China market and potentially to overseas markets.

With the introduction of SunGold in 1998 (Zespri, 2022) another challenge was overcome. Introducing a new product to the international markets. SunGold had market appeal, but the fruit had different

handling requirements that needed to be met. It was essential that the addition of the new cultivar (SunGold) would add to the market share rather than have a corporate cannibalism effect and consume the existing market share of Hayward. It was key for SunGold to further support the Zespri brand. This was done relatively successfully with both varieties having a market demand and share. According to Zespri (2021) in 2014/2015, 11 million SunGold trays were sold. A significant increase occurred in the years following (2015/2016) reaching 27.5 million trays. While green kiwifruit experienced a growth from 8.972 trays per hectare (2014/2015) to 11,048 trays per hectare (2015/2016). A significant key outcome during the years 2015/2016 was the positive consumer reception of SunGold globally.

2.2.2 Kiwifruit Export Supply Chain

In the New Zealand horticulture sector, collaboration between science and industry with their different global reach has been essential to developing the supply chains. Consumer demand is built upon premium quality and the prestigious New Zealand history in supplying fruit to export markets. To maintain and grow this demand, the industry faces challenges with fruit wastage and storage life in the duration of transporting the produce on a lengthy supply chain.

Some key science and industry innovations within the supply chain include:

- Selective breeding
- Fertiliser and crop management
- Post-harvest storage
- Integrated fruit production (IFP)
- Innovative Packaging
- Controlled Atmosphere (CA)
- Effect of Ethylene
- Establishment of kiwifruit maturity indices
- Supply chain management systems
- Development and use of grading technologies

The global supply chain (Figure 5) below, starts with the production of produce and then goes to grading, packaging and the storage of the produce. This then leads to appropriate transport, distribution, and consumer markets. Delivering fresh kiwifruit requires intensive management of from

grower to consumer. Zespri has an integrated supply chain system, with emphasis on supply chain efficiency to unlock significant value for the industry.

Zespri™ has an integrated production and delivery system, beginning from the growers to the retail. This system involves six major principles, which include: total integration of processes, traceability and transparency, ethical business practice, sustainable development, food safety and GE free. Zespri has a quality assurance system that can trace a tray of kiwifruit right back to the grower. Enabling continual improvement and innovation to meet consumer demand for premium, delicious, safe and nutritious food.

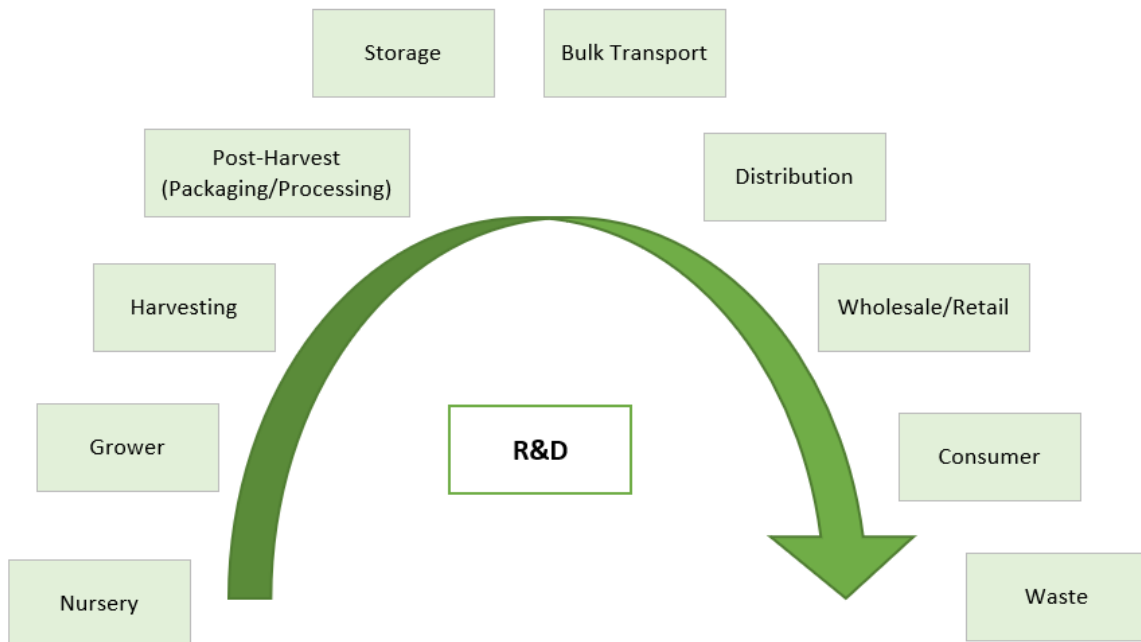


Figure 5. Brief overview of Supply Chain from Grower to Consumer in Horticulture.

Figure 5 above shows a brief outline of the supply chain from grower to the consumer while R&D work is constantly being done to create a more efficient system with minimal waste at each step in the chain. Growers in New Zealand are primarily family-run sections supported by temporary, seasonal workers. Hewett, E. W. (2006) identifies that with increasingly complex demands of consumers and the growing population, horticultural sectors need to incorporate and embrace the advances in technology being developed. Hewett, E. W. (2006) literature states that the variability among produce will be minimised

through seed and plant selection and breeding. Also, through fast, accurate and consistent post-harvest sorting and packing systems.

Due to the distance New Zealand has from main markets, it's essential for successful management of the supply chain to ensure produce reaches desired destination in top quality. To conquer this, the New Zealand horticulture sector has shifted away from traditional practices to adopting innovative solutions. To make this shift innovative uses of information technology were introduced to the supply chain. Strategic long-term relationships were developed with collaborative partners regarding packaging, storage and transport to the required market). Different systems have been developed to rapidly share information among partners within the supply chain with smart outsourcing work reducing costs.

The management for postharvest is to retain fruit quality for consumers, delay the ripening process and stability. While the fresh fruit and vegetables move throughout the supply chain reaching both the domestic and international markets. Zespri alongside many fruit and vegetable growers in the horticulture industry face the challenge of retaining fresh and premium quality of the produce. To meet the consumer's desire and demand. To ensure the postharvest sector of the supply chain is running effectively, the following critical factors should be optimised: harvest maturity indices, temperature management, atmosphere modification, ethylene, packaging for consumer demand and fruit grading (Shewfelt, R. L., & Prussia, S. E., 2022). In New Zealand, the relationship between science and industry is closely linked. This allows findings to be quickly adopted by the industry and integrated into the supply chain. This has cultivated a culture that has greatly benefited New Zealand with a competitive advantage in the Northern Hemisphere. This research allows growers to harvest their produce more efficiently at optimal harvest maturity. This will reduce wastage and increase quality end-product for consumers. This will play an integral role in the post-harvest step of the supply chain, which will influence the steps leading to the retail consumer acceptance.

2.2.3 Consumer's Acceptance

Through market research it has been identified that sensory characteristics and health (taste, flavour and appearance) are the predominant reasons consumers buy fruit. In a survey conducted by Zespri (KiwiTech Bulletin) in the UK found that 80% of the consumers considered fruit taste to be of higher importance in comparison to the fruit price. Being able to meet and satisfy the consumer expectations, leads to higher chances of them returning and buying more kiwifruit.

Research conducted by Zespri (2021) have found that kiwifruit dry matter content has a positive influence on consumer taste preference with the majority preferring kiwifruit with a higher DM. Zespri (2021) identified that a DM range of 16 – 20% has been associated with consumer satisfaction. A DM value within this range provides high quality fruit and ensures a prolonged storage life. If the DM is lower than 15% in kiwifruit, which can be due to premature harvesting, it is less likely to meet consumer satisfaction according to research conducted by Zespri. DM directly influences the taste. This is because at harvest the majority of DM in kiwifruit is in starch form. As the ripening progresses, this starch is broken down into simple soluble sugars. These are the sugars tasted when the kiwifruit is being consumed. A higher DM correlates to a higher SSC when fully ripe and ready for consumption.

In the Japanese market it is clearly identified that fruit taste is the most important aspect, over the fruit's size or price. The taste of a ripe kiwifruit is primarily driven by the amount of sugars and acids in the fruit. The sugar provides the 'sweetness', while the acids give notes of tanginess. The volatiles of the fruit contribute to the flavour when consumed.

2.3 Kiwifruit Botany and Morphology

For optimum harvest time, scientists have developed a criterion for the harvest maturity indices. This criterion has been altered and refined as further research has developed with increased understanding of the kiwifruit's physiology, morphology and botany. Each cultivar of kiwifruit has particular characteristics. This plant can be characterized by its fleshy roots, bushy nature, and its tendency to distribute in the upper substrate of the soil. Kiwifruit is a dioecious plant where both male and female flowers appear on the different plants. The fruit is a berry of ovoid shape dependent on the cultivar, each cultivar slightly varies in shape. These berries gather in clusters on the vines.

2.3.1 Fruit Botany, Structure and Shape

Fruit Structure

The fruit's axile placenta is majority formed with homogeneous, large parenchymatous cells. At the base, middle and top areas of the kiwifruit, cross sections made through the placenta show three main

vascular tissues (See figure 6, noted as CP, PP and OP). Which are amphicribal bundles with xylem in stellate-shaped arrangement, obvious vascular cambium and developed secondary phloem. Guo, X.-M., (2013) identified in literature that as the central parenchymatous areas of vascular bundles gradually decrease, the secondary phloem does not decrease. This suggests the developed phloem provides an important structural basis for the transport of nutrients.

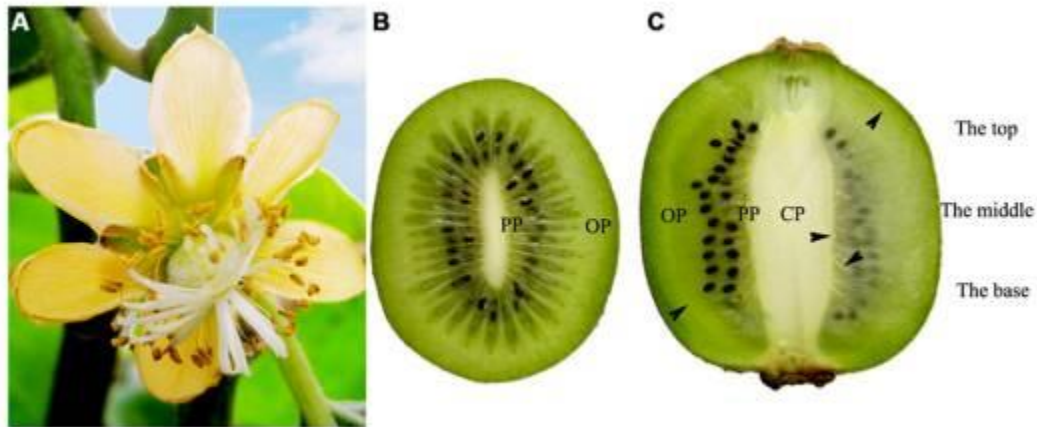


Figure 6. *Actinidia deliciosa var deliciosa* flower (A), mid-cross section (B) and longitudinal mid-section of the fruit (Guo, X.-M., 2013).

An important role in the fruit development are the vascular bundles which are the main transport channels for water and nutrients within the fruit, helping to develop kiwifruit and the fruit's quality. Like most fruits, the storage quality is highly correlated to the calcium concentration (Moor, U., et al., 2006). Fruits with low calcium are correlated with fruit disorders like lowered fruit production and thinning of foliage.

Role of Nitrogen and Calcium on Kiwifruit Post-Harvest

When compared to other fruits, like apples, it may be expected that the mineral content of the fruit would play an important role influencing post-harvest fruit quality (Moor, U., et al., 2006). There is conflicting evidence in literature on this subject that leads us to suggest that again the growing conditions themselves play an important role influencing mineral uptake and possible distribution in plants. It's been shown that high N concentrations in the fruit or the petiole sap is highly correlated with rate of softening after harvest. However, in other parts of the world like USA, experiments applying a

range of N concentrations to another type of soil had no effect on total soluble solids (TSS) and firmness at harvest or after 4 months in CA storage (Costa et al, 1997).

Calcium is an element that plays a very important role in postharvest quality of many products because of its seminal role in maintaining integrity of cell walls and membranes and because it acts as a second messenger in important cellular processes.

Influence of Water

It has been shown that withholding water from vines early in growing season will reduce yield by 25%; withholding water from the later part of the growing season will reduce final fruit size slightly effecting the overall quality (Miller, S. A. et al., 1997). But could potentially enhance the soluble sugars and total soluble solids. This effect is maintained through 12 weeks at 0C, and hence is likely to result in a sweeter, more preferred fruit by the consumer.

In some countries (e.g. USA & Chile), it is necessary to irrigate through the entire growing season, providing a minimum of 100 - 150 litres per plant. Essential to avoid periods of sustained unmanaged water stress in the plant, otherwise fruit quality and yield will be compromised. However, in New Zealand there is enough rain to maintain healthy levels of hydration preventing water stress within the plant. This consequently means no irrigation required either.

2.3.2 Fruit Growth Phases

Kiwifruit development follows five main growing stages, starting with the bud development. Bud development is an essential part of the growth. When the plant goes into dormancy, the buds from the previous year's crop have closed up, with potential of ostiole (a diameter of around 2 mm). The active buds start to enlarge, with some white trichomes covering the scales. In the next few days, increased swelling occurs where the bud starts to begin to form. With the bud beginning to form on leaves and flowers, brown trichomes and scales surround the forming bud. The scales then detach, revealing green leaf tips covered in brown trichomes (Kobayashi, S., et al., 2008).

After the bud development phase, the leaf formation phase is the first major growth. Which then leads into a cluster of leaves which can be observed throughout each day. These leaves begin to unfold and spread away from the stem. Around 2 - 8 or more fully formed leaves begin to expand and further grow. An important growth cycle for leaf development is 'proliferation', where the shoots achieve roughly 10% of their eventual size. The shoots then roughly achieve a length of around 50% of their eventual size, leading to achieving a size of 90% of their full intended length until the end of the growing season.

After the initial bud and leaf formation phases, inflorescence development occurs. This is the final development stage. The appearance of singlet or triplet flowering buds appear, they are closed with no peduncle, visible greenish sepal and covered with trichomes. The swelling of inflorescence buds are developing flowers while still closed, however, the peduncles are growing longer. Formation of a white/green flower with elongated reddish peduncles continues to grow and flourish. The pedicles start to elongate while becoming thicker. The corolla becomes visibly apparent, as it is longer than the calyx. The corolla phase forms white petals with the first hollow ball, with only one petal remaining attached. The first flower to open is the corolla bell-shaped according to Kobayashi, S., et al., (2008), where approximately 10% of blooms are open initially at blossoming.

This then leads into the fruit development (Figure 7 below). As the flowering phase ends, ripening fruits can be observed in the final fruit development stages. Around 10 weeks after anthesis, the fruit grow into their full size, become hard and develop colour changes from white to brown. The seeds turn black and fruit begins to squish down. The kiwifruit ready for harvesting will have a soluble solids content around 14 - 16%. This will provide consumers with kiwifruit that has optimal flavour and texture.

The final stage is then reached, the beginning phase of senescence. The last stage is where softening starts to occur, becoming consumer ready, for consumption. During the beginning of the final stage, the fruit is still firm but with a significant increase in soluble sugars in the fruit. Richardson, A.C. et al (2011) describes the softening phase to occur in four parts. The first being the initial decrease in firmness. Second, rapid softening. Third, continued loss of firmness but at a slower rate. Fourth part is the fruit production of autocatalytic ethylene. The cells produce aroma volatiles and further decrease in firmness as the start of senescence begins. The colour also changes from a bright green to a yellow type green.

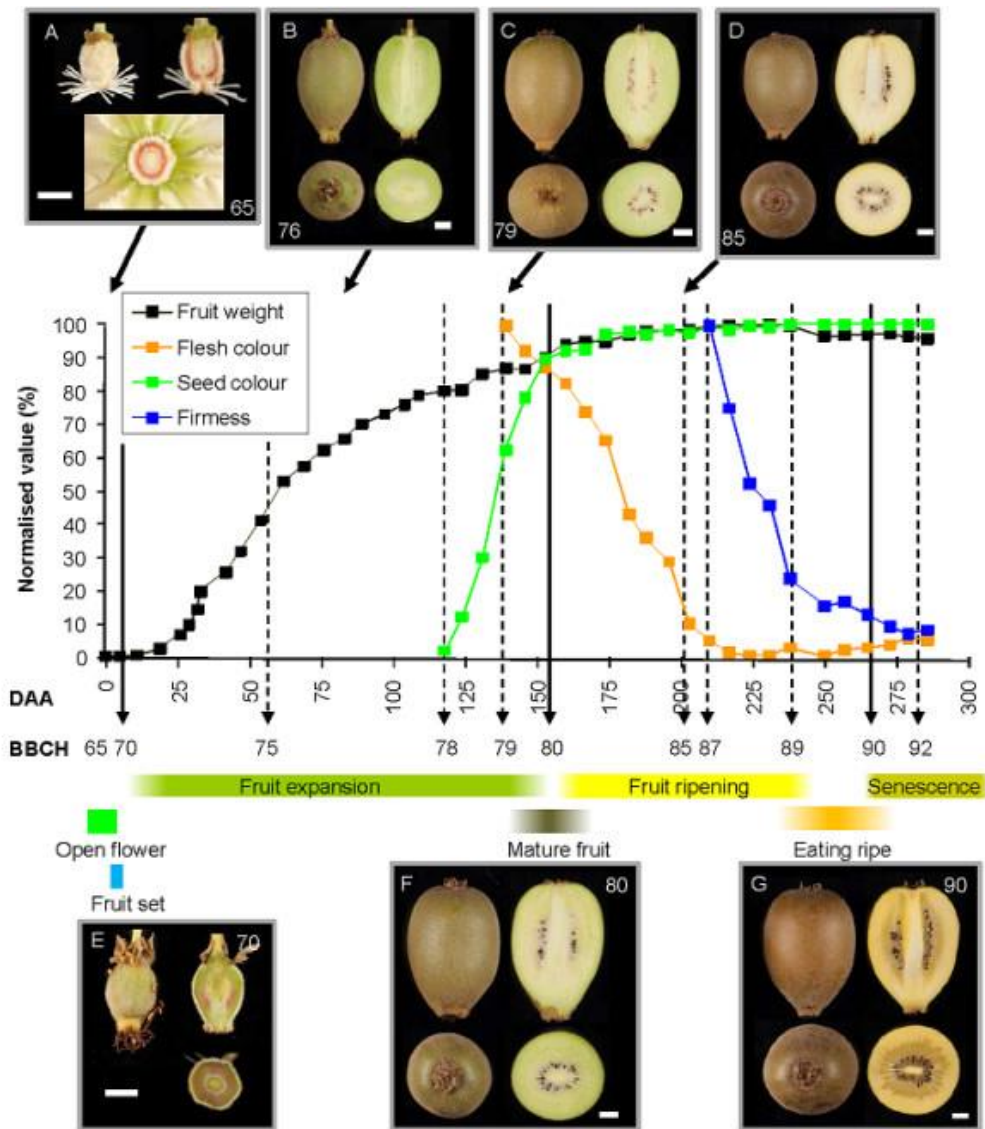


Figure 7. Kiwifruit development diagram (Richardson, A.C. et al., 2011)

Stage 70 in figure 7 above, reveals the fruit is set, petals abscised from the flowers and the beginning of fruit growth. Stage 80 reveals the mature fruit with seeds within fruit over 95% black. In stage 90, the beginning of senescence occurs, and kiwifruit starts to produce autocatalytic ethylene. At point F, in figure 7, is the optimal mature fruit ready to meet consumer demands of a quality kiwifruit.

2.4 Kiwifruit Maturation and Ripening

The harvest time for kiwifruit is critical because the ripening rate is dependent on the fruit maturity at harvest. Kiwifruit is harvested commercially when the fruit is mature but firm and unripe. This allows for the kiwifruit to then be stored for months at low temperatures (0 -1°C) allowing for an extended marketing period and shelf life. Appropriate harvesting time leads to sufficient carbohydrates present ensuring the fruit has the desired taste, texture, juiciness, and flavour when consumed. For optimum harvest time, scientists have developed a criterion for the harvest maturity indices.

Kiwifruit is a relatively new fruit in comparison to well-established apples and citrus fruits, but in recent decades vast amounts of research has been focused on kiwifruit and addresses issues relating to vine productivity, performance and influences on fruit quality at harvest and after storage (Warrington and Westob, 1990). Industry continues to require information to improve produce, storability (especially for exportation), transportation and the ability to deliver high quality products to their consumers.

Kiwifruit has been largely successful due to its ability to be stored for extended periods of time at 0 °C. However, there are limitations to the fruit's quality after long term storage. This initiates a challenge to post-harvest scientists, to understand and manipulate those factors that influence deterioration rate and quality after storage. High variation in maturity stages affect post-harvest quality and the rate of ripening within a consignment, causing logistical difficulties.

Main factors limiting the kiwifruit life, include:

- Premature softening during storage
- Development of post-harvest decay arising mainly from infection by *Botrytis cinerea*, *Cryptosporiopsis sp.* and other fungi.
- Physiological disorders include1 “soft patches”, low temperature breakdown and physiological pitting.

The lack of uniformity of firmness and taste when eating ripe, as well as the presence of mature but very firm fruit in supermarkets, may present a problem to unaware consumers. Lack of knowledge around kiwifruit ripening, it can ripen rapidly when put next to a ripe banana or apple. Physiologists have

addressed issues relating to vine performance, productivity and factors affecting fruit quality both at harvest and after storage.

2.4.1 Dry Matter (DM) Accumulation

An example of a kiwifruit weighing 110 g at harvest with a DM of 17% should consist of approximately 18.7 g of dry weight and 91.3 mL of water. From that 18.7 g dry weight, 10 g would be sugars, 4.3 g of fibre and 1.7 g acids (Zespri, 2007).

The industry in the 2000's started developing a protocol for utilising DM as a predictor for harvesting kiwifruit. Using DM as a basis for identifying the harvest period to pick fruit with maximum taste when consumed. Zespri (2007) identified that a SSC of 18 % at harvest would provide fruit with maximum consumer acceptability, at ripe eating time SSC would be greater than 14.5 %. The ability to use DM as a quality attribute, helps growers to harvest kiwifruit that is consistently tastier, high quality and more acceptable for consumers.

The DM content is made up of both cell structural material and stored starch. During the ripening process, the stored starch is what's broken down into soluble sugars. The higher the content of DM, the greater the concentration of soluble sugars it will contain when fully ripened. Throughout the growing season the fruit will continue to accumulate DM, but once harvested, the DM of the fruit is fixed. Setting the upper limit for the soluble sugars the fruit can develop when ripe. Thus, the measurement of DM at harvest is an important parameter in predicting the final sugar concentration at consuming ripeness, sometimes referred to as ripe soluble solids (rSSC) and measured as brix (Burdon. J et al., 2013).

2.4.2 Starch Accumulation (pre-harvest) and Degradation (post-harvest)

Starch accumulation occurs during the early stages of fruit development. Kiwifruit at harvest contains DM that is majority in the form of starch, with only a small amount of soluble sugars present in the juice. After harvest, as it continues to ripen the starch is broken down into simple soluble sugars, which is the 'sweetness' consumers taste when the kiwifruit is consumed. Kiwifruits contain a range of compounds that are soluble in water, for example, sugars, amino acids, some pectin's, acids and vitamin C. These all

form the “soluble solids” component of the fruit as they are soluble compounds. The main component of the total soluble solids is the sugar content in the kiwifruit. The sugar content in fruit increases as the fruit matures and ripens, thus, the soluble solids content of the fruit can often but not always be indicator of the fruit’s maturity and the stages of ripeness (Hopkirk, G., 1986). The soluble solids content is an important parameter for the quality of the fruit.

Starch degradation occurs during fruit development and is essential in plant growth. Starch is degraded to soluble sugars. Kiwifruit stores a large amount of starch which can reach approximately 40% of dry matter in mature kiwifruit (Hu, X., Kuang et al., 2016). High starch-containing fruit like kiwifruit experience degradation of the starch to soluble sugars when commercially harvested and picked from the vines (Hu, X., Kuang et al., 2016). The starch degradation in the initial stages of postharvest is unique compared to many other fruits. Usually starch to sugar occurs in fruit development (pre-harvest) (Hu, X., Kuang et al., 2016). Fruit undergoes softening when harvested from the vine, influencing the maintenance of the texture and flavour. Thus, understanding the importance and mechanisms of starch degradation allows for better understanding of the postharvest ripening of the kiwifruit during the supply chain, before reaching the consumers.

2.4.3 Carbohydrate Metabolism

During the postharvest period, kiwifruit are experiencing many changes as they ripen. From modification of the cell wall, development of fruit volatiles, conversion of starch and organic acids to sugars producing a unique blend within each kiwifruit. Ripening is commonly associated with increased transient respiratory, often referred to as climacteric. Multiple studies have based research on the metabolic changes that occur during the climacteric period. Understanding the climacteric induced changes in kiwifruit, aids in better handling and control of the fruit ripening process. According to (MacRae, E et al., 1992), studies have shown that the climacteric was initially correlated to the release of carbon from starch, and later the activation of glycolysis via high fructose-2,6-bisphosphate. A further two studies according to (MacRae, E et al., 1992) found that other fruit attribute the predominant control of the respiratory burst during the climacteric to a stimulation of carbon flow through glycolysis.

It has been identified that there are two classifications of fruit regarding climacteric and non-climacteric ripening. The majority of fruit display alterations in colour, texture, flavour and pathogen susceptibility

during the maturation period. These two classifications have been previously used to distinguish between fruit depending on respiration and ethylene biosynthesis rates. For example, fruits including tomatoes, avocado, banana, peaches, plums and apples etc are climacteric fruits which are distinguishable from non-climacteric fruit. Fruits including strawberries, grapes and citrus etc are non-climacteric. They are distinguishable during ripening through their increased respiration and ethylene biosynthesis rates. Non-climacteric fruit ripening doesn't require ethylene but may respond to the presence of ethylene. However, in climacteric fruit, ethylene is required for coordination and competition of ripening.

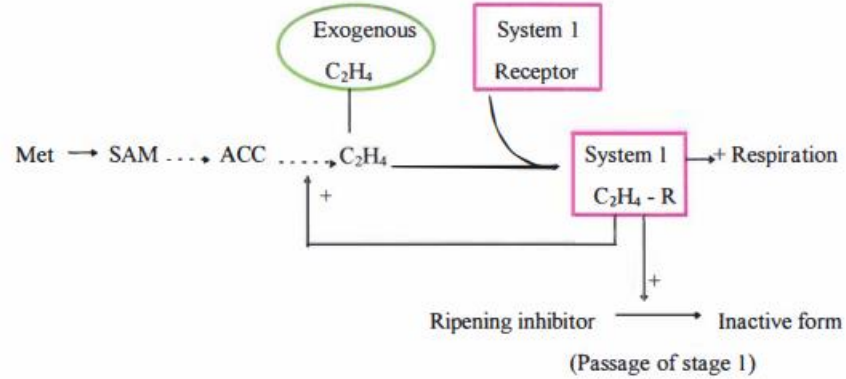
2.4.4 Role of Ethylene

Kiwifruit are extremely volatile when in contact with exogenous ethylene. An example of this is that kiwifruit will soften rapidly at 20 °C when exposed to as little as 1 ppm for a few hours. Fruit softening is enhanced at 0 °C when ethylene in the environment surrounding the fruit is present at concentrations as low as 0.01-0.03 ppm (Jefferet and Banks, 1996; McDonald, 1990).

Research has shown that ethylene production is very low during the first two softening phases and yet the climacteric is associated only with the final phase of softening. With rapid increase in ethylene production occurs only when fruit has softened to <20 N. Moreover, climacteric ethylene production does not occur at temperatures < 12-14 °C, and yet fruit soften consistently at 0 °C (Sfakiotakis, 1997).

A photoionisation detector to detect the presence of volatile organic compounds, has shown that kiwifruit produces low amounts of ethylene at 0 °C. While, both ACC and ACO activity are present during this time (Kim et al, 1999). There are two distinct classes of ethylene action known as system 1 and system 2 receptors. These different systems are based on the fruit responsiveness to the addition of ethylene. Pre climacteric (immature) fruit produces a low level of ethylene which corresponds to system 1. This is essential for inducing ACO activity and accelerating the passage of the pre climacteric phase. The "ripening inhibitor" is destroyed when system 1 ethylene is in conjunction with the pre-existing system 1 receptor. With the inactivated "ripening inhibitor", the development of system 2 receptor becomes functional in mature fruits. System 2 induces development of ACS while system 1 induces the development of ACO. Development of both ACS and ACO create autocatalytic production of system 2 ethylene, beginning the synthesis of ripening enzymes.

Stage 1 (Immature fruits):



Stage 2 (Mature fruits):

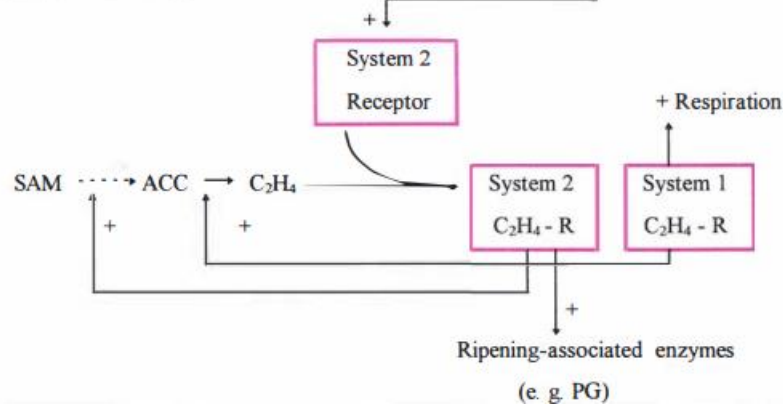


Figure 8. Stages of ethylene action on regulating the ethylene biosynthesis of fruit maturation (Oetiker, J. H., & Yang, S. F. (1995))

It is possible that the base level of ethylene corresponds to system 1 ethylene production. It may be the changing ability of fruit to soften with increased maturity. Ethylene is widely thought to have a coordinating role in regulating ripening of fruit (theologis, 1993). The model above (Fig 8) shows the stages of ethylene action on regulating ethylene biosynthesis in fruit maturation and ripening. This background knowledge on the ripening and maturation process emphasises the importance of harvest maturity. Incorporating methods that efficiently and non-destructively estimate the key parameters like DM and density to estimate the optimal harvest maturity. Positively influencing the post-harvest maturation and ripening process of the kiwifruit.

2.4.5 Soluble Solids (SSC) Evolution (pre and post-harvest)

A ripe kiwi fruit allows the SSC to indicate the perceived sweetness when it is consumed. An important characteristic when consumers choose to buy kiwifruit. SSC is measured using refractometers which use light refraction to measure the sugar content of liquids. The light refraction % is correlated to the concentration of sugar. Refractometer readings are recorded as a percentage (%) sucrose and are calibrated with the assumption that the only compound in the solution being measured is sucrose, giving a good estimate of %SSC in kiwifruit.

To produce a high-quality flavoured kiwifruit, it is essential for adequate storage of soluble sugars as starch reserves. While the net starch degradation occurs postharvest, nearly all the starch has been converted into soluble sugars by the time the fruit is consumed (Huan, C., 2021). The SSC as measured in brix is an important parameter for the maturity of kiwifruit at harvest. Brix provides better information on its maturity compared to DM. SSC has high influence over consumer acceptability. The SSC provides the sweetness that consumers demand.

2.4.6 Density Changes

The utilisation of density to predict DM, SSC, maturity, quality and defects in both fruits and vegetables has been around for a long time. The changes in density help to grade fruit and provide premium quality of fruit for consumers. Jordan, et al., (2000) has identified that density at harvest time for kiwifruit is highly correlated with both SSC and DM. Density of unripe kiwifruit was investigated by Jordan, et al., (2000) as a way to determine the current fruit DM and SSC, to then estimate these parameters later on, once fruit had ripened. In another study done by Léchaudel, M., & Joas, J. (2006), where the ripe-stage eating quality of Mango was being investigated. It was noted that increased fruit density was positively correlated with the eating quality. In contrast to this Del Mundo et al. (1984) had identified that this increase is not significant.

For apples, a study done by Jan, I., & Rab, A. (2012) found that there was a significant decrease in the apple's density with increased storage duration. After 150 days there was a significant effect on the density loss, however, the effect of storage duration was not significant on the apple's density when stored up to 120 days. According to (Bayindirli., 1993), the apple density is a function of both solutes and air spaces dissolved in the cell sap. This study done on apples identified that the fruit loose

considerable amounts of moisture in storage duration, with the density then decreasing during storage. This shows that a loss in moisture results in decreased density. Thus, in fresh fruits the density is high and declines during the storage period. Potentially from the collapse of intercellular spaces and moisture loss (Mitropoulos and Lambrinos, 2000).

2.4.7 Key Correlations between DM, Brix and Density

There is a relationship between brix at consumption and brix at harvest however there is not a direct correlation (Jordan, R. B. et al., 2000). When the fruit is ripe, brix is a combination of soluble solids at harvest and DM. At harvest it is a measure of the fruit maturity and does not influence what the consumption brix will be. Not all DM at consumption can be converted to brix at consumption as some DM is bound up in cell structural components. The relationship between DM at harvest and brix of ripe fruit is directly correlated. It is, however, influenced by variety, the time the fruit has been in storage and how much water loss has occurred from the fruit. The longer the storage period, the more respiration occurs which burns up the sugars. This is offset by water loss from fruit transpiration as with increasing water loss the sugars become more concentrated.

The correlation between dry matter and SSC enables the industry to provide high quality fruit to consumers, delivering the correct taste and quality. The DM content is the ratio between the water content and the dry weight. Commonly, fruit with high DM has the sweetest taste and strongest flavour overall (Palmer, J. W. et al., 2010). There is also an increase in vitamin C, acidity, and sugar content with increased DM. This provides insight that the consumer preferences for high DM fruit may reflect more than just the added sweetness. In kiwifruit the majority is water while the rest is made up of solids (dry weight). Therefore, the dry matter content of a fruit is a function of both the water and solids it has accumulated during the growth period on the vine.

Determining the density, helps to predict the DM which is used to indicate the maturity and quality for kiwifruit. DM is sensitive to growing conditions and agricultural practices which vary between seasons, location and harvest time. These parameters help provide valuable information around the quality of the orchards and fruit produced. The DM during post-harvest and storage does not change according to Crisosto, G. M., (2012).

2.5 Standard Methods to Evaluate Fruit Maturity

2.5.1 Destructive Methods

Traditionally, measuring the quality attributes of kiwifruit requires destructive methods like DM (slicing) and SSC (squeezing juice from the fruit).

2.5.2 Dry Matter

Figure 9 shows a standard Hayward kiwifruit, showing the ratio between kiwifruit's DM and water percentage. A standard common procedure used in industry involves measuring the DM by slicing two 3 – 5 mm thick equatorial slices and proceeding to dry them (figure 10) at 65°C for 24 hours. The dry matter fruit was calculated from the final dry weight and initial wet weight of these slices. To then be recorded as a percentage of fresh weight. Dry matter at harvest is used to indicate the SSC when ripe under a range of harvest maturities and supply chain management conditions (Zespri, 2008).



Figure 9. Composition of a kiwifruit with a DM of 17% (Zespri, 2008).



Figure 10. Dehydrator used for DM experiments (Sunbeam Food Dehydrator – DT5600, 2022)

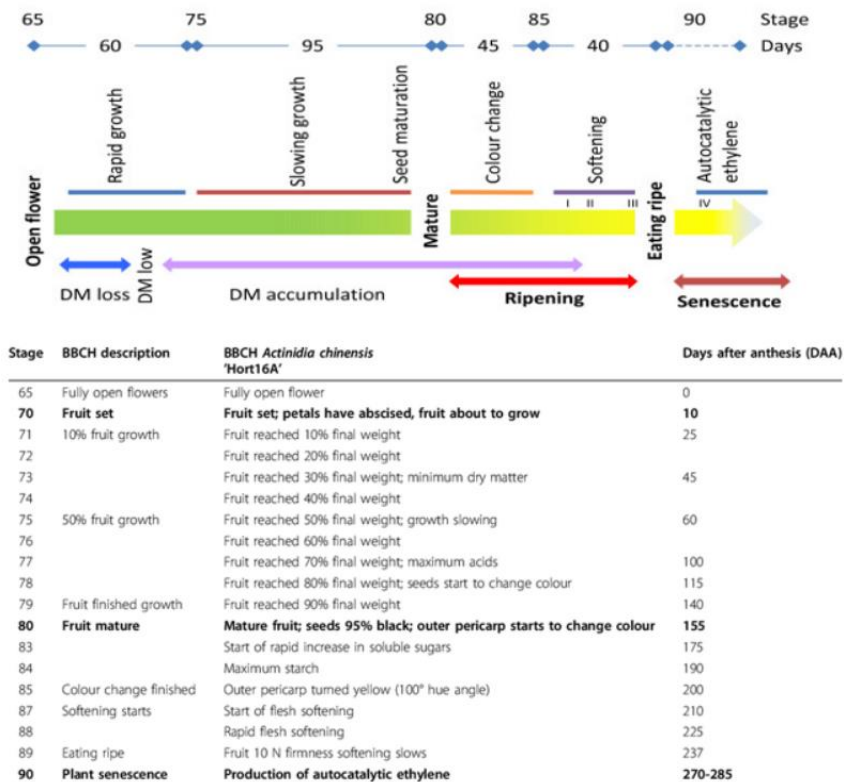


Figure 11. Different phases of kiwifruit (Richardson, A.C. et al., 2011).

Kiwifruit accumulates dry matter while the fruit is on the vine, once picked accumulation begins to cease. As seen in figure 11 above, there is DM loss in the initial stages of flower opening where rapid growth occurs. As the fruit starts to grow (stage 71) DM starts to accumulate. As the kiwifruit reaches 30% final weight, minimum DM is attained. In stage 80, fruit matures with seeds 95% black and the outer pericarp starts to change colour. Internally there is a rapid increase in soluble sugars and maximum starch is attained. At stage 87, the kiwifruit flesh starts to soften progressively.

2.5.3 Soluble Solids Content

There are two common methods used for SSC, one is where juice drops are taken from both the stem and blossom end. While the other involves taking juice drops from the centre of the kiwifruit. In a paper by Zespri (2008), it illustrates how to cut both the stem and blossom end at a distance of 15 mm in from each end (figure 12). During the SSC method, it is important to ensure the fruit is dry as any presence of moisture may mix and dilute the fruit juice and lower the readings.

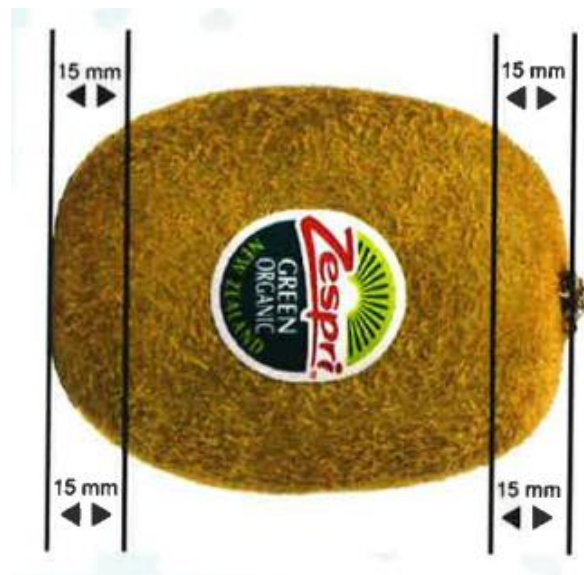


Figure 12. *Kiwifruit dissection for SSC measurements, (Zespri, 2008).*

The two different methods may provide slightly different readings, thus, once one method is chosen it will be used throughout the project to maintain consistency.

2.5.4 Non-Destructive Methods

The kiwifruit industry consistently requires DM and SSC measurements to ensure the fruit is at consumers acceptability. These measurements are commonly destructive, with dry matter traditionally requiring the fruit to be sliced and dried. While SSC traditionally requires the fruit to be cut and squeezed for a refractometer to identify the brix %. All destructive measurements are very time consuming while also altering or damaging the fruit, this is a problem as the fruit cannot be sold. Thus, there has been a shift, with many recent studies researching non-destructive methods for obtaining DM and SSC.

Current literature for kiwifruit has shown that the following non-destructive methods used to estimate SSC and DM are:

- NIR (Near-infrared spectroscopy)
- NMR (Nuclear magnetic resonance spectroscopy)
- Density
- Dielectric power spectroscopy (DS)
- Acoustic impulse resonance frequency
- Hyperspectral Imaging (HSI)

Among the above non-destructive methods, the majority of research is surrounding NIR with variations of handheld ultra-compact NIR, Vis/NIR and FT-NIR. NIR spectroscopy is tested to identify whether post-harvest ripeness and physicochemical properties of kiwifruit could be determined non-destructively.

NIR is based on the absorption of electromagnetic radiation at wavelengths in the range of 780 to 2,500 nm. The light interacts with the sample and the detection measures its transmittance and absorbance. Absorbance is a measurement of light that is absorbed by the sample. The sample is illuminated with a spectrum of near infrared light, which can be absorbed, transmitted, reflected, or scattered by the sample. Models for predicting firmness, dry matter and soluble solids content were developed from NIR interactome measurements using a narrow spectral range from 800 – 1100 nm. Both DM and SSC could be predicted with very good accuracy.

Previous research has provided relevant information that NIR and density (submergence) measurements can be used to predict kiwifruit parameters like dry matter and SSC. For the industry, this research provides the possibility for fast on-line grading for consumers' taste preference.

McGlone, A., et al. (2002) used a NIR method using a specially developed laboratory system which contained a wide band light source, fruit holder and a non-scanning polychromatic/diode array spectrometer. Kiwifruit were placed upon the fruit holder with stem calyx axis horizontal, with irradiation from light source below. Similar to three-dimensional scanning. The light entered the fruit through exposed regions of the kiwifruit flesh.

To digitise and amplify the spectral signal a 15-bit ADC electronics was used, alongside a PC running software for the data acquisition and spectra storage. The kiwifruit were measured in 10 batches with a separate reference and dark current spectrum recorded prior to each batch. A 41 teflon block placed above the fruit holder was recorded as the reference spectrum. While the dark current spectrum used a recording of a steel ball covering the fruit holder – preventing light from reaching the sensor. Each kiwifruit required two separate spectral measurements on opposing sides of the median equator. When converted to relative spectra, the two measurements were averaged, providing a mean spectrum for each kiwifruit. Limitations of NIR are the specific lighting conditions required, accurate calibration and the orientation of the kiwifruit. It is also costly and may not be feasible for implementing on an industrial scale.

Nuclear magnetic resonance (NMR) has been investigated (Wang, D, et al., (2021)) for the rapid determination of fruit and vegetable quality. It has shown potential for evaluating firmness and juiciness of apples and SSC in apples and strawberries. Method for NMR involves using a Maran Benchtop Pulsed NMR Analyzer (Resonance Instruments, Witney, UK) operating at 23.2 MHz and equipped with an 18 mm variable temperature probe, using a CPMG sequence. NMR has been noted for its ability to probe water state and dynamics in food. For apples, this information provides how it may be affected by pre- or postharvest treatments. In a study by Wang, D, et al., (2021), the NMR results were found to be in agreement with previous research conducted. Results obtained by Jordan, R. B. et al., (2000) reveal that NIR is a superior method in comparison to NMR. With NIR showing a correlation of 80-82% variation in the prediction of DM and SSC. NMR only explains 50-58%.

Hyperspectral Imaging (HSI) application and research has experienced major growth and application in diverse fields. HSI has more than 100 bands, providing a wide range of spectral information. This technique combines spectroscopy and conventional imaging to obtain both spatial and spectral information. A hyperspectral image (also known as a hypercube) visualizes the biochemical constituents of a sample. Zhu, H., et al. (2017) identified the feasibility of HSI in the Vis/NIR spectral region of 380 – 1023 nm. The firmness and SSC attributes of a kiwifruit were better predicted in the spectral range between 450 – 1100 nm (Zhu, H., et al. 2017). Acoustic impulse resonance frequency measures the firmness in relation to the elastic properties of the fruit. The acoustic impulse has a drawback compared with HIS as it requires the spectral data from a single point. While, HSI has advantages of receiving spatially distributed spectral responses at each pixel of the fruit image. Zhu, H., et al. (2017) also identified that a key step in the HSI methodology is monitoring the position and size of ROIs. As it may have an influence on the overall HIS result.

A study conducted by Fazayeli, A., et al. (2019) noted that Dielectric Power Spectroscopy (DS) is a technique for analysing molecular dynamics. DS determines the dielectric properties to observe the electrical response when the current passes through the material. It assesses the dielectric constant and dielectric loss which provides information on the kiwifruits ability to store and discharge electrical energy. It is low cost and can predict some physicochemical indices of kiwifruit during storage. Research by Fazayeli, A., et al. (2019) identified that this technique has the capability to predict firmness with a R^2 value of 0.92. However according to Novas, N., et al (2023) some limitations include its complexity in being implemented in packhouses and its easily influenced by external factors like probes altitude, size of beaker and the amount of water under which the calibration has been performed. It also has high energy consumption.

For years, the density of fruit has been used to estimate their DM, SSC, maturity, defects and quality. Helping to grade the fruit. Kiwifruit density measured at harvest is positively correlated with DM and SSC of ripe fruit. Alongside this, an important relationship identified is shown between consumer acceptability and both DM and ripe SSC. Due to the relationship between DM and ripe SSC, DM is a target parameter for NIR. An alternative method like density, allows for assessing the kiwifruit non-destructively. Fruit density can be used to assess these parameters due to major components - sugar

and starch. These components have similar densities and are greater than the density of water. Therefore, fruit density is higher for those with more solids.

At harvest, the majority of the kiwifruit's carbohydrate is starch which hydrolyses to sugars upon ripening. Requiring methods to estimate potential SSC at harvest. Due to the variation in individual kiwifruit, it is difficult to quantitatively follow the changes in composition, DM and ripening times. Using density potentially allows individual fruit with vastly different DMs to be assessed during development and storage.

Density of the fruit measured by Jordan, R. B. et al., (2000) was based on the Archimedes principle using an apparatus purpose built for the volumetric measurement of the fruit by full submergence in 5L of clean tap water. The fruit were pre-submerged, prior to being submerged in the apparatus. This was done to help in minimising air bubbles on the surface of the fruit during the submergence density being recorded. Suitable procedures and corrections were used throughout the methodology - volume of suspension apparatus, fruit and water temperatures.

2.6 Methods to Evaluate Volume and Density

In the kiwifruit industry there have been standard methods developed and used throughout the years. With growing trends in high quality produce and products for consumers, methods are continually being developed to keep up with the growing trends. Emphasising the efficiency and predictability of fruit quality. In this case, to determine kiwifruit quality the main methods used include dry matter, soluble solids content, submerged volume/density and digital volume/density. These involve both destructive and non-destructive techniques. The digital volume and density is a new novel technique using a 3D scanner to build a 3D version of the kiwifruit. This non-destructive technique opens many new viable opportunities for the industry.

2.6.1 Fruit Flotation

Non-destructive fruit volume estimation can be used as a ripeness index to predict optimum harvest time, yield or to study the relationship between fruit expansion rate and susceptibility to physiological disorders such as fruit softening. In a paper by Jordan, R. B. et al., (2000) , the volume was measured through the determination of buoyant force and water being displaced where volume is calculated from the object weight and the force. In the horticultural industry, the fruits and vegetables produced provide great variation in both size and dimensions. Commonly a digital calliper is used with 0.01mm accuracy alongside water displacement methodology. The displacement of water allows the volume of the fruit to be measured. With the density of water being 1g/cm³, the volume for each fruit is equal to the mass of water displaced when immersed into the water. The fruit volume and densities were then calculated using the following equation.

$$V_f = \frac{m_d}{\rho_w} \quad (\text{Eq 1.1})$$

Where,

V_f is the volume of the submerged solid of interest (mL)

m_d is mass of water displaced (g)

ρ_w is the density of water (g/L)

$$\rho_f = \frac{m_f}{V_f} \quad (\text{Eq 1.2})$$

Where,

ρ_f is the density of fruit (g/L)

V_f is the volume of the fruit (mL)

m_f is mass of the fruit (g)

2.6.2 Digital Volume (Three-Dimensional Scanning)

Three-dimensional scanners can simultaneously collect shape and colour data. A 3D scanned colour surface is called texture. Three-dimensional scans are compatible with CAD software and 3D printing. A 3D scan can give a lot of information about an object, in this case the digital volume and digital surface area of a kiwifruit. There are a range of categories in which 3D technologies fall into, some of these include laser triangulation, structural light, photogrammetry, contact-based 3D scanning technologies and laser pulse. In this research, the 3D scanner used (Shining 3D) in this research can be categorised into the photogrammetry 3D scanning technology (photography). Photogrammetry is the science of making measurements from photographs, especially for recovering the exact positions of surface points. Photogrammetry combines a mix of both computer vision and powerful computational geometric algorithms.

The principle of this technique is to analyse several photographs of a static subject, taken from different viewpoints and to automatically detect pixels correlating to a unique physical point.

Photogrammetry is the process of taking many photographs of an object from a variety of angles and stitching them together to create a 3D model. A standard digital camera can be used with specific software that detects overlapping patterns to build up a 3D reconstruction of the photographed object. Through comparing pixel colours and defining anchor points, photogrammetry software evaluates and creates 3D models of a vast majority of objects.

A benefit of this technique is the ability to provide realistic 3D models as the photographs translate to great materials and textures. Allowing you to create accurate digital twins. A downside is the difficulty to capture points that have a smooth, flat or solid-coloured surface as these objects have no visual pattern to detect.

Its main challenge is to examine tens or hundreds of photos and thousands of points with high accuracy. To run these intensive algorithms, a powerful computer is required. The main advantage is the acquisition speed (approximately 12 - 15 minutes for kiwifruit) and the ability to pick up colours and textures. This technology is also capable of reconstructing subjects at a large scale (using a drone). The resulting quality produced is dependent on the resolution of the input photographs. This technique can be quite slow, depending on your software and PC setup.

Photogrammetry works like aerial photography. The latter can be used to take images and get a general sense of typography. However, in contrast to aerial photography which contains positional errors, photogrammetry is more accurate when measuring distances, areas or direction.

2.7 Conclusion and Further Investigations

In conclusion, the literature review covered a range of research from the kiwifruit industry, exportation, production, supply chain and consumer acceptance to kiwifruit botany and morphology, kiwifruit maturation and ripening. The standard methods to determine fruit density and methods to determine volume and density were also researched and relevant literature obtained. The importance of this research is linked back to the increasing difficulty of sorting and grading fruit while being labour intensive in a changing, technology driven generation.

With recent advances in imaging technologies, it is now feasible to measure volume accurately and non-destructively and therefore the density. A focus of this project is to assess the industrial opportunity for the exploitation of imaging technologies as a means of determining the important parameters of DM and SSC. With the rise in technology being implemented into the horticulture sector to create a more efficient system and less waste, a range of new methods were identified in the literature. From NIR, NMR, dielectric power spectroscopy and acoustic impulse resonance frequency. NIR was found to be superior to NMR, showing a correlation of 80 – 82% variation in the prediction of DM and SSC. While NMR showed a correlation around 50%. At present NIR and physical drying are the most common methods for determining DM and are competitors of the digital scanning method. However, physical drying is destructive and time consuming while NIR is non-destructive, but the accuracy is affected by light conditions, orientation of the fruit and calibration quality. In addition, NIR is an expensive method.

The industrial opportunity and motivation for this research project is to assess the potential for fast on-line grading in the packhouses to meet the consumer demands and ensure the growers pick at the optimal harvest time. There is opportunity that digital density will offer a method with less waste and higher efficiency while retaining the premium quality of the kiwifruit.

Chapter 3: Materials & Methodology

3.1. Fruit material and experimental design

This project used multiple methods to obtain approximate maturity and fruit quality data across a wide range of *Actinidia chinensis* (Planch) – three cultivars from three different growers, with eight different count sizes. The main methods used to determine maturity indicators include soluble solids content, dry matter, 3D scanning and submerged volume determination.



Figure 13. Layout of the 25 Cell Trays. (G1 = Grower 1, C1 = Count size 1).

Figure 13 above shows the tray of 25 count size which was used for all the kiwifruit measured. Each 25 cell tray was labelled like figure 13, to balance the number of growers and count sizes evaluated each

day. Consequently, giving each day the same number of growers and sizes to evaluate. This design was implemented to block the variability given by storage time. To understand the labelling on the tray, the following examples are important to note: G1.C1 (Grower 1, Count Size 1), G2.C1 (Grower 2, Count Size 1), G3, C1 (Grower 3, Count Size 1), G2.C1 (Grower 2, Count Size 2) etc.

‘RubyRed’, ‘SunGold’ and ‘Hayward’ kiwifruit cultivars were used in the duration of this project. All the *Actinidia chinensis* (Planch) varieties were sourced from Zespri, Bay of Plenty region, to the Massey University Postharvest lab. Fruit were collected by the MAF team and I, at harvest and stored in trays into the refrigerated container at 1 °C to maintain harvest maturity and extend the storage life.

Fruit Material

Each *Actinidia chinensis* (Planch) variety was sourced from 3 different growers with 8 different count sizes (25, 27, 30, 33, 36, 39, 42, 49) to provide suitable coverage across fruit size and grower line, and facilitate investigation of the potential effects of these variables on non-destructive measures. This will give insight to any variability between grower lines, to understand if the different growing conditions influence the density and DM measurements.

Table 1. Summary table of kiwifruit information used in the measurements.

RubyRed				
Date of Arrival	Grower	KPIN	Count Sizes For Each Grower	Fruit Total
11/03/2021	1	27844	25, 27, 30, 33, 36, 39, 42, 49	312
11/03/2021	2	48785		
11/03/2021	3	7829E		
SunGold				
Date of Arrival	Grower	KPIN	Count Sizes For Each Grower	Fruit Total
28/04/2021	1	40265	18, 22, 25, 27, 30, 33, 36, 39	312
28/04/2021	2	77543		
28/04/2021	3	79303		
Hayward				
Date of Arrival	Grower	KPIN	Count Sizes For Each Grower	Fruit Total
26/05/2021	1	18966	18, 22, 25, 27, 30, 33, 36, 39	312
26/05/2021	2	32153		
26/05/2021	3	74595		

Before data collection started, 312 fruits from each cultivar were sorted into trays (See figure 13). This was conducted by placing a count size from each grower into the trays making up a total of 24 fruit per

tray. There were 13 randomised trays produced for each of the cultivars with an additional tray each for backup or further investigation. It took 4 - 7 weeks to finish measurements for both 'SunGold' and 'RubyRed'. To overcome changes in DM due to water loss during the weeks of measurements, the trays were stored in polyliners and placed in a refrigerated container to mitigate water loss and changes in DM. Mitigating changes in DM will allow for measurements resulting in higher accuracy.

Due to COVID-19, experiments for the 'Hayward' cultivar were extended by a further 6 - 8 weeks due to limited access to the lab. During this extended time, the 'Hayward' kiwifruit cultivars were kept in the refrigerator container to delay the ripening process and metabolism of the harvest maturity.

3.2 Non-Destructive Methods

3.2.1 Fruit Mass

The mass of all kiwifruits were measured at room temperature (approximately 20°C), both on arrival and on the day of experimental evaluation using a digital balance (PG503, Mettler Toledo, Palmerston North, New Zealand). The mass of kiwifruits measured on the day of the experimental evaluation, had the kiwifruit tray removed from the refrigerator storage the day before. To then measure the mass at room temperature on the day of measurements. The measurement on the day of experimental evaluation served as input for the calculation of density and the difference between this and the arrival mass served to quantify a mass loss during storage. Tracking the mass loss was important, as it allowed to observe potential water loss and understand the potential influence it may have on the experimental results. Water loss directly influences the DM, which would affect the resulting density of the kiwifruit.

3.2.2 Three-Dimensional Scanning Method

Preliminary Trials

Before experimental trials were conducted, preliminary trials were done with spare kiwifruit to understand the best methods of approach for 3D scanning (SHINING 3D, Hangzhou, China). and volume-submergence. Preliminary trials for the 3D scanner involved learning how it worked with different kiwi fruit shapes, the base to which the fruit was held in place, reflectance of the base and fruit, turntable count and calibration.

Three different bases (a black bolt, blue milk bottle lid and a constructed small transparent cup) were trialled for holding the kiwifruit in place while scanning was conducted. This was an essential part of executing a successful 3D measurement. A successful base allowed for kiwifruits of ranging sizes and shapes to be held in place avoiding imbalanced movements during the turntable rotations. Thus, quality images could be taken of the kiwifruit at multiple angles.

The black bolt was not picked up in the scanning images due to its low reflectance, this was ideal as only images of the kiwifruit were being picked up. However, the black bolt base was not able to hold larger kiwifruits in place so was not used for the experimental trials. The blue milk lid was able to hold bigger kiwifruits in place but due to its colour, the scanning images incorporated the lid into the kiwifruit shape, causing irregularities. The makeshift transparent cup provided a stable base for various kiwifruit shapes and sizes and did not get merged into the kiwifruit scans. Hence, the transparent plastic cup of 300 mm³ was selected for the experimental trials. It was also identified that two batches of 8 turns was sufficient for capturing high quality 3D images of each kiwifruit while being time efficient.



Figure 14. *Kiwifruit being scanned by the SHINING 3D using a black plastic base (one of the bases trialled for experiments).*

Data collection procedures

All three-dimensional scans collected in this work were captured using the EinScan-SP (SHINING 3D, Hangzhou, China). The scanner is a structured light scanner which infers the three-dimensional structure of scanned objects via the observed deformation of light patterns projected on the surface of the object of interest. After the custom script, relevant values are produced for the important parameters (e.g. Volume, Surface area). Which were used in equation 2.1, to produce the resulting digital densities. The digital volume and density for the different cultivars are compared with the traditional submerged

volume and density. With other comparisons made between DM, SSC and between the different cultivars. The steps taken to collect a single scan are illustrated in **Figure 15** and described in detail below. The estimates time required for this process ranged between 12 – 20 minutes depending on kiwifruit shape, colour and size. Oblong flat shaped kiwifruits required more images to be taken, and thus the process below took more time.

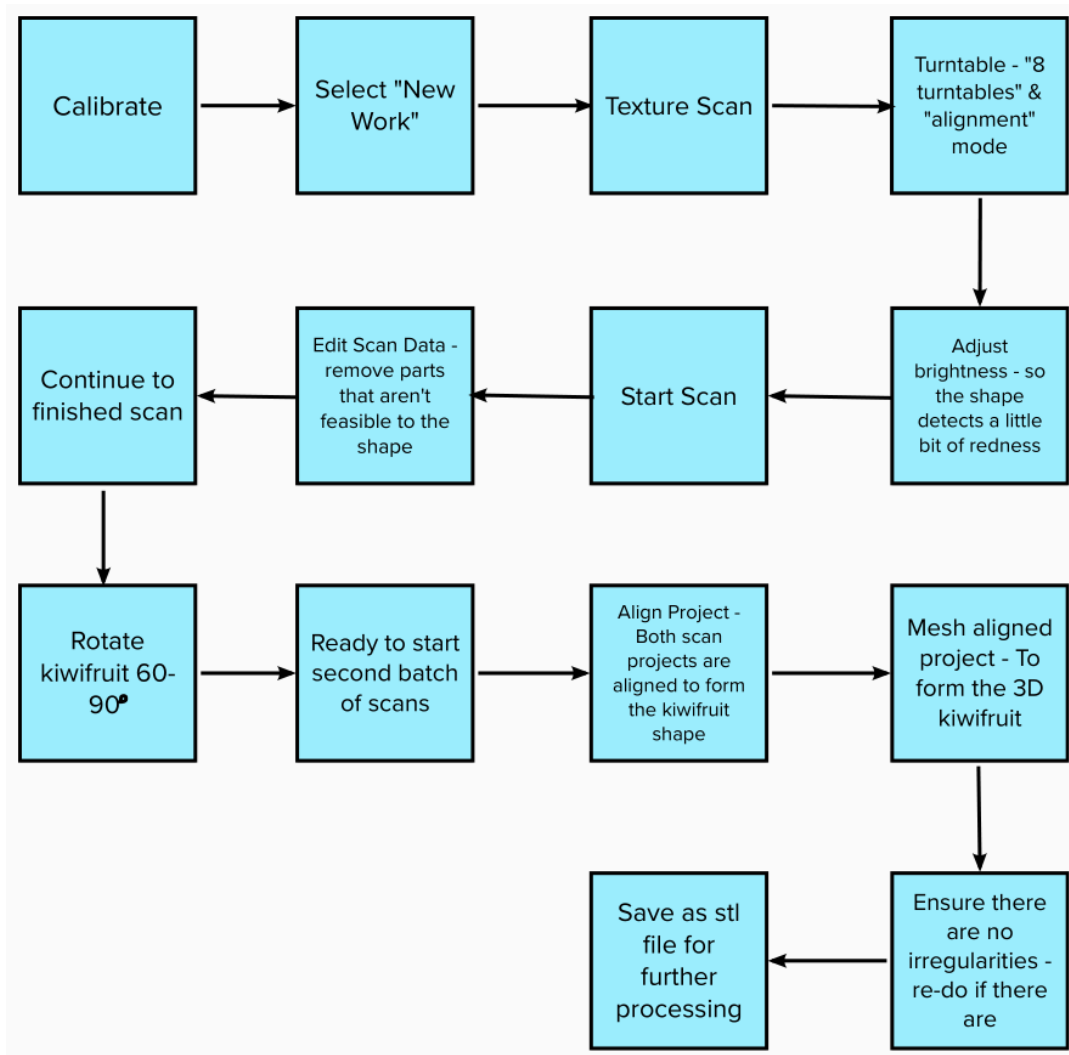


Figure 15. *Process Flow Diagram of 3D Scanning Technique.*

1. Calibration of 3D Scanner

Before starting the scans, it's essential to calibrate the scanner to get accurate scan results. This was done by following the calibration steps that the scanner software provides. This entails using the

calibration kit (e.g. black support board with white dots) provided with the scanner. **Figure 16** below shows the setup required to start the calibration process. The calibration support and board are placed in the centre of the turntable. The patterned dots will light up as red on the computer screen, showing that it is in the correct position and ready to be scanned. The board is then rotated 90 degrees and placed back on the support for further scanning. This is repeated multiple times with the dots in different positions. A white piece of paper is then used for further calibration (white balance test) before the software automatically calculates and archives the current conditions. In the case of failed calibration, it's important to re-calibrate following the same steps.

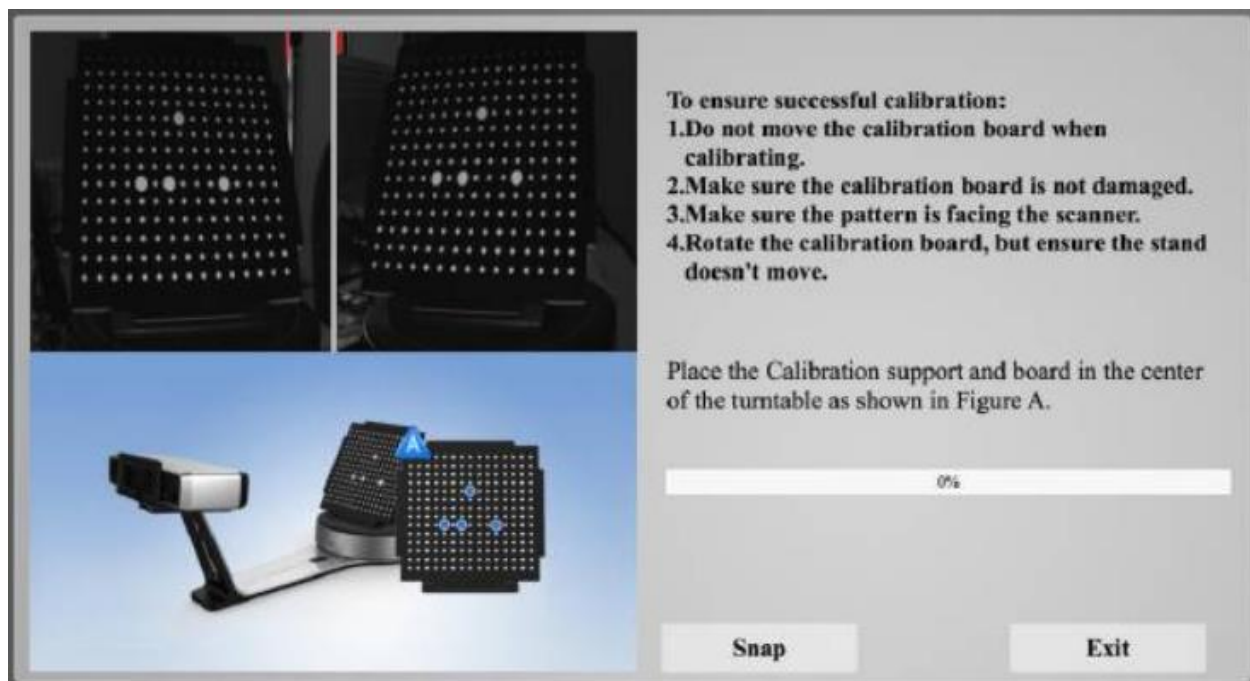


Figure 16. Software showing calibration setup.

2. New Work

Selecting “New Project”, allows you to enter the project name, making it easier to locate files and saved data. Especially with so much data being saved and accumulated over the experimental period. It is essential to save under files that make coherent order for later data analysis.

3. Texture Scan

To capture the colour pattern of the kiwifruits surface.

4. Turntable

Without the turntable option, only a single piece of data will be produced. From preliminary trial scans it was determined that 8 turntables with 2 different rotations of the kiwifruit was optimal. These set parameters will provide a proficient amount of scan while being time efficient for the scope of the project.

5. Brightness

It is important to maintain the same brightness for each of the scans to get consistent results. Through preliminary test scans, it was identified that the ideal brightness is when there is slight redness captured on the fruit. Usually around bar 3 on the brightness scale.

6. Start Scan

Click the “start” arrow button to initiate scanning. The turntable will start rotating so more scans are being captured and collected.

7. Edit Scan

Finished scan is then presented, often parts of the background were scanned and incorporated in the end scan. These parts require editing to remove the excess scans, so the final shape is not corrupted.

8. Finish First Scan Batch

The first 8 scans are completed.

9. Rotate

The kiwifruit is then rotated between 60 - 90 degrees. Providing a different angle of the fruit to be scanned. Ultimately forming the optimal 3D version of the fruit.

10. Start Second Scan Batch

Click the “start” arrow button to initiate scanning. The turntable will start rotating so the second batch of scans are being captured and collected.

11. Align Project

Once both batches of scans are edited and finished, they need to be aligned to form the 3D kiwifruit shape.

12. Mesh

The aligned two batches of scans are then meshed to form the 3D version of the kiwifruit.

13. Checking

Double check the mesh worked. If not, re-align and re-mesh the kiwifruit.

14. Save As

Ensure each meshed kiwifruit is saved with an appropriate and findable file name. Save in the form as an stl file (stereolithography) which has the ability to stored information about 3D models and an object file to get a 3D image of the kiwifruit.

15. Volume and surface area calculation

The volume and surface area of each kiwifruit scan was determined from the .stl files using a custom script written in python (included in appendix 7.1) and executed in the 3D modelling and rendering software, Blender 2.79b (Blender Foundation, Amsterdam) which provides inbuilt functions for the calculation of these parameters. The accuracy of this digital determination of volume and surface area was further investigated in an experiment described in section 3.5 Validation of this work.

Blender provides the freedom to create and is licensed as GNU GPL, owned by its contributors. Thus, it will always be a free and open software. It supports the entirety of the 3D pipeline, from modelling, rigging, animation, simulation, rendering, composition, and motion tracking. Blender's API is used for python scripting to customise the application and write specialised tools.

Having determined the volume of each kiwifruit, their density was calculated according to the following equation,

$$\rho_f = \frac{m_f}{V_f} \quad (\text{Eq.2.1})$$

Where,

ρ_f is the density of fruit (g/L)

V_f is the volume of the fruit (mL)

m_f is mass of the fruit (g)

The 3D Shining Optical Scanner is utilised to obtain multiple 3D images (8s per scan speed) of the kiwifruit. The camera (with 1.3 Mega Pixels) is placed directly facing the position in which the kiwifruit will sit. The majority of the scanner was covered to maintain consistent lighting. Each kiwifruit was placed at approximately the centre of the field of view of the imaging system. Fruit were placed on top of the transparent cap to hold them at a good height while keeping the fruit stationary throughout the rotations. The turntables were set to 8, allowing for multiple images to be taken of the different kiwifruit faces. After the first set of 8 turns, the fruit is rotated between an angle and then undergoes another 8 turns. Allowing for more of the kiwifruit to be captured. This provides a more efficient depiction of the kiwifruit and thus an increased accuracy in results.

Before destructive experiments were conducted, each kiwifruit was scanned for the digital volume and surface area, determined from the .stl files generated (meshed kiwifruit. stl, figure 17 below). A typical scan for a kiwifruit can be seen in Figure 17 beside the actual kiwifruit.



Figure 17. *Meshed kiwifruit .stl file.*

With the actual kiwifruit side by side with the digital version using the software, they were observed to be quite similar. This was a common result when conducting the 3D scans on all the kiwifruit. The actual and digital often looked very similar, with a few scans showing odd results. Indicating for a re-scan to be done.

3.2.2 Submergence volume and density measurement

Preliminary trials for volume submergence involved creating a valid set-up to obtain efficient data of the submerged kiwifruits. A metal wire was used to create a wire net (refer to draft drawing in Figure 18) attached to a clamp stand for when the kiwifruits are submerged, preventing the fruit from touching any parts of the jar. Enabling the volume of the kiwifruit to be accurately recorded. It is important to note that this measurement was conducted following the completion of 3D scanning of the kiwifruit.



Figure 18. *Draft drawing to create metal wire net, capturing the kiwifruit.*

3.2.2.1 Submergence Volume-based Method

The volume of fruit was measured using the gravimetric displacement method which utilises Archimedes principle. This method is simple and well suited to the measurement of the volume of irregular solids (Burdett, 1979).

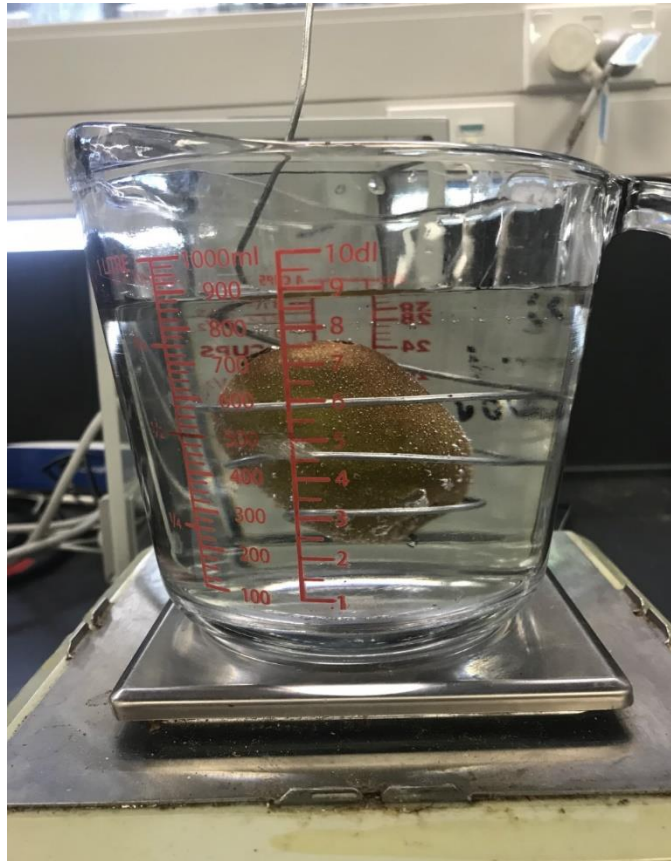


Figure 19. *Submerged kiwifruit captured underneath the water by the metal wire.*

The setup includes a 1L glass jar filled with water up to 800 mL, corroborated by weight when placed onto a balance. A wire net attached to a clamp stand resting on the adjacent benchtop is submerged below the water surface and the balance zeroed. At this point any object, such as kiwifruit, which is placed in the wire basket and submerged will result in the scale reading a mass which is equal to the volume of water displaced. Therefore, if the density of water is known, the volume of the submerged object can be calculated as,

$$v_f = \frac{m_d}{\rho_w} \quad (\text{Eq. 2.1.})$$

Where,

V_f is the volume of the submerged solid of interest (mL)

m_d is mass of water displaced (g)

ρ_w is the density of water (g/L)

Since the measurements in this work were carried out in a laboratory temperature controlled at 20 °C, at which the density of water is ~1 g/mL, the volume of the submerged object in mL can be taken as the direct reading of the balance in grams, and this simplification was made in this work. The kiwifruit flesh temperature was also 20 °C.

Immediately prior to volume measurement, the surface of kiwifruit were wetted to minimise the effect of air bubbles which can add experimental error when present on the surface. This was achieved by submerging fruit in a separate jug filled with water for a period of one minute. Upon removal from the wetting jug, the fruit were submerged in the glass jug located on the balance and the mass of the water displaced was recorded prior to the kiwifruit being removed and placed onto a paper towel for drying. This procedure was repeated for all kiwifruit.

Having determined the volume of each kiwifruit, their density was calculated according to the previously presented equation 2.1, with the only difference being that the volume determined by submergence was used instead of the digitally determined volume.

3.3 Destructive Methods

3.3.1 Total Soluble Solids Content (SSC) Method

Prior to measuring the total soluble solids content (SSC), each fruit was submerged in the glass jug located on the balance and the mass of the water displaced was recorded prior to the kiwifruit being removed and then dabbed dry with two paper towels and placed back into the correct position in the kiwifruit 25 cell tray. The SSC measurement was conducted 1 hour (drying time at 20 °C) after the kiwifruit had been submerged for volume calculation.

The SSC of each kiwifruit was recorded using a digital refractometer (Atago, Japan, Palette PR-32 α). Each kiwifruit was sliced at both the blossom and stem end (see Figure 20) to extract 3-4 drops from each end for the SSC reading (Li et al., 2015). It is important to be careful to not allow seeds, hairs or any other foreign material from entering the juice being measured as it may alter the readings. At the beginning of the SSC experiments, the refractometer needs to be calibrated using distilled water to obtain a reading of 0 %.

The recording was taken based on the light reflectance and direction change when entering the kiwifruit juice. The refractometer measures the degree to which the light changes direction, called the angle of refraction. This was carried out for all three cultivars. Although it is common in other studies to use the equatorial fruit portion for the assessment of SCC (Sfakiotakis et al., 2003), in this work the equatorial portion will be used for the estimation of dry matter. Therefore, the stem and blossom ends were used for SCC measurements.



Figure 20. *Refractometer recording SSC from the kiwifruit liquid.*

3.3.2 Dry Matter (DM) Method

As DM is an important parameter, duplicate measurements of the kiwifruit were conducted to increase accuracy of the DM results. DM methodology has variability within each kiwifruit depending on the amount of seeds present, slice width consistency, slice position (e.g. how close to blossom end the slice was extracted) and balance calibration settings. To try to mitigate all these variabilities, replicating the measurements for each kiwifruit aimed to produce more concise results.

This meant for the 24 kiwifruits being experimented on, 48 DM samples would be further analysed. Providing more results to assess the DM consistency and to evaluate any variance in the measurement. The duplicate measurements were also used to get a mean value between the two results produced. Providing an overall DM with slightly increased accuracy. So, when being used in correlation with other important parameters, the results are as concise as possible even with human error.

After SSC refractometer readings were taken of all the kiwifruits within the tray (24 kiwifruit), dry matter readings were then conducted in duplicate. Thus, all 48 (24 kiwifruit per tray layer duplicated) petri dishes were pre-weighed and placed onto two layers of the fruit dryer (figure 21). The kiwifruits were then sliced (5 mm, equatorial) from the blossom end and placed onto petri dishes and weighed to record the initial wet weight. The same kiwifruit was sliced again, using the same technique, and weighed to record a second wet weight. Replicate measurements were done for increased accuracy of the DM results.



Figure 21. SunGold DM after being in the fruit dehydrator for 16-24 hours.

Both tray layers (holding 48 petri dishes) were placed in the fruit dehydrator (Ultra FD1000 Digital Dehydrator, New Zealand) simultaneously which was set to 65 °C and left overnight for 16-24 hours. The petri dishes were then re-weighed to record the dry mass, which in conjunction with the initial wet mass was used to calculate the dry matter content as a percentage (Gullo et al., 2016; Lai et al., 2018) according to the following equation,

$$DM = \frac{DW-TW}{FW-TW} * 100 \quad (\text{Eq 2.3.})$$

where:

DW is the dry weight of the fruit slice and petri dish (g)

TW is the weight of petri dish (g)

FW is the fresh weight of the fruit slice and petri dish (g)

DM is the dry matter as a percentage of fresh weight (%)

3.4 Validation Method

A validation method provides data with information that allows data from experiments to be compared. It's important in ensuring that experimental results are valid. Method validation is a key element in the establishment of reference methods and to test the suitability of methods.

3.4.1 Sphere

A sphere-shaped object (pool ball in this case) was used due to its known volume. In this case, two different pool balls were used in different colours. The different colours reflect differently when being scanned, to get the best possible 3D scan of the sphere. However, neither of the balls allowed for efficient scanning, as the rotation would get mixed up and mesh the pool ball to form an odd-looking ball shape.



Figure 22. *Pool ball used as a sphere-shaped object for 3D scanner validation.*

3.4.2 3D printed Cube

Using a 3D printer (Creality 3D Printer Ender-3, China), a 5.0 cm by 5.0 cm cube was printed. Providing an object of known volume to be scanned by the 3D scanner. Multiple attempts were made to obtain a quality scan of the cube, however, due to the evenness of the object, it was hard for the scanner to differentiate between the different faces. So, when the different scans were meshed, an odd-looking cube was formed. So, another attempt was made with cornflour covering the different surfaces of the cube (figure 23). This improved the quality of the scans, as more of the surface was picked up by the scanner. However, meshing of the scans remained a problem with little differentiation between the different cube faces.

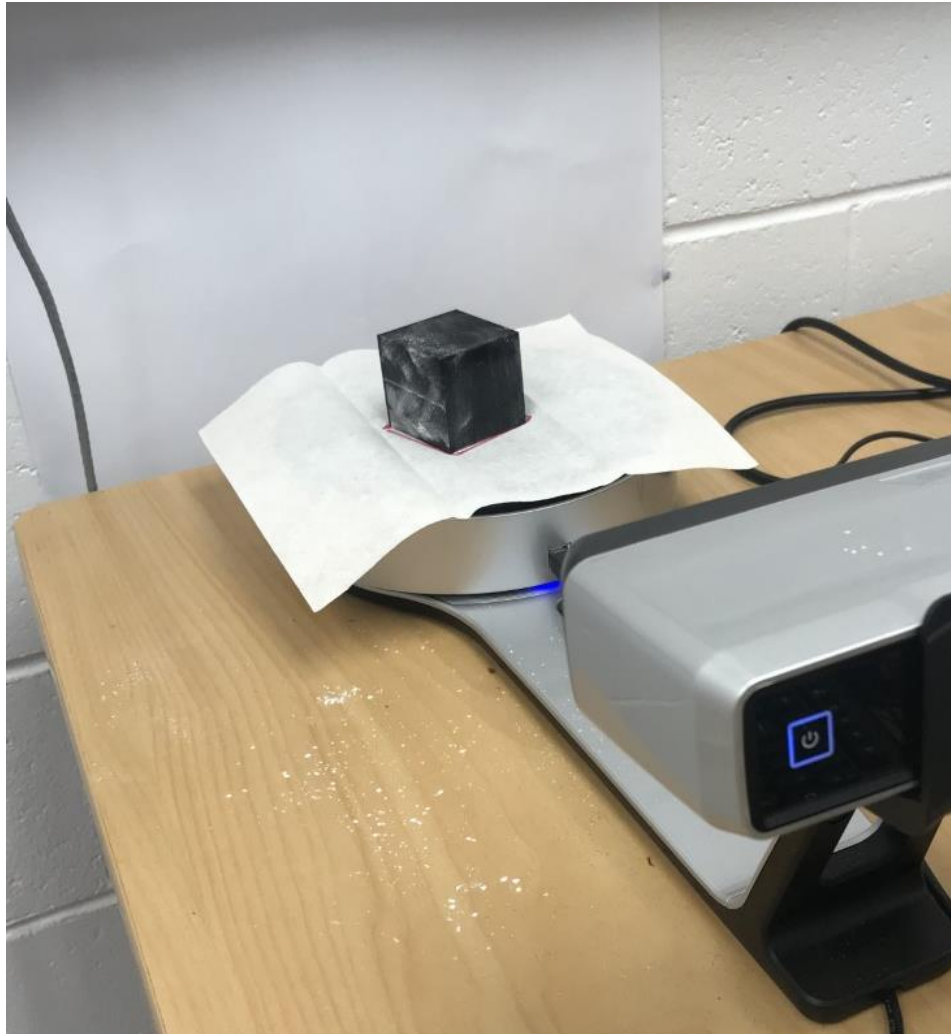


Figure 23. *3D scanning of 5.0 x 5.0 cm printed cube.*

The cube was then spray painted yellow, and green circular stickers were put onto the different faces of the cube. The yellow colour was picked up by the 3D scanner efficiently and the green dots helped to differentiate the different faces of the cube. Thus, when meshed, a cube was formed.

3.5 Validation

A validation method was conducted using the 3D scanner which will be used in further experiments on the kiwifruit. First, to validate this technology, a shape of known volume was used to prove that the 3D volume and surface area values are within the parameters of the known shapes volume and surface area values. It was decided that the ideal known shape to use was a cube, printed using a 3D printer from the Massey Agrifood Digital Labs. 3D printing the cube allowed for a chosen known length of 5 by

5cm to be used. This printed cube was then 3D scanned nine times to get averaged value for both the volume and surface area.

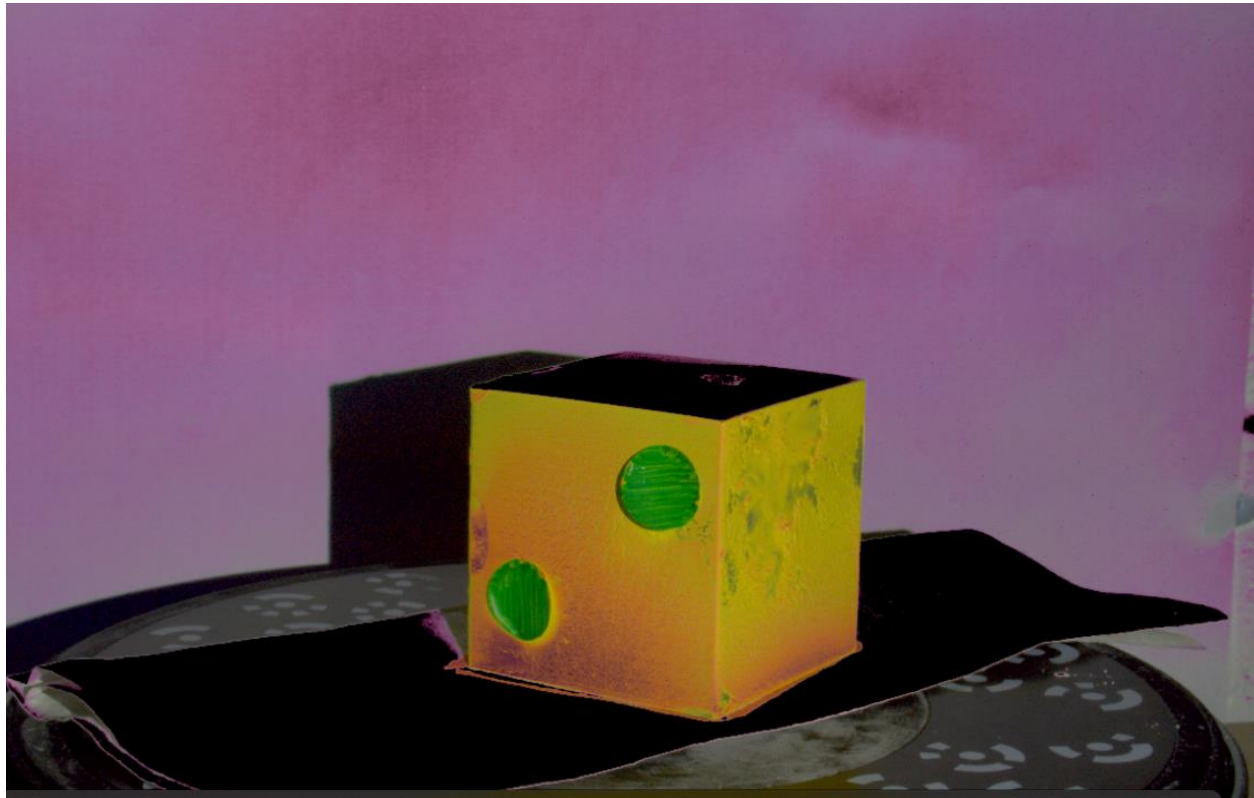


Figure 24. *Cube being scanned for the validation results.*

Figure 24 above shows one of the appropriate setups required for the scanner to capture images of the 3D printed cube. The base of the scanner is covered in patterned white dots and lines to help the scanner's orientation when capturing multiple images of the desired object. In this case, we added a paper base layer with a stencilled square. This was done to validate the consistency of the 3D scanner. Thus, when the first rotation of scans were completed, the cube was rotated to another side, and was to remain in the same spot. The stencilled square on the paper helped to keep the cube in the same spot, to maintain consistent images. Thus, when merging the different groups of scans, it's more cohesive rather than jumbled and mis-aligned. Around 19 images were captured with varying angles and faces of the cube. These images were then combined using the relevant software, to mesh into the 3D digital cube. This cube data will be used to compare and validate with kiwifruit data.

3.6. Data analysis

The raw data results were collected straight onto an excel spreadsheet. The following tools were used to both retain a large amount of data in a functional, accessible manner and to help analyse the data results.

Data analysis tools:

- Excel
- Graphs – Dot plots, line graphs, histograms.
- Linear regression
- Standard deviation
- T-tests
- Normality Test

These functions were used in conjunction to analyse the data points from the three cultivars. The techniques helped to show potential relationships between key parameters as well as potential unexpected correlations. Graphs were done for all cultivars and parameters. These were compared and observed for key findings and observations. Linear regression was used to predict the dependent variable using the independent variable. The analysis tools provided key insights and potential ways the data can be used for further research.

Linear regression was used in the modelling process for the different quality parameter modelling, especially density, DM and SSC. The raw volume, DM, SSC and mass measurements were used directly for the modelling. However, for the digital and submerged density measurements, calculations using the raw volume and mass data determined the density values for the modelling. The standard deviation for each modelling was used to measure the dispersed data in relation to the mean. T-tests were also conducted in the validation method to determine the upper and lower limits for density, to validate the elimination of outliers.

3.1.1 Preliminary Work

In figure 23 above, is an image taken of the cube in the process of being scanned. Many images were captured from the scanner, to build a digital version of the cube. The image shows the cube is brightly lit, and the yellow colour is being picked up well in contrast to the background. It can be seen that a base layer of paper is used to help centre the cube and keep it consistent throughout all the images.

Known Volume and Surface Area Values

a (cube length) = 5 cm

$$SA = 6a^2$$

$$SA = 6 \cdot 5^2$$

$$\text{Surface Area} = 150 \text{ cm}^2$$

$$V = a^3$$

$$V = 5^3$$

$$\text{Volume} = 125 \text{ cm}^3$$

3D Volume and Surface Area Values

The table 2 below shows the values obtained from the 3D scanner, showing the digital volume ranges between 121 and 123 cm³ giving an average volume value of 122.2 cm³ this is within 3 cm³ of the actual volume of 125 cm³. For the digital surface area the values range between 147 cm² and 149 cm² giving an average surface area of 148.9 cm². This is within 2 cm² of the actual surface area of 150 cm². These results show a good correlation between the digital and actual volume and surface area.

Table 2. 3D printed cube values.

Filename	Volume (ml)	Surface area (cm²)
3D cube1.stl	121.24	148.27
3D cube2.stl	122.00	148.59
3D cube3.stl	121.57	148.97
3D cube4.stl	122.01	147.81
3D cube5.stl	122.76	149.24
3D cube6.stl	121.51	148.89
3D cube7.stl	123.09	148.85
3D cube8.stl	123.08	149.82
3D cube9.stl	122.53	149.67
Average 3D cube	122.20	148.90
Actual cube	125	150

Table 3. Measurements of Actual 3D printed Cube (SA in cm² and Volume in mL).

Measurements of actual cube		
Volume (Measured)	SA (Measured)	Length (Measured)
123.21	148.56	49.76
122.84	148.27	49.71
127.42	151.93	50.32
127.04	151.62	50.27
124.93	149.94	49.99
126.05	150.84	50.14
125.23	150.18	50.03
125.38	150.3	50.05
126.43	151.14	50.19
124.7	149.76	49.96
126.05	150.84	50.14
126.13	150.9	50.15
125	150	50
126.66	151.32	50.22
121.8	147.43	49.57
122.02	147.61	49.6

Using the scanned measurements to compare against the actual measurements allowed T-tests to be performed, providing the following tables 2 and 3. These T-tests showed whether the difference

between the two groups were significant or not. The statistical significance is determined depending on whether the alpha (α) is below or above 5% (0.05). In Table 4 and Table 5, both show that they are statistically significant. Meaning the difference between the two groups is statistically significant.

Table 4. Volume T-test.

	<i>Variable 1 (Measured)</i>	<i>Variable 2 (Scanned)</i>
Mean	125.055625	122.1994211
Variance	3.03554625	0.481650502
Observations	16	9
Pooled Variance	2.147234686	
Hypothesized Mean Difference	0	
df	23	
t Stat	4.678005061	
P(T<=t) one-tail	5.19276E-05	
t Critical one-tail	1.713871528	
P(T<=t) two-tail	0.000103855	
t Critical two-tail	2.06865761	

Table 5. Surface Area T-test.

	<i>Variable 1 (Measured)</i>	<i>Variable 2 (Scanned)</i>
Mean	150.04	148.9016683
Variance	1.9436	0.403490892
Observations	16	9
Pooled Variance	1.407909875	
Hypothesized Mean Difference	0	
df	23	
t Stat	2.302463016	
P(T<=t) one-tail	0.01534899	
t Critical one-tail	1.713871528	
P(T<=t) two-tail	0.030697979	
t Critical two-tail	2.06865761	

Chapter 4: Results & Discussions

4.1 RubyRed Cultivar Results

Relationship between Surface Area, Mass and Volume

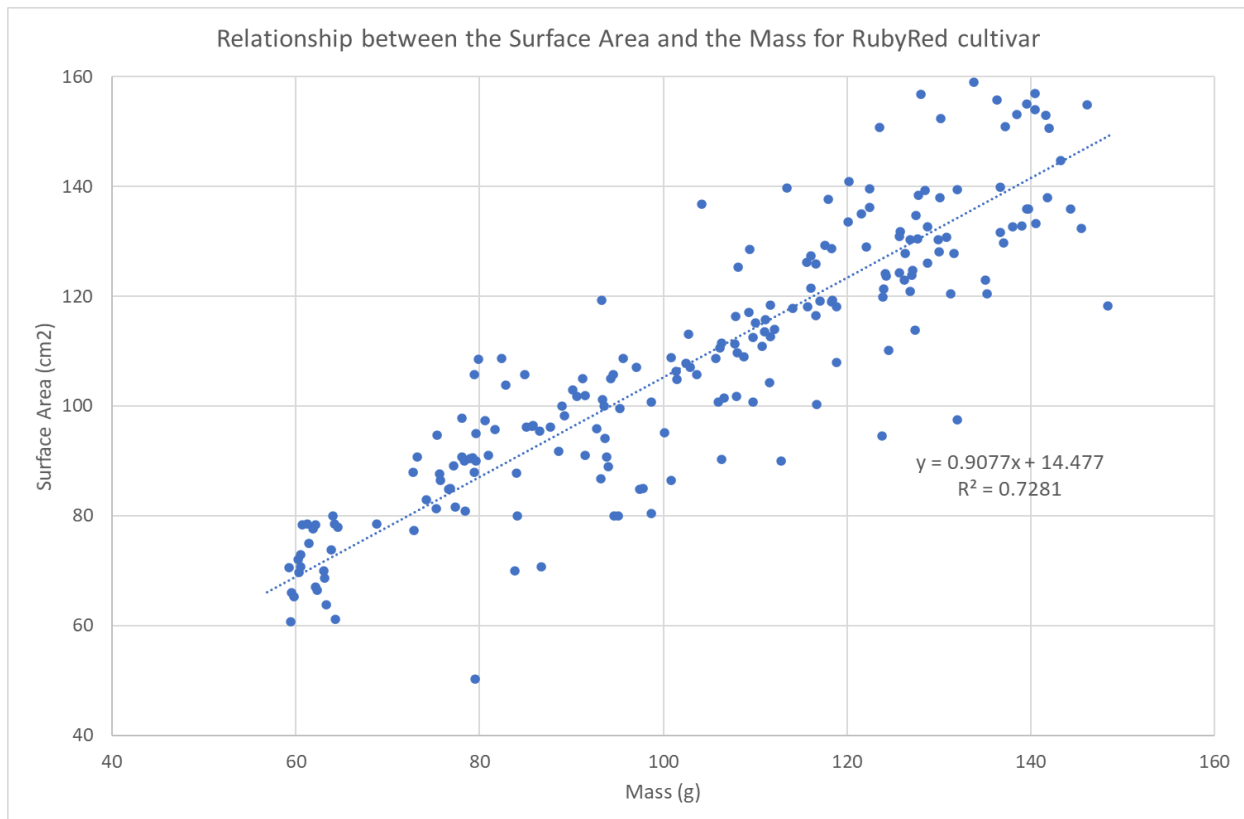


Figure 25. Graph representing the relationship between the surface area and mass for the RubyRed cultivar.

The positive correlation between the mass and surface area for RubyRed was to be expected, as the surface area of the RubyRed kiwifruit increases in value, it is assumed the mass will also increase. However, water loss could have an influence on the resulting mass. This would be more prominent in kiwifruits that have been kept for longer storage times or at temperatures higher than 0°C.

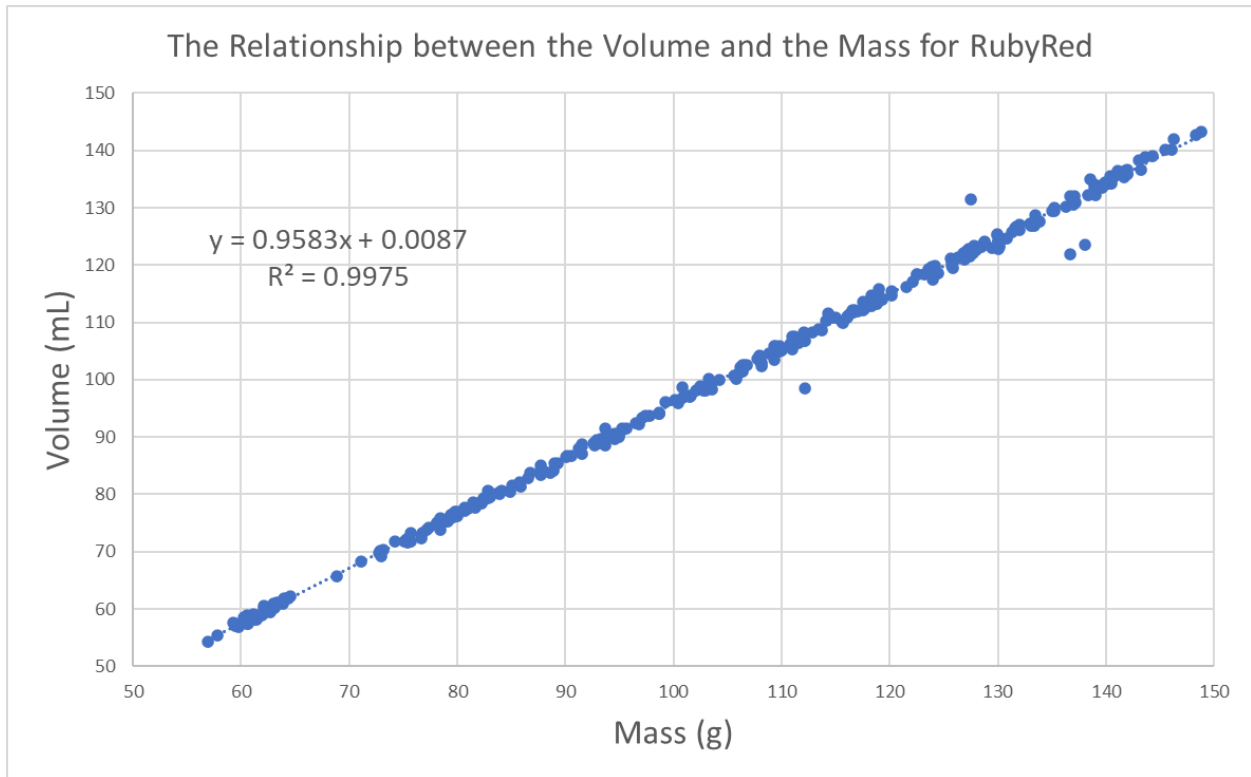


Figure 26. Graph representing the relationship between the volume and mass for RubyRed.

The above relationship between the mass and volume was to be expected. As the volume of the RubyRed kiwi fruit increases as does the mass. The majority of the data follows the line of best fit, where the R value shows that 99% of the data is being accounted for. Both the mass and volume can be used interchangeably. This is a very strong positive relationship.

Relationship between Submerged and Digital Volume

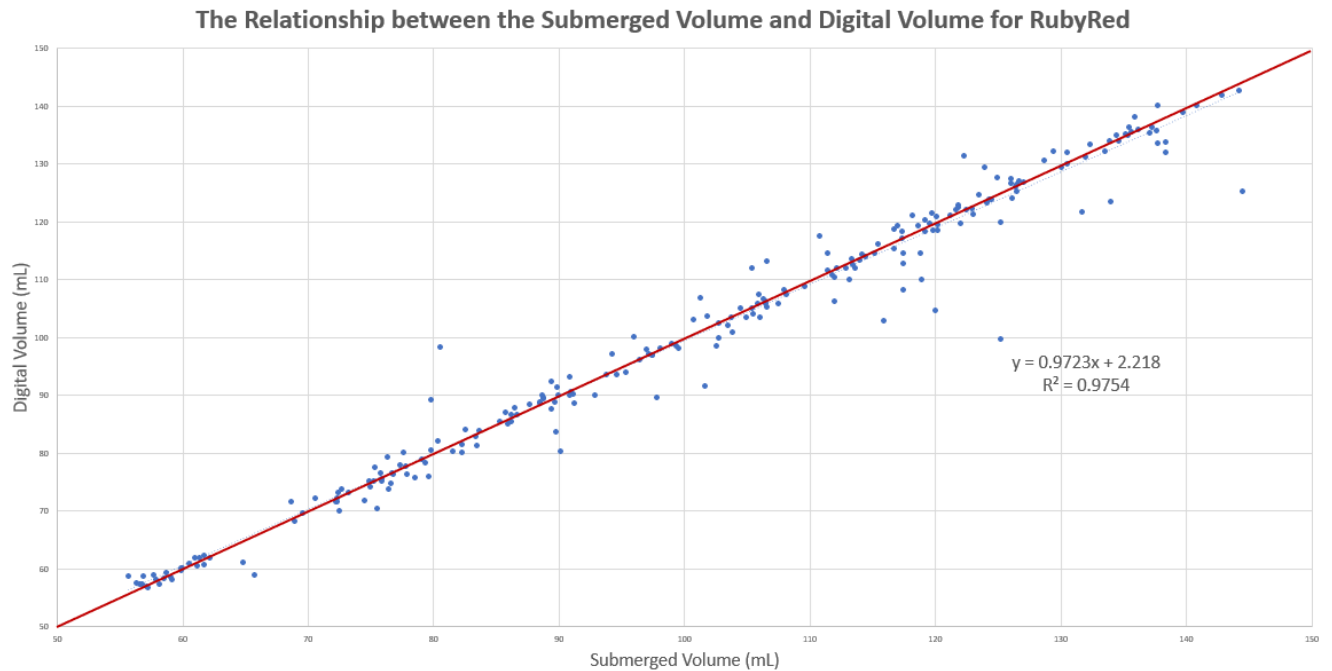


Figure 27. Graph showing the relationship between submerged and digital volume for RubyRed.

This graph (Figure 27) has an $x=y$ line which shows the ideal relationship of 1:1, showing that the submerged volume and digital volume can be used interchangeably. This means that both the submerged and digital methods are suitable. The regression line has an R^2 (coefficient of determination) value of 0.974, which shows that the line of best fit accounts for 97% of the variation.

An ideal result would have been a line of perfect fit, where both variables (submerged and digital volume) are interchangeable, however, human error could have caused a lack of measurement accuracy. This is especially probable for the RubyRed cultivar, as it was the first kiwifruit cultivar to undergo all the experiments, so human error was more likely. The human error can be found in the placement of the kiwifruit rotation, certain angles capture more of the kiwifruit and is then able to create a digital version of the kiwifruit with increased accuracy.

Relationship between Density and Dry Matter

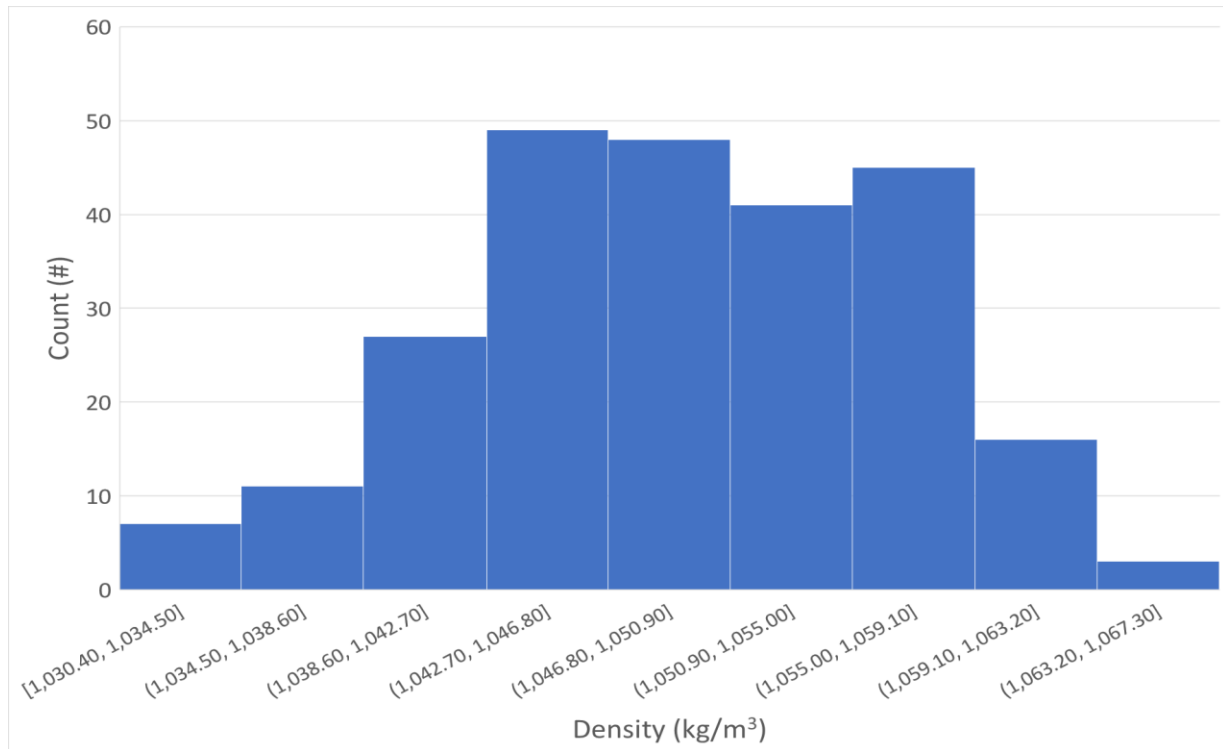


Figure 28. Histogram for the Density of the RubyRed Cultivar.

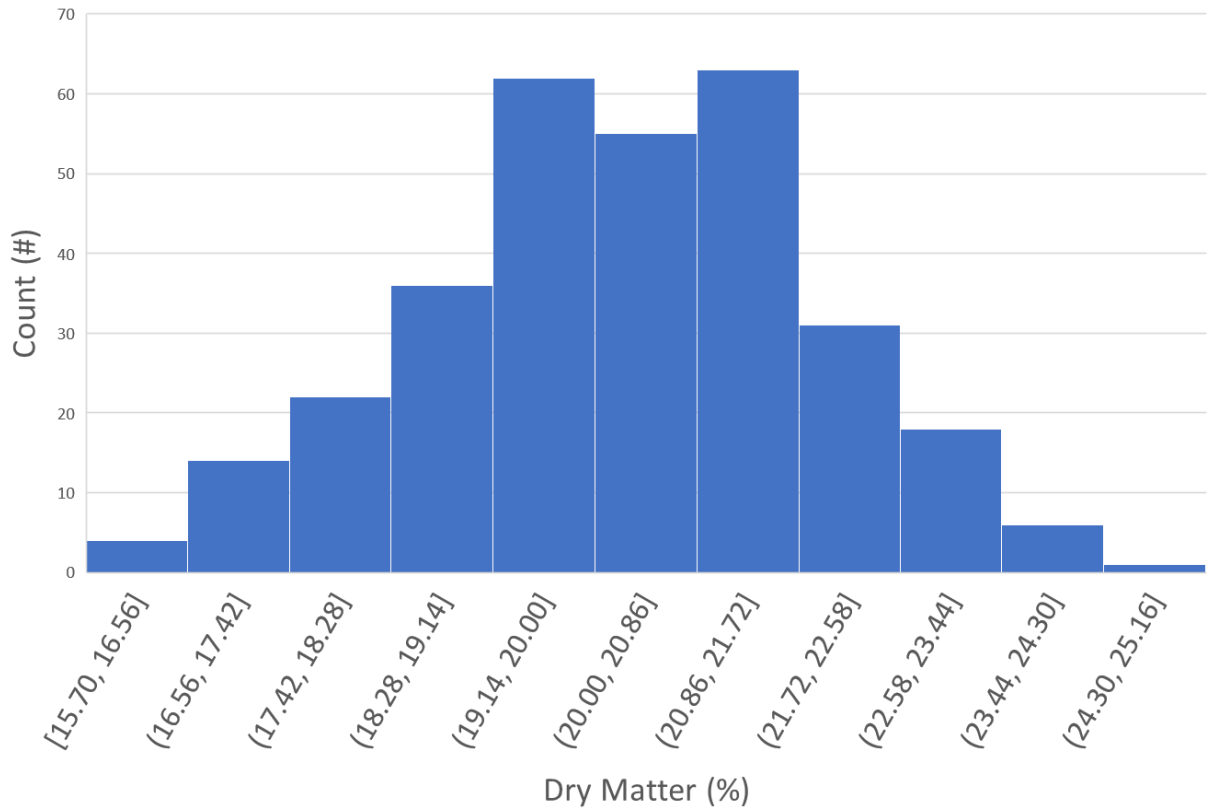


Figure 29. Histogram of Dry Matter for the RubyRed Cultivar.

Histogram plots were created to describe the population of the dry matter captured in the experiment. The plot shows a normal distribution. Figure 30 below shows a relatively positive correlation between the submerged density and DM (duplicate DM measurements) with 74% of the data being accounted for by the line of best fit. Compared to the previous graph above (figure 28) there is a wider spread of the data with a few outliers being removed when the upper and lower limits were identified.

In figure 30 below, the graph is showing the relationship between DM and submerged density for the RubyRed cultivar.

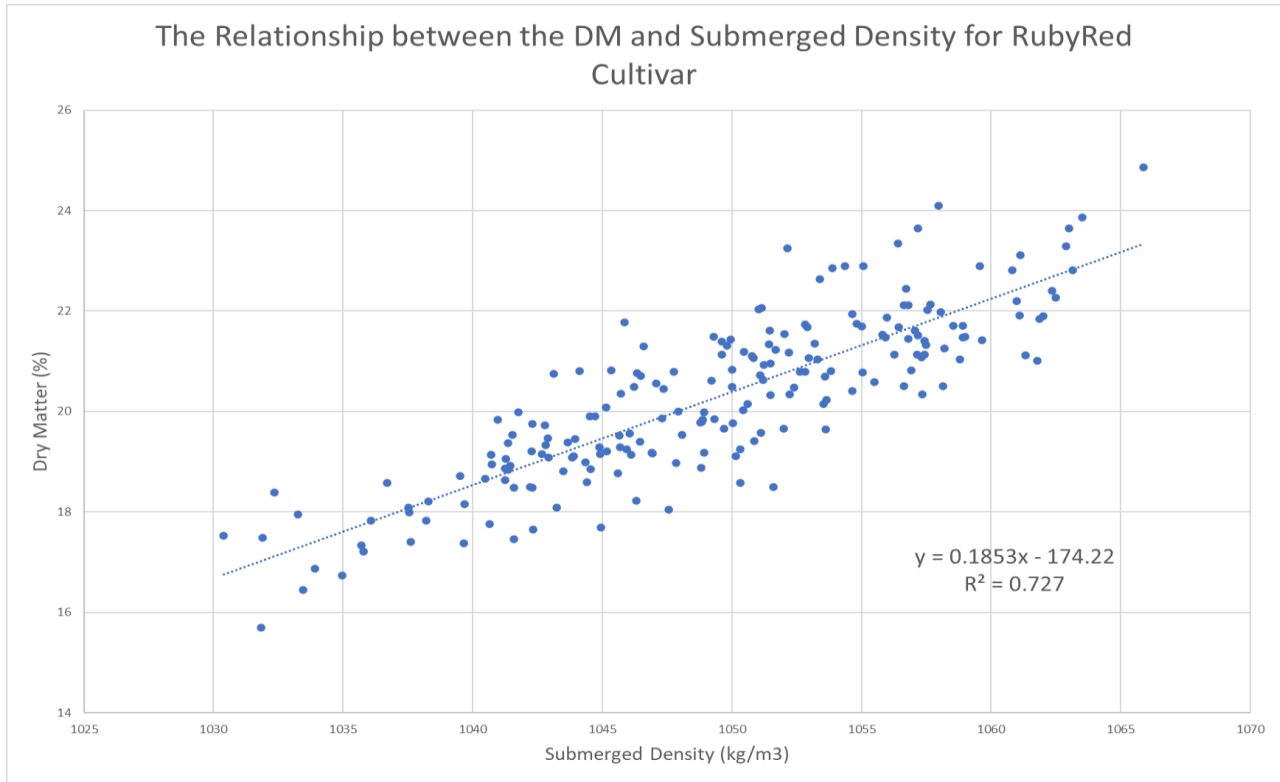


Figure 30. Graph showing the relationship between DM and submerged density for RubyRed.

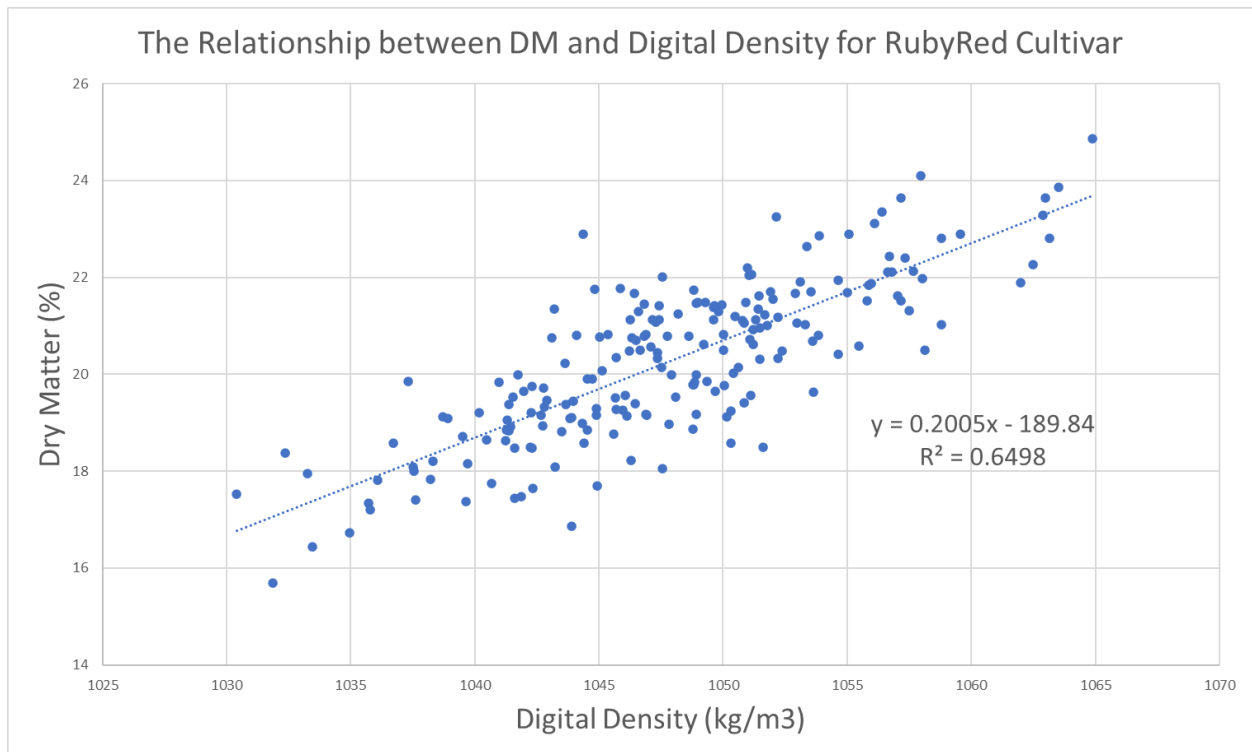


Figure 31. Graph showing the relationship between DM and digital density for RubyRed.

This graph shows that the digital density and DM have a relatively positive linear regression with a slightly weaker relationship as only 65% of the data is being accounted for by the line of best fit. The spread of data points seems to be slightly more densely populated in the central area (1040 - 1055 kg/m³) compared to the submerged density graph (figure 30) above. An R² value of 65 % shows there is a moderate relationship between the two parameters, however, the value is lower than expected. This resulting R² value is lower in comparison to the R² value of 73 % produced by the submerged density graph (Figure 30) above. This may be due to outliers or the method of submergence in this case is slightly more accurate as it follows the line of best fit closer compared to the digital values. However, the digital values are from a highly new technique that requires more practice and optimal parameters. As discovered later, the data for digital improves as the methodology becomes easier to understand and follow.

The data on the graph has given an R² value of 65%, this is lower than the ideal value. However, this cultivar was the first to be experimented with more human error and RubyRed had a variety of misshaped kiwifruits making it harder to pick up efficient scans. The DM range for RubyRed is observed to lie between around 16% and around 25%. This is quite a large range, with a relatively high DM.

The results from this relationship show a relatively strong correlation between the DM and submerged density for RubyRed which provides valuable insight to potential uses of density to determine RubyRed maturity. With minimal research conducted on the RubyRed cultivar, these data points, linear regression and graphs represent novel information for growers. With RubyRed being commercialized it is beneficial to understand the quality parameter correlations. Notably, the DM and density (submerged and digital) relationships showed positive relationships with R² of 73% for submerged and 65% for digital. This is a good base for further research to allow growers to incorporate digital non-destructive methods to help determine the optimal period to harvest the kiwifruit.

Relationship between total Soluble Solids Content

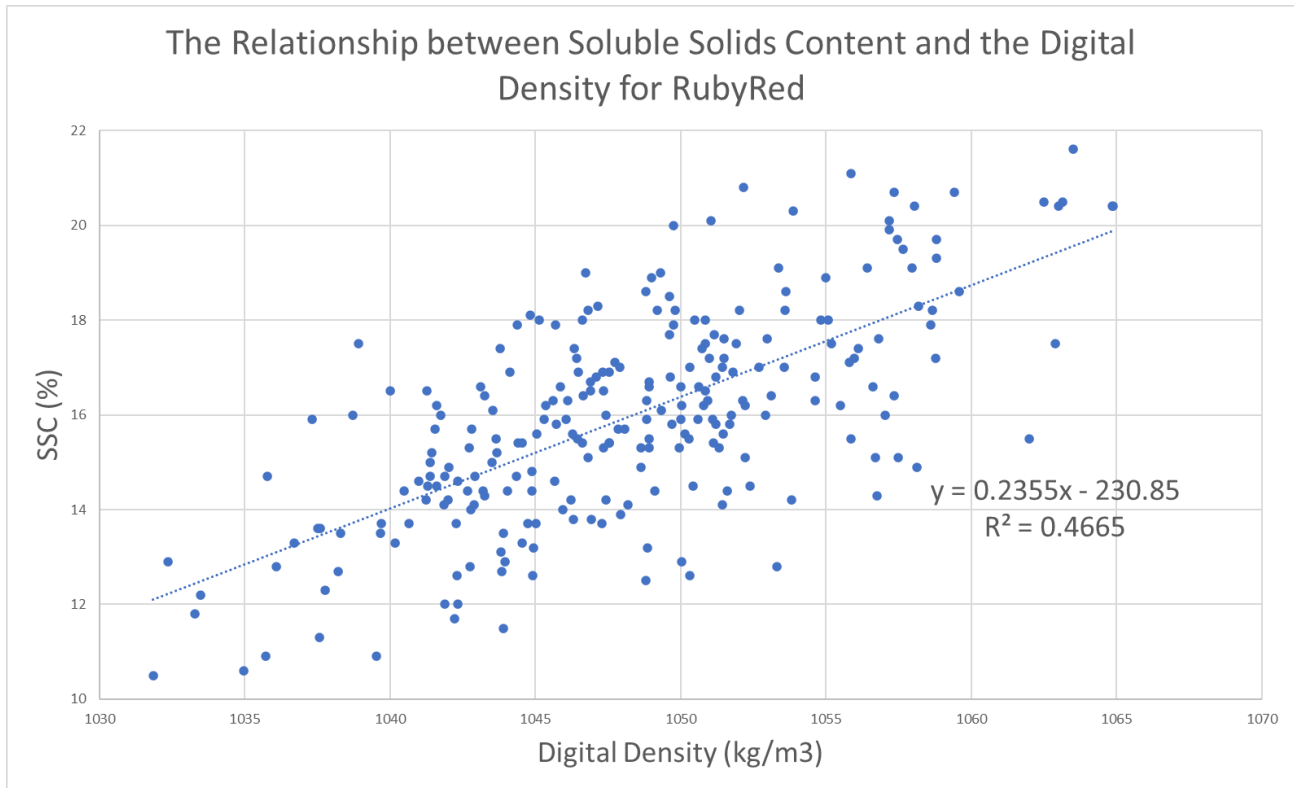


Figure 32. Graph representing the Relationship between SSC and Digital Density for RubyRed.

The graph in figure 32 above, shows the relationship between the SSC and digital density for RubyRed. It shows a weak relationship between the two parameters, with an R^2 value of 0.47. The SSC range is from 10 - 22%, which extends over quite a large range. While the density ranges from 1030 - 1065 kg/m³. The data predominantly lies between the SSC range of around 14 - 18%.

The R^2 value of 50% is relatively low but still shows a positive correlation between the SSC and digital density for the RubyRed cultivar. Only 50% of the data is being accounted for. This relationship is new and never been observed before. The closest comparison is using literature by Jordan et al. where Hayward has shown to have a stronger relationship between SSC and density with an R^2 value of 85.1%.

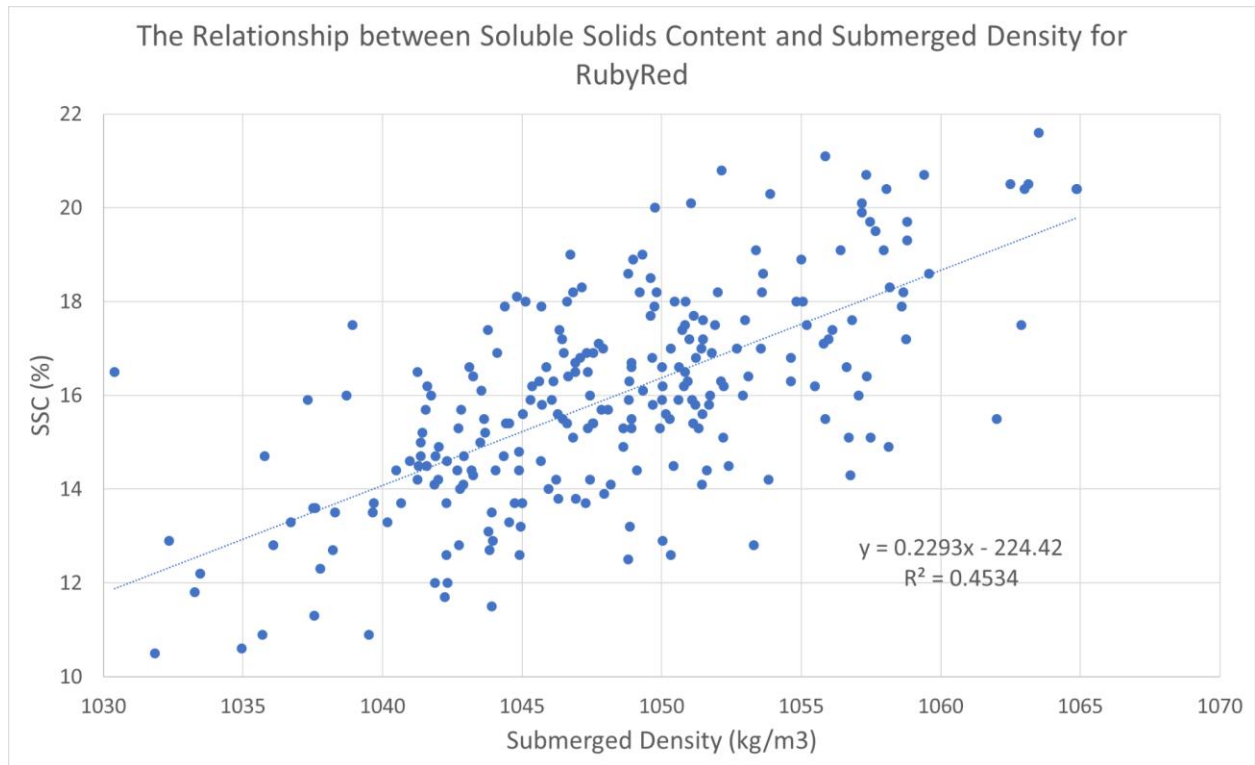


Figure 33. Graph representing the Relationship between SSC and Submerged Density for RubyRed

Similar to the graph in figure 33, a weak correlation between the SSC and submerged density can be observed. The resulting data points show that 45% of the data is being accounted for. This shows that kiwifruits with a higher soluble solids content, generally have a higher density. This is to be expected, as sugar forms the main component of the total soluble sugar contents. As the amount of sugar increases within the kiwifruit, the density is expected to increase also. The correlation between the two parameters could be stronger. Especially when comparing to literature by Jordan, where 85.1% of the data was being accounted for, on the graph of SSC and Density for Hayward.

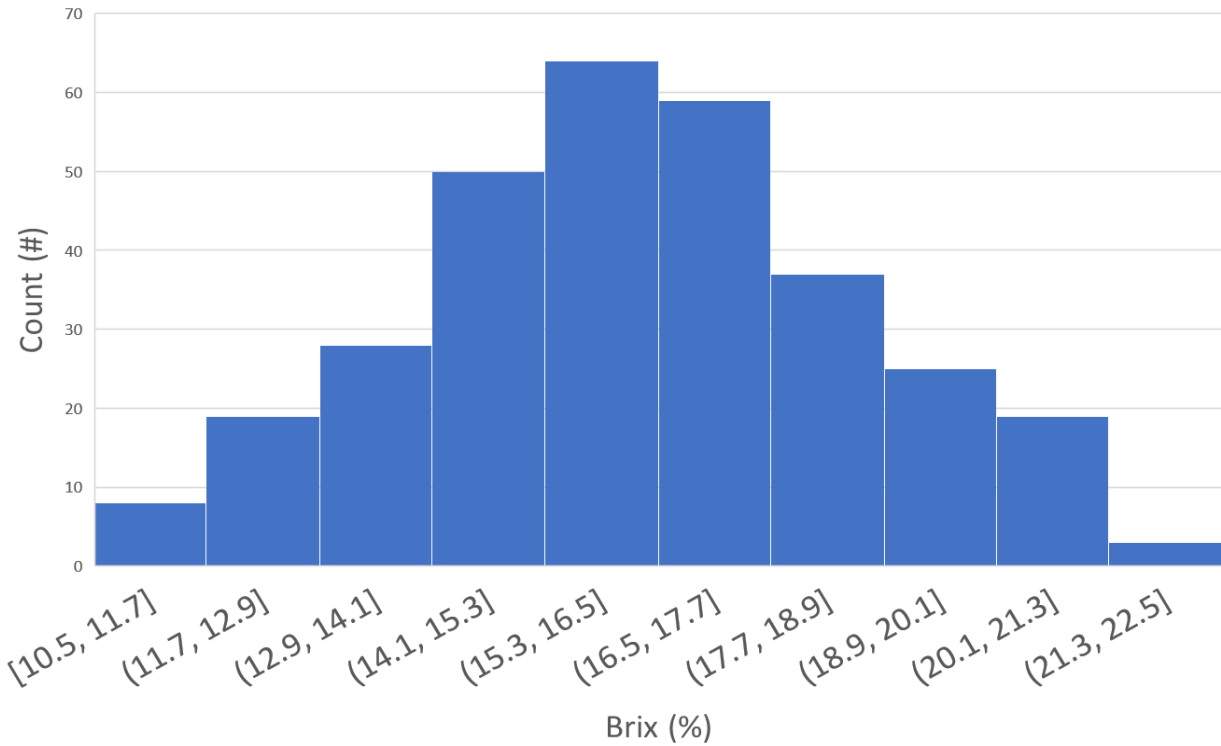


Figure 34. Histogram of Brix for the RubyRed Cultivar.

This histogram in figure 34 above represents a centred common “bell curve”. The peak data points for the RubyRed cultivar lie between 15.3 - 16.5% brix.

4.2 SunGold Cultivar Results

Relationship between Surface Area, Mass and Volume

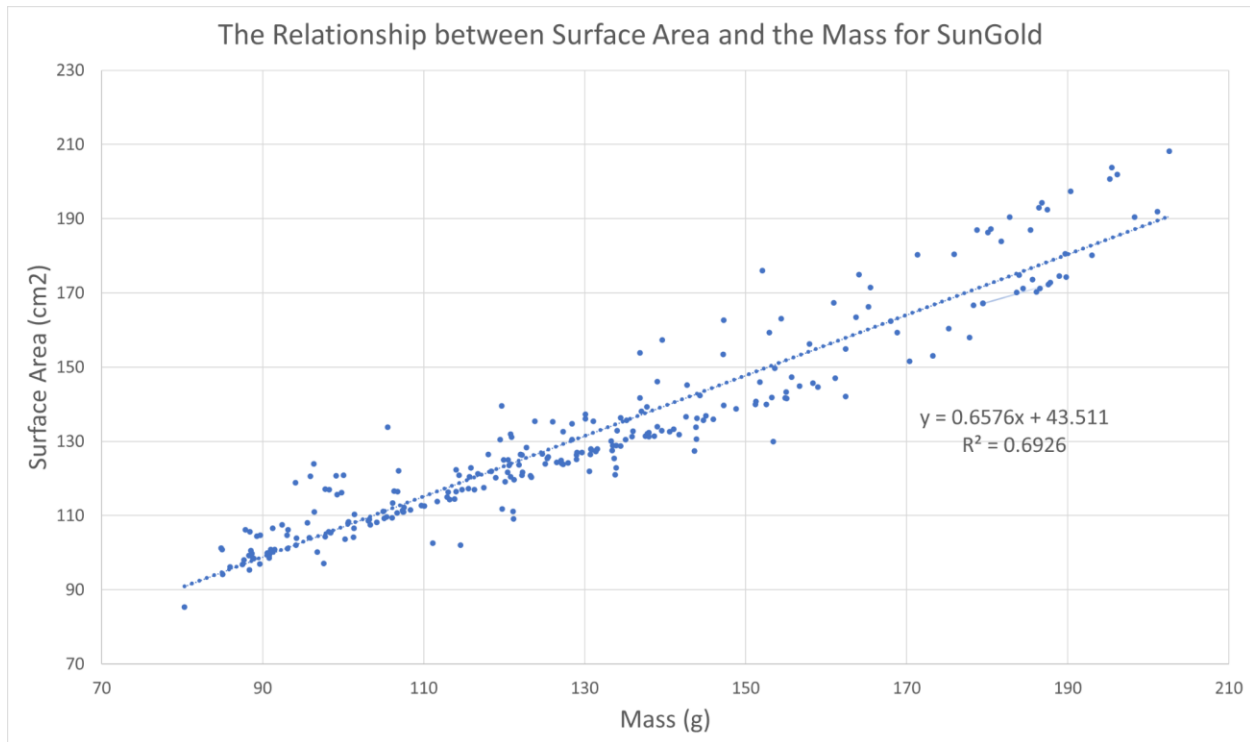


Figure 35. Graph representing the relationship between the surface area and mass for the SunGold cultivar.

A positive correlation between the mass and surface area for SunGold can be observed, with approximately 70% of the data being accounted for. This was to be expected, with surface area of the kiwifruit increasing, it is expected that the mass will also increase. This relationship is important for modelling and predicting potential water loss in kiwifruit.

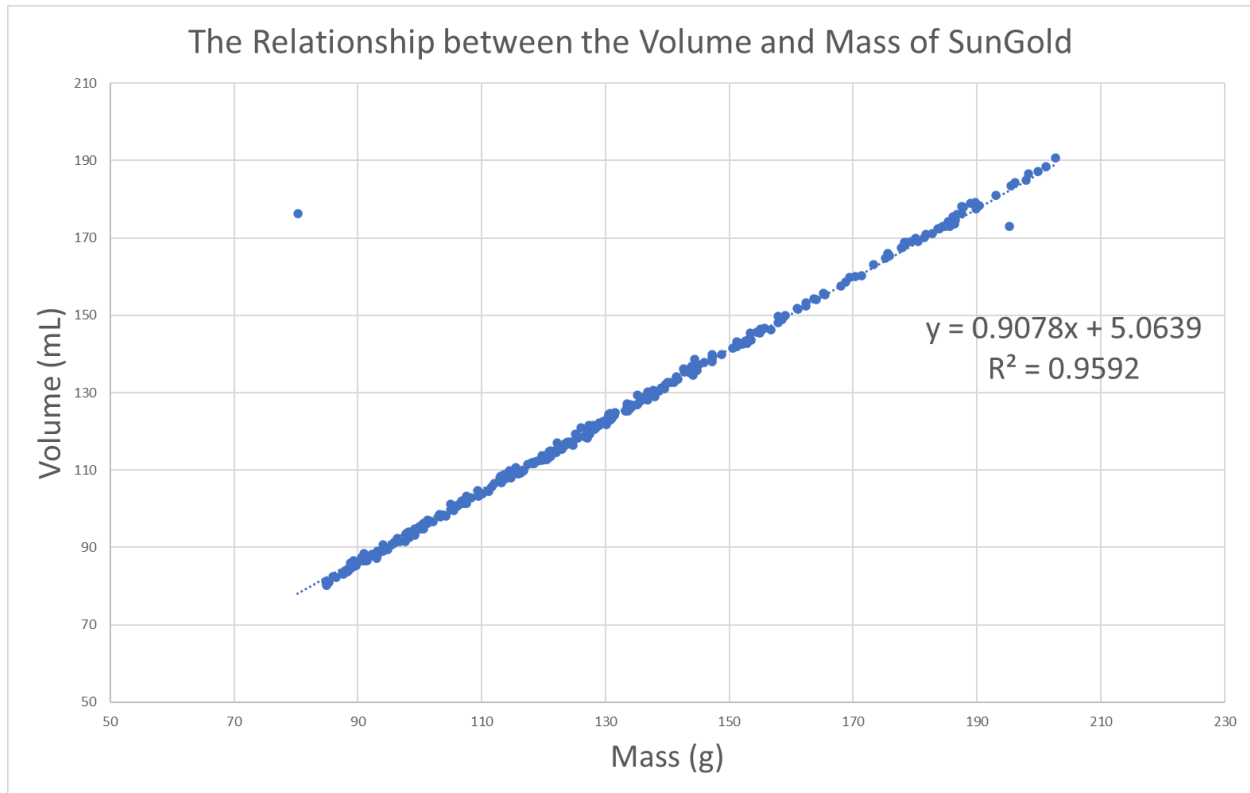


Figure 36. Graph representing the relationship between the volume and mass for the SunGold cultivar.

Apart from a few outliers the majority of the data follows the line of best fit, which is further confirmed from obtaining an R^2 value of 96%. This positive relationship was to be expected, because as the kiwifruit volume increases, the mass of the kiwifruit will also increase. Which can be seen in the graph above.

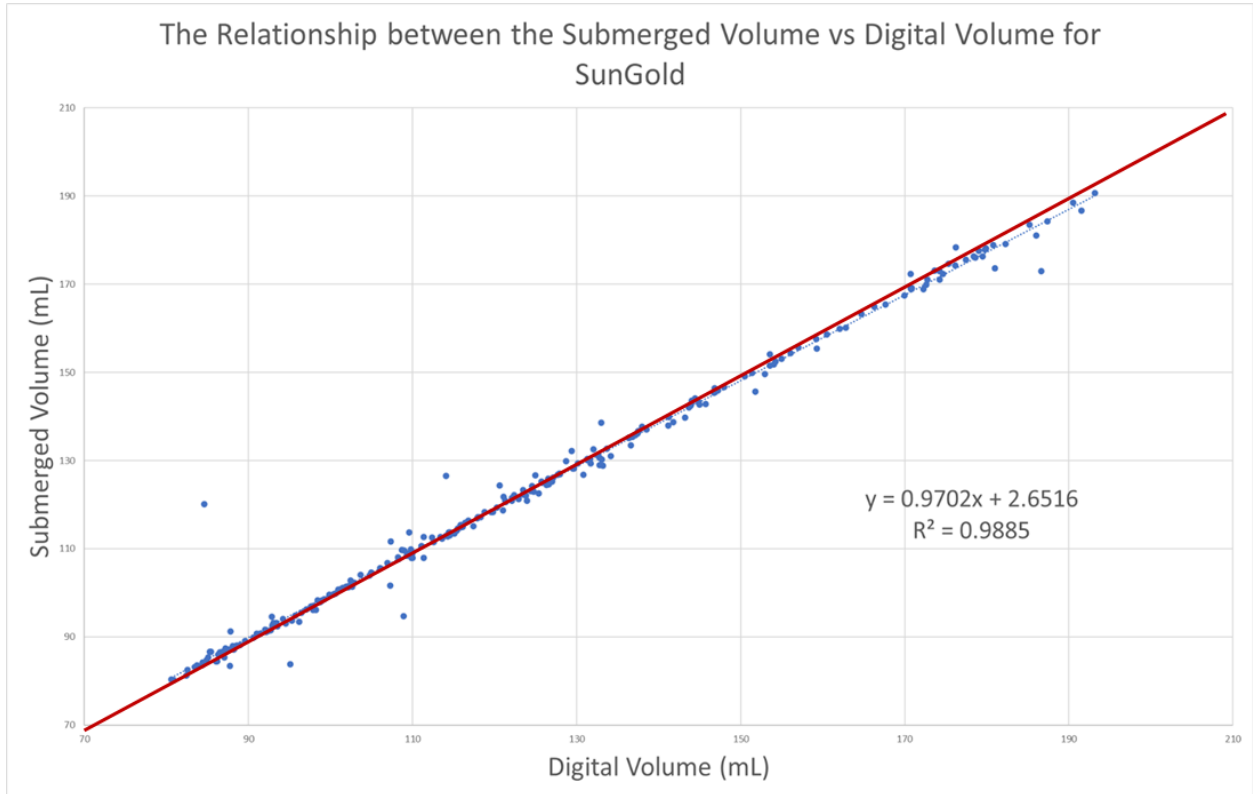


Figure 37. Graph showing the relationship between submerged and digital volume for SunGold.

This graph is showing the correlation between the submerged volume and the digital volume for the SunGold cultivar. A red line is fitted onto the graph representing when $x = y$, showing the ideal fit. The line of best follows it closely with 99% of the data being accounted for. This shows that for SunGold which is more consistently shaped, that submerged or digital volume could be used interchangeably.

There are few outliers identified using a t-test. These outliers were likely due to human error, however, overall compared to the RubyRed cultivar there are minimal outliers. With increased human accuracy because of more practice and experience the results were found to be better. It can be observed that the digital volume at higher values, seems to have a slightly overestimated volume. The shape of the SunGold cultivar was more symmetrical and oval, allowing the scanner to capture better images and thus increase efficiency of the results.

Relationship between Density and Dry Matter

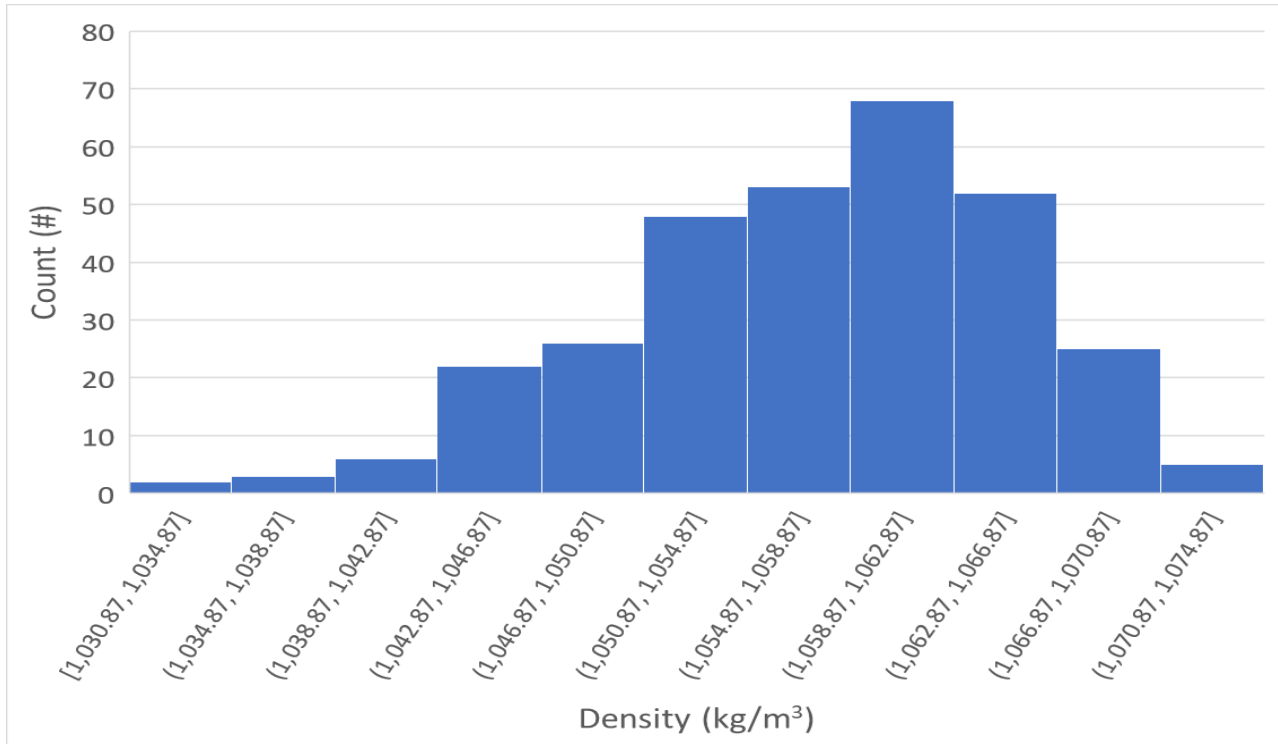


Figure 38. Histogram for the Density of the SunGold Cultivar.

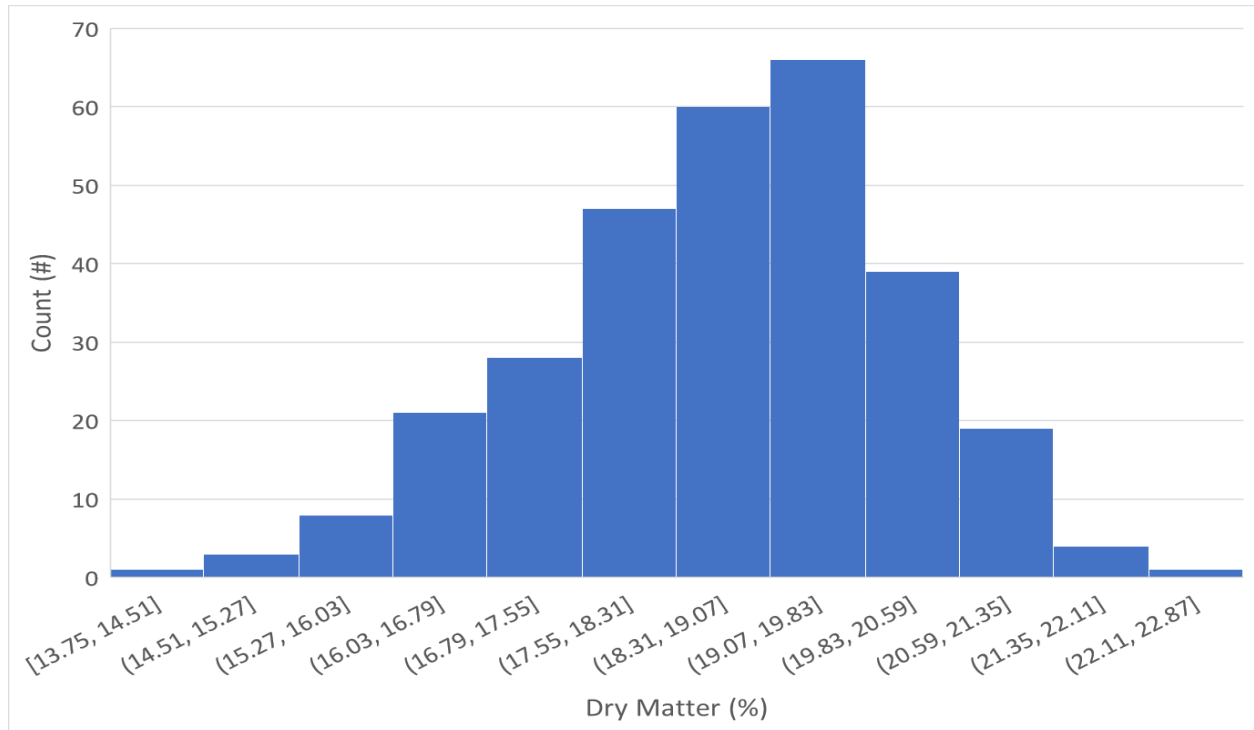


Figure 39. Histogram of Dry Matter for the SunGold Cultivar.

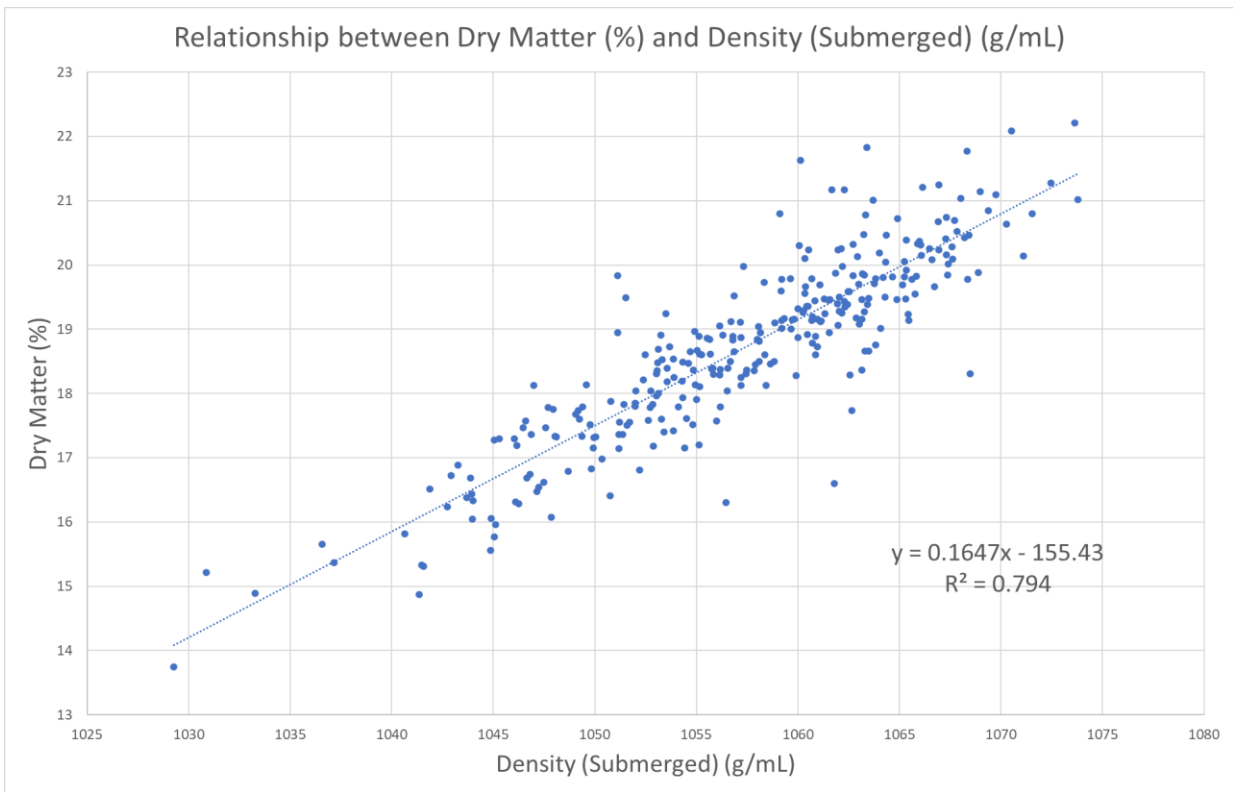


Figure 40. Graph showing the relationship between DM and submerged density for SunGold.

Figure 39 showing the histogram plot of SunGold's dry matter follows a centred standard bell curve. With the peak amount of data points lying between 19.07 - 19.83% DM. This is relatively high DM values.

The graph above (Figure 40), like the previous ones for RubyRed (Figures 30), shows a positive correlation between the dry matter and submerged density for the SunGold cultivar. The DM values range from around 14% to around 22%, extending to a relatively high DM content. In comparison to literature of Hayward (Jordan et al., 2000), the DM range extends from 14 - 19.5%, representing the typical range for the Hayward cultivar. According to FreshFacts (2021) the DM average for SunGold is 16.1%. From the data above, the average DM is determined to be 18.7%. A DM of 15 - 20% is associated with consumer satisfaction while a DM with less than 15% can result due to early harvest. These often do not meet consumer satisfaction. As kiwifruit DM at harvest is correlated with the SSC, according to Zespri (2021) it has been determined that minimum DM content that kiwifruit should have is 14-15% and should not exceed 18.2% during harvest. Staying between this range will provide the desirable level of SSC, meeting consumers taste standards.

It can be observed from the graph above (Figure 40) that there is a relatively strong relationship with 80% of the data being accounted for following the line of best fit. This shows that the submerged density has the potential to estimate DM. This is the first time SunGold is being measured and correlated between important parameters. The results are similar to Hayward kiwifruit in previous literature noted by Jordan. R. et al., (2000), where 82.6% of the data follows the line of best fit for the density and DM of Hayward kiwifruit cultivar.

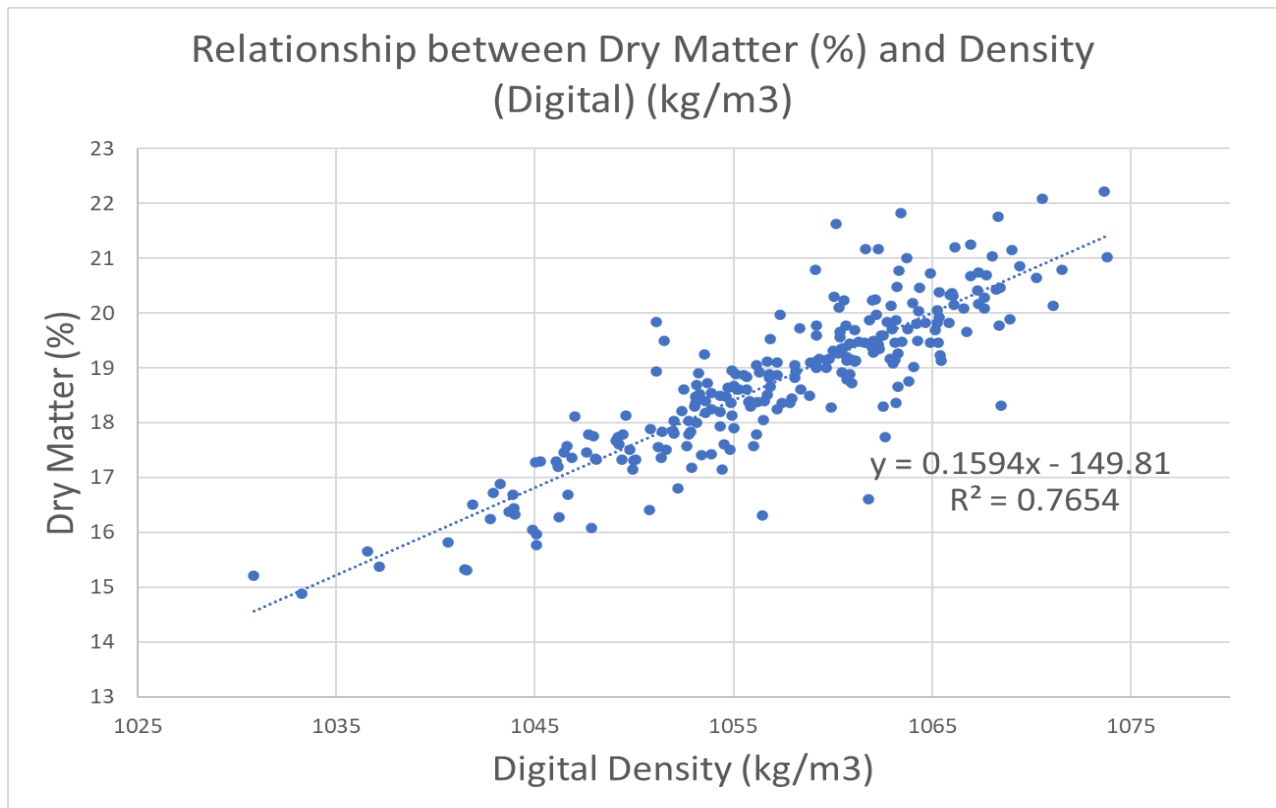


Figure 41. Graph showing the relationship between DM and digital density for SunGold.

This graph in figure 41 is showing a similar trend compared to figure 39, looking at the relationship between the submerged density. However, the R^2 value on this graph is slightly lower. It still rounds to 80% of the data being accounted for. This reveals that digital density has the potential to be used for the estimation of DM. This graph observing the correlation between the digital density (Figure 41) is similar to the graph above (Figure 40) looking at the submerged density. This was to be expected as both the submerged and digital densities are highly correlated.

The submerged and digital densities for RubyRed are strongly correlated (Figures 30 and 31) with an R^2 value of 0.64, but the SunGold results had an increased correlation in comparison with an R^2 value of 0.7654. Likely due to increased human accuracy when carrying out the experiments. However, the digital density has a slightly lower R^2 value, showing a slightly weaker relationship compared to the submerged density and DM.

Relationship between total Soluble Solids Content

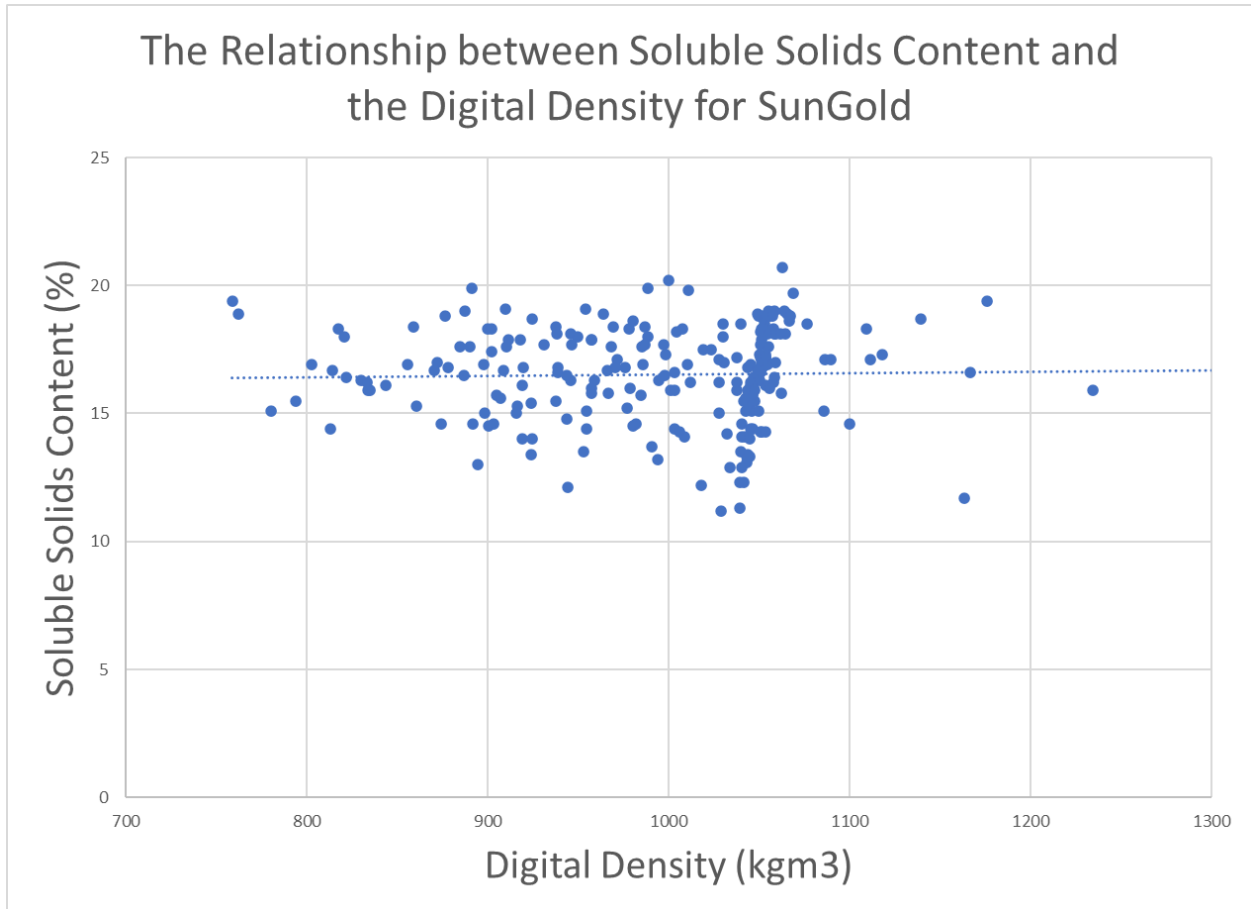


Figure 42. Graph representing the Relationship between SSC and Digital Density for SunGold.

This graph shows there is no relationship between the SSC and digital density for the SunGold cultivar. The data is spread over a digital density range from 750 - 1250 kg/m³, and a SSC range from approximately 10 - 20%. There is a slightly higher density of data points around 1050 kg/m³ on the digital density axis.

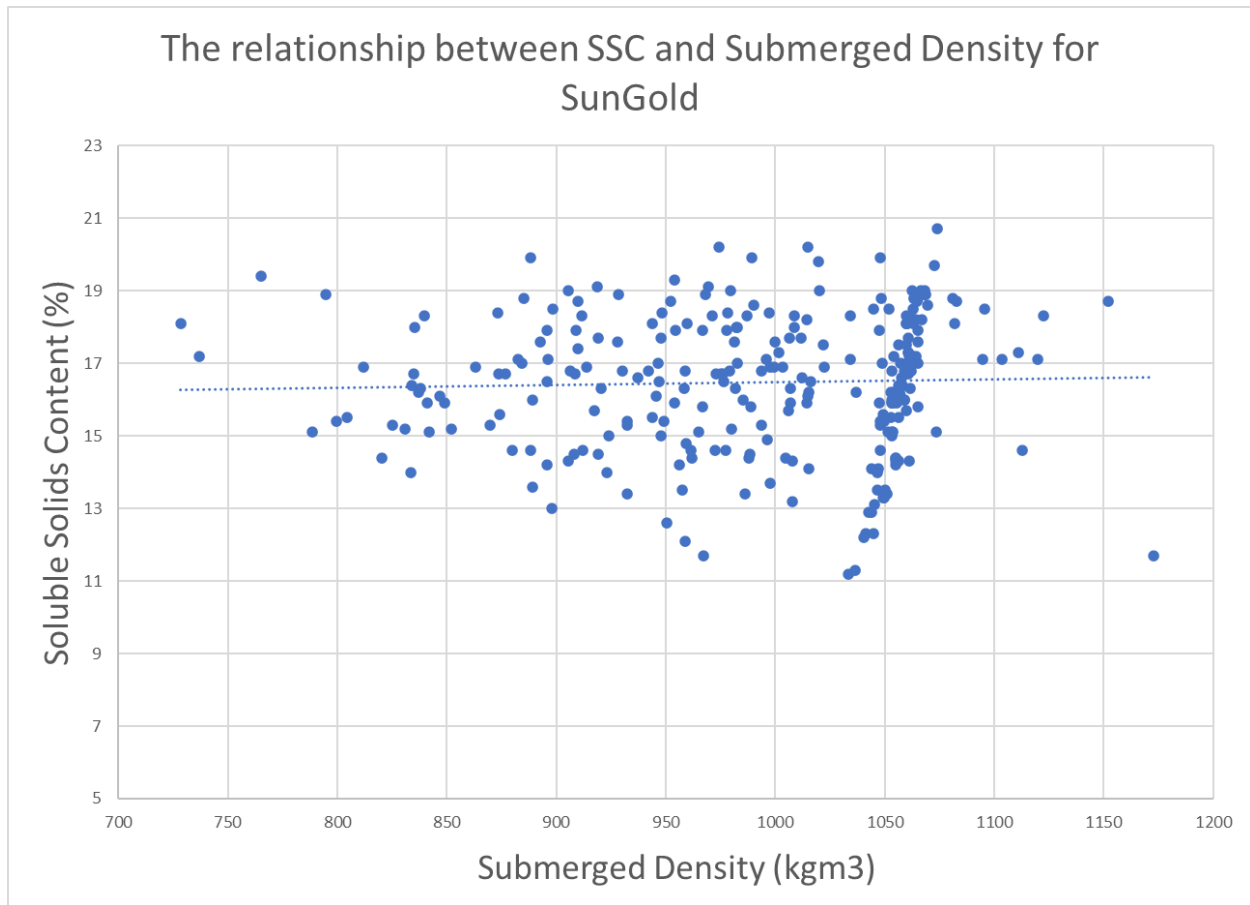


Figure 43. Graph representing the Relationship between SSC and Submerged Density for SunGold.

Highly similar to the graph (Figure 42) above (Figure 43), there is no relationship between the SSC and submerged density. The data is predominantly spread between submerged densities 800 – 1100 kgm³ and SSC values 11 – 21%. As stated above, the results were expected to have a positive relationship. With the SSC and submerged density having a proportional relationship, kiwifruits with higher densities having higher SSC values. However, no relationship is observed. The lack of relationship between SSC and submerged density is due to all the fruit having already converted into brix. They are in the process of ripening and all the fruit will eventually have brix in the range between 14 – 20.

This relationship is an important parameter in helping to predict kiwi fruit maturity, one of the pre-harvest strategies implemented to maintain optimal post-harvest quality.

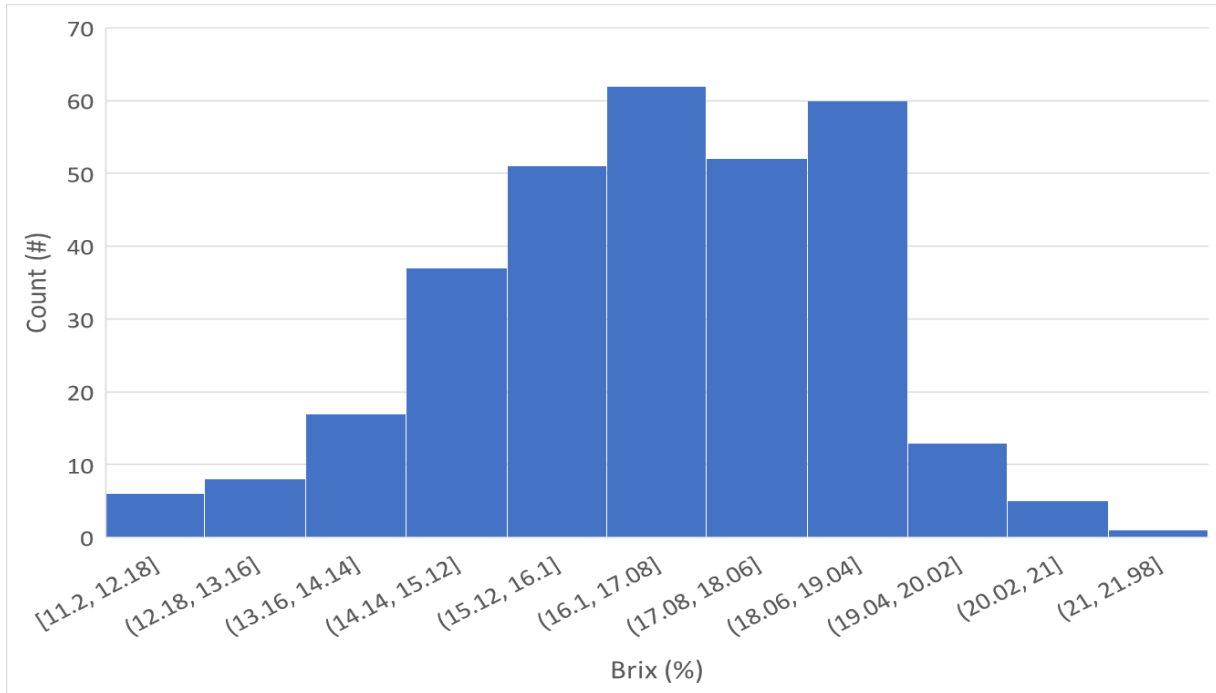


Figure 44. Histogram of Brix for the SunGold Cultivar.

4.3 Hayward Cultivar Results

Relationship between Surface Area, Mass and Volume

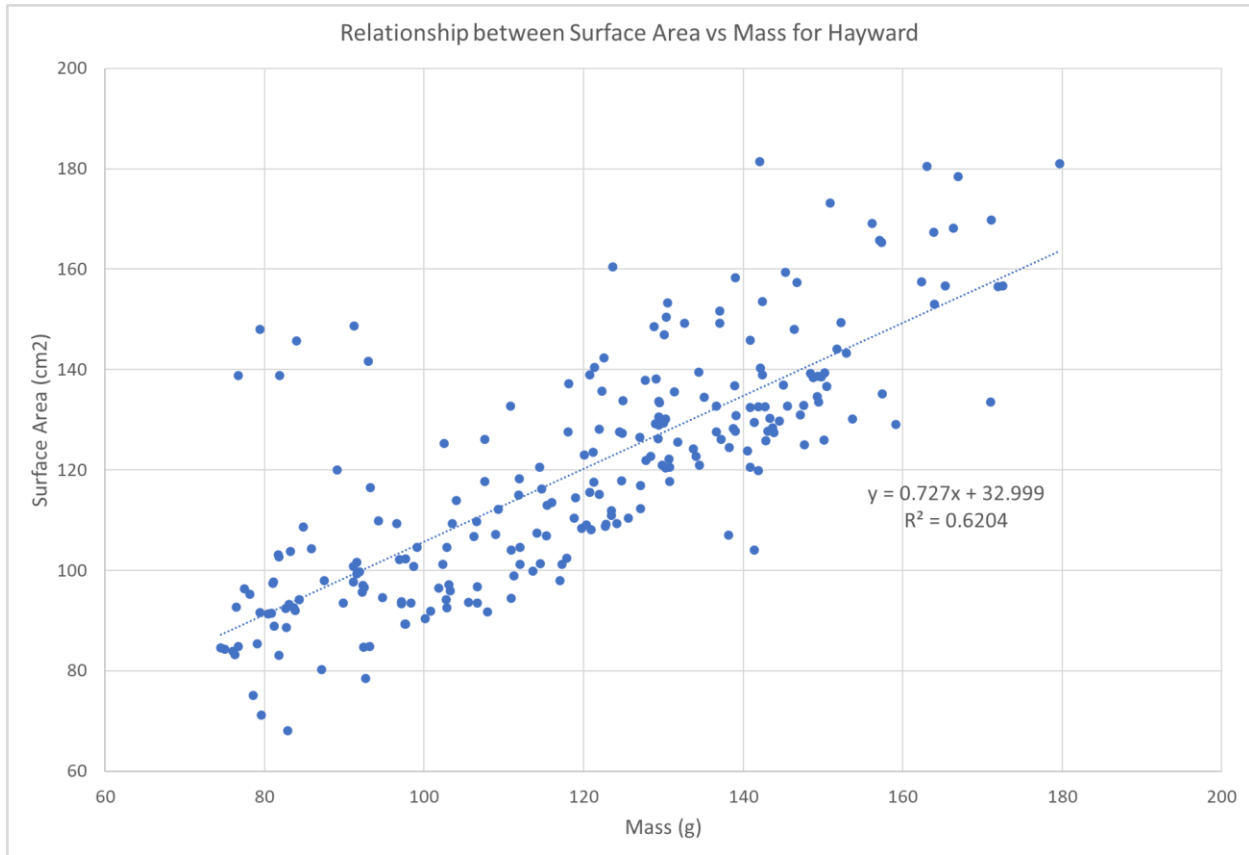


Figure 45. Graph representing the relationship between the surface area and mass for the Hayward cultivar.

This graph shows a positive relationship between the surface area and mass for Hayward. A large majority of the data follows the line trend, with 62% of the data being accounted for. This positive correlation is to be expected because with the surface area of the kiwifruit increasing the size and therefore mass of the kiwifruit increases as well. There are a few outliers with high SA and low mass, this is potentially due to human error or potentially a lot of water loss has occurred. Compared to SunGold, the Hayward data has further spread around the line of best fit, which is somewhat evenly spread.

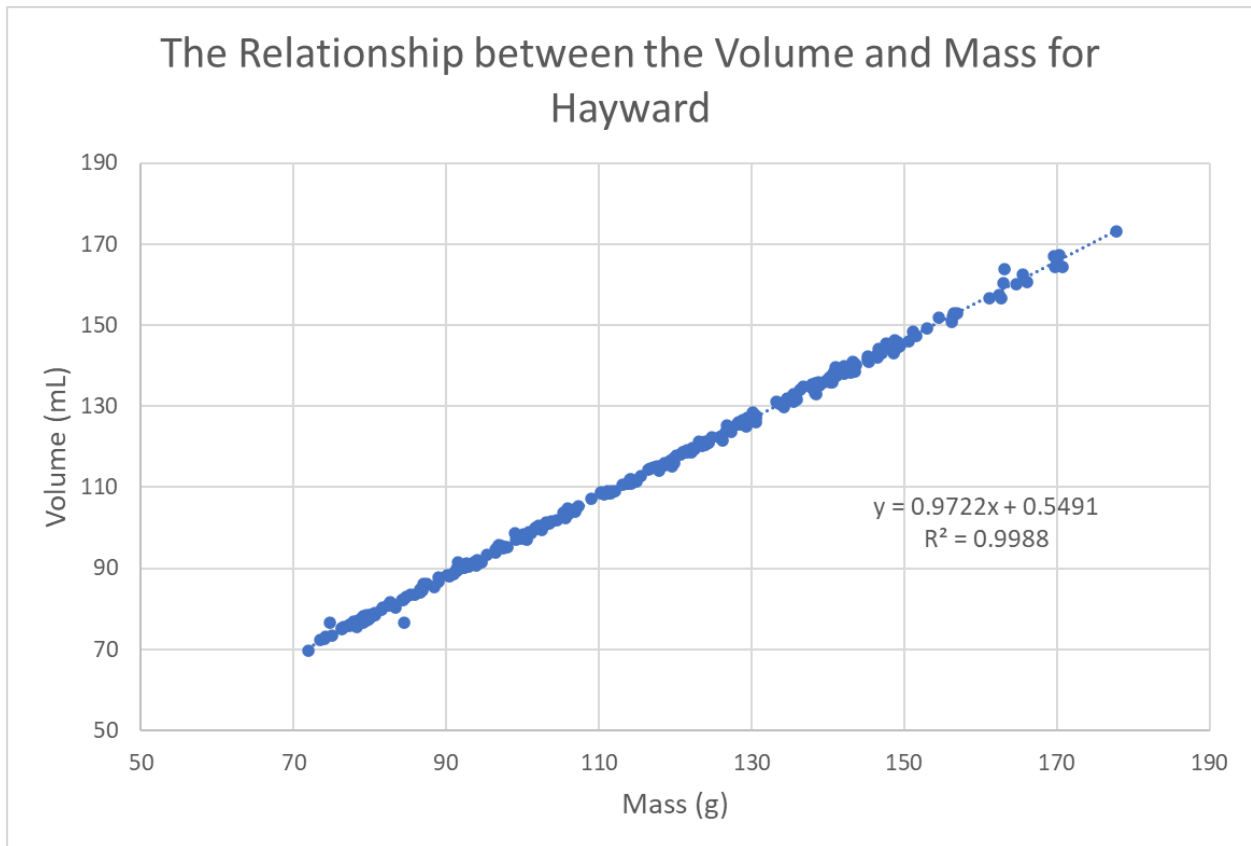


Figure 46. Graph representing the relationship between the volume and mass for the Hayward cultivar.

Similar to the graphs for RubyRed and SunGold, a very strong positive relationship can be observed where 99% of the data is being accounted for. This was an expected result and shows that the kiwifruits volume and mass are directly proportional. As one increases, so does the other.

Relationship between Submerged and Digital Volume

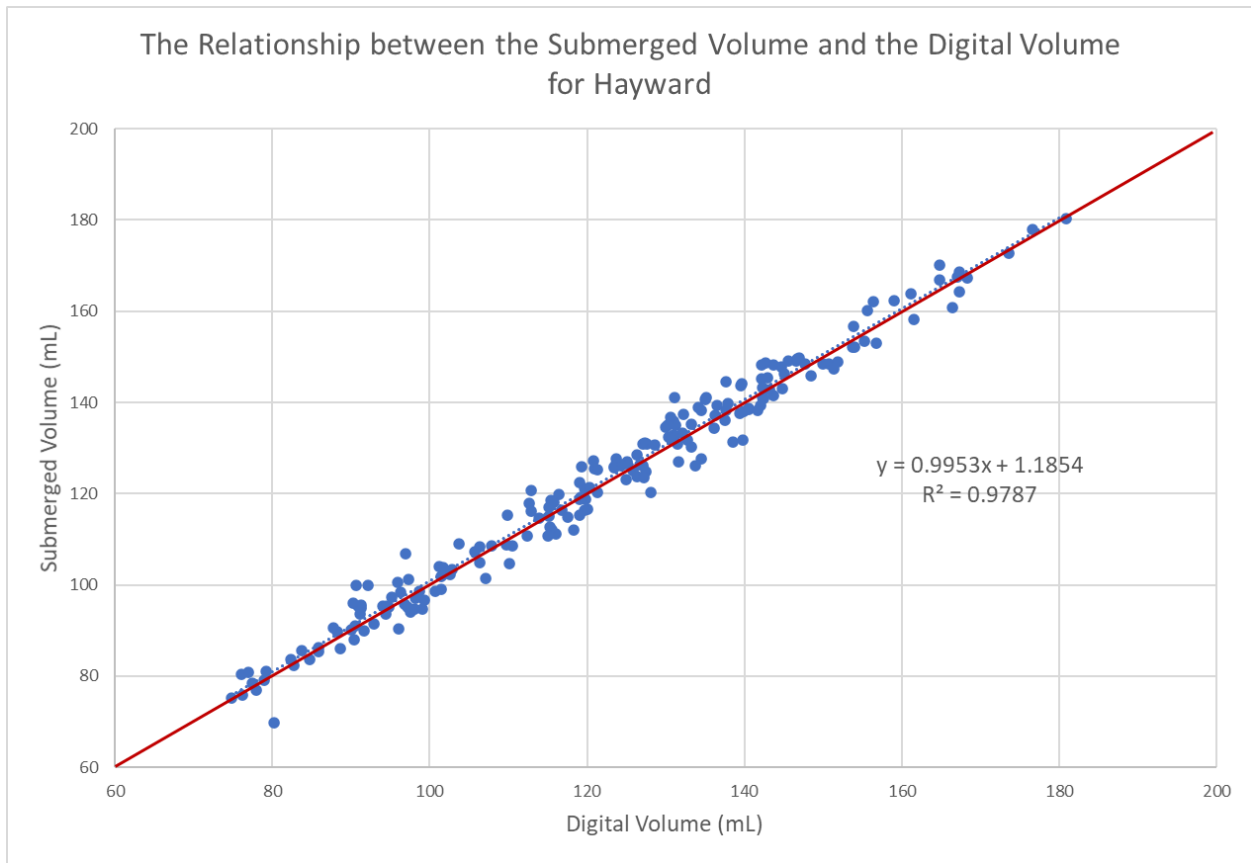


Figure 47. Graph showing the relationship between submerged and digital volume for Hayward.

This graph for the Hayward cultivar follows the same trend as RubyRed and SunGold. All have a strong positive relationship between the submerged volume and the digital volume. It can be observed that 98% of the data is being accounted for. The red line ($x = y$) is the ideal fit, and the data follows this closely, revealing that both the submerged and digital volume for Hayward can be used interchangeably. There are no big outliers, which is likely due to better efficiency when carrying out the experiments.

Relationship between Density and Dry Matter

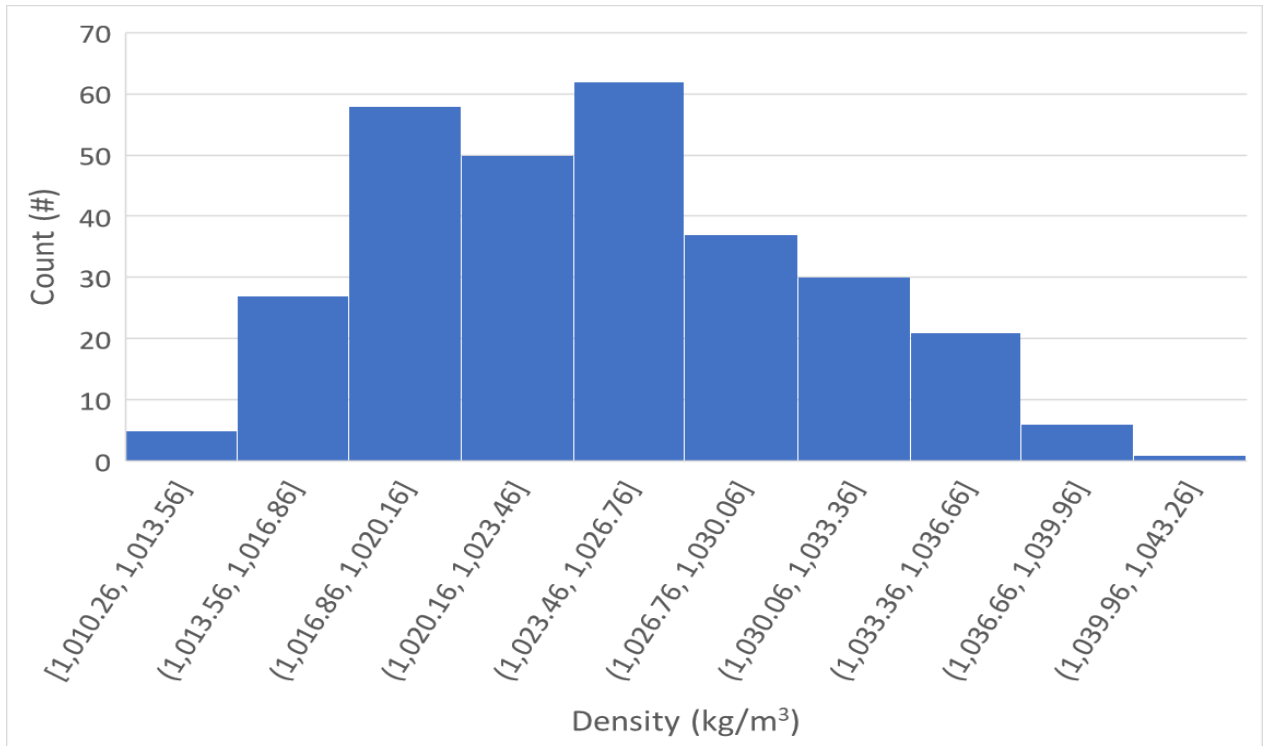


Figure 48. Histogram for the Density of the Hayward Cultivar.

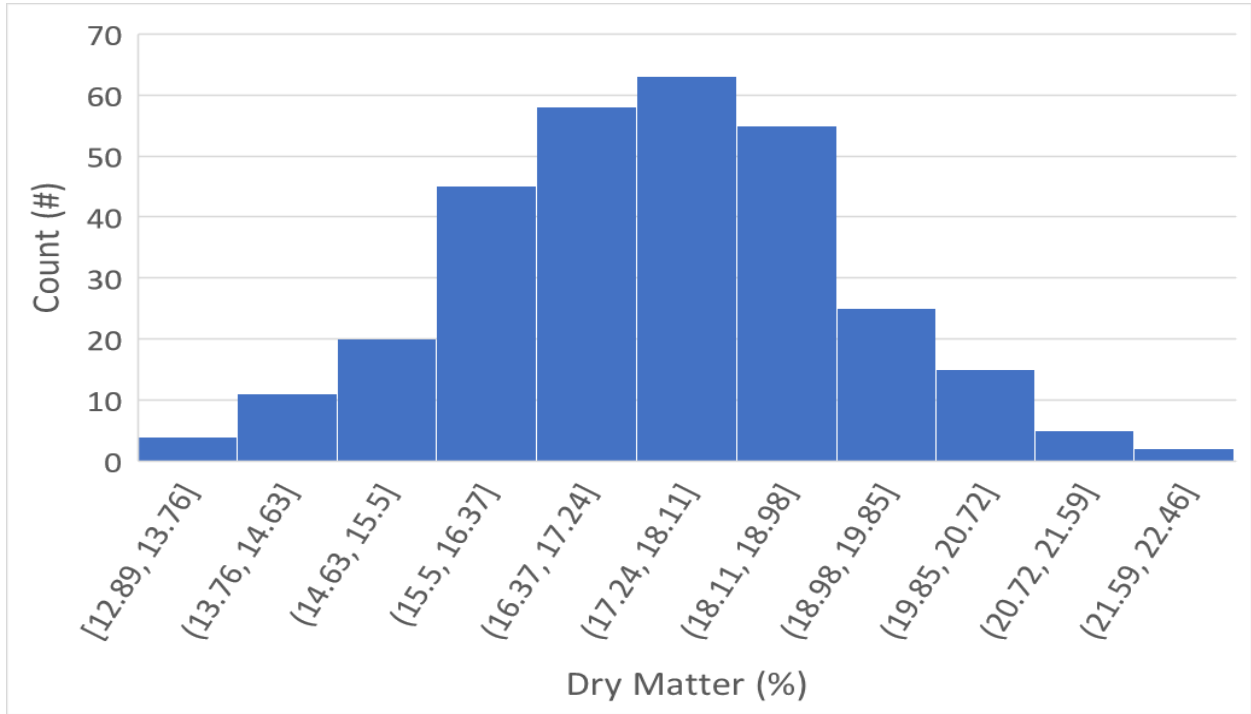


Figure 49. Histogram of Dry Matter for the Hayward cultivar.

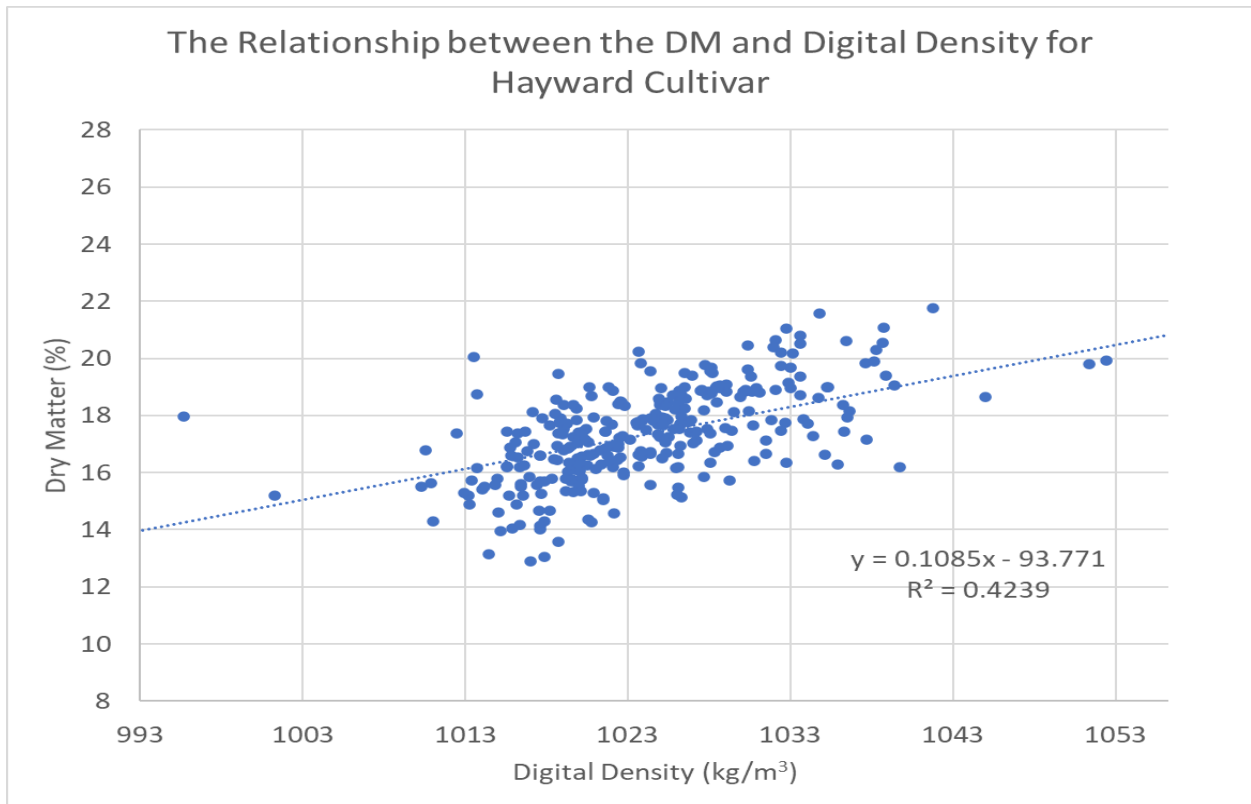


Figure 50. Graph showing the relationship between DM and digital density for Hayward.

The graph in Figure 50 above, shows the results for Hayward’s DM and density relationship. The relationship had a lower correlation than expected, with a weak relationship between the density and DM of the kiwifruits.

This is likely attributed to the prolonged shelf life during COVID lockdown when experiments were intended to take place. Due to lockdown restrictions, lab time and slots were particular and pushed experiments to be less consistent which may be the cause for the unexpected weak correlation between the two parameters. It prolonged the experimental time which allowed the kiwifruits to mature reaching a plateau (ripe eating soluble solids) influencing the SSC of the kiwifruit and therefore the DM and density. When observing the results for Hayward in Jordan. R. et al., (2000) research, the relationship between DM and density had a very strong relationship with over 90% of the data being accounted for.

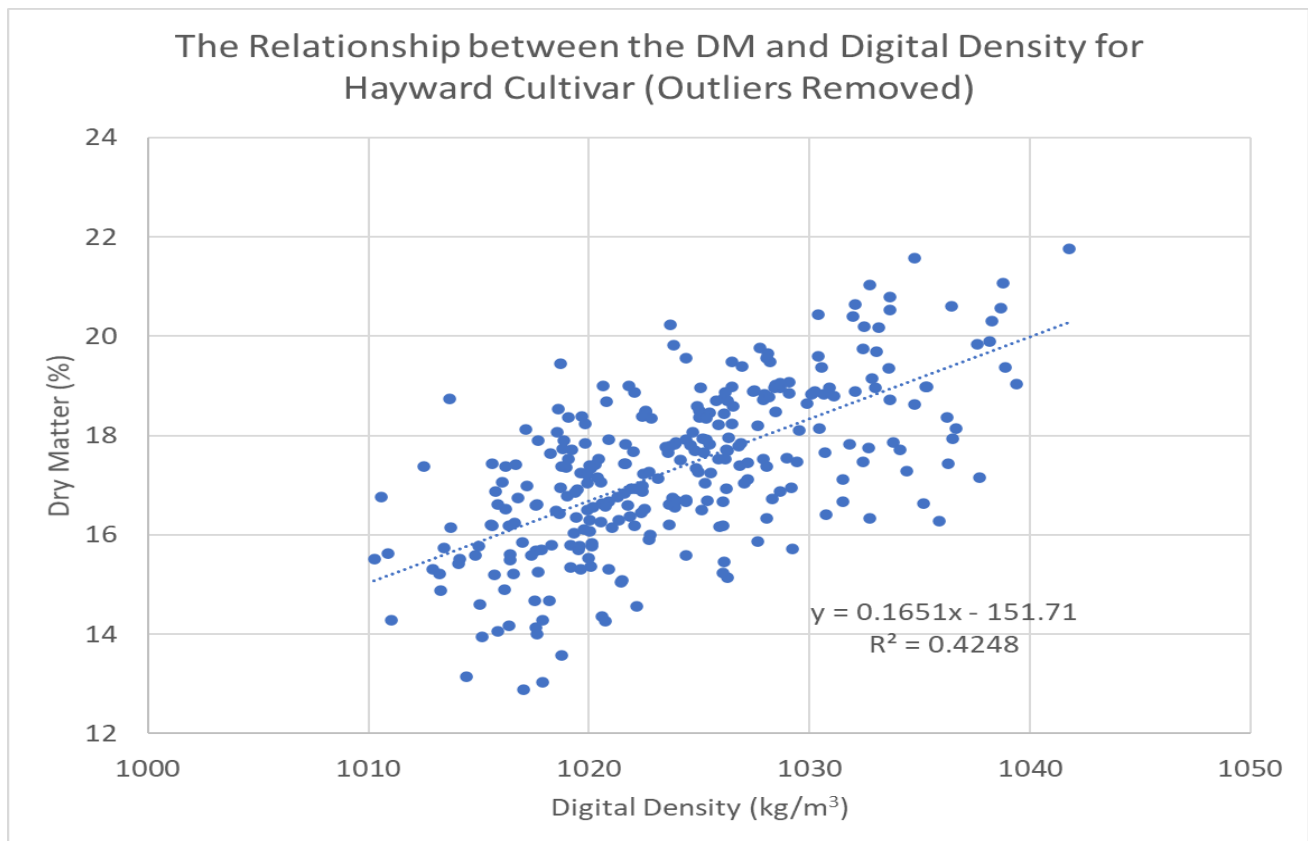


Figure 51. Graph showing the relationship between DM and digital density for Hayward with outliers removed.

Previous results indicated data points lying outside of the upper and lower limit, these outliers were removed to observe any difference this may have on the correlation between the DM and submerged

density. The results show that the removal of these outliers only slightly increases the R2 value by 0.009. This is a negligible difference and does not make an overall difference to the weak relationship between DM and submerged density.

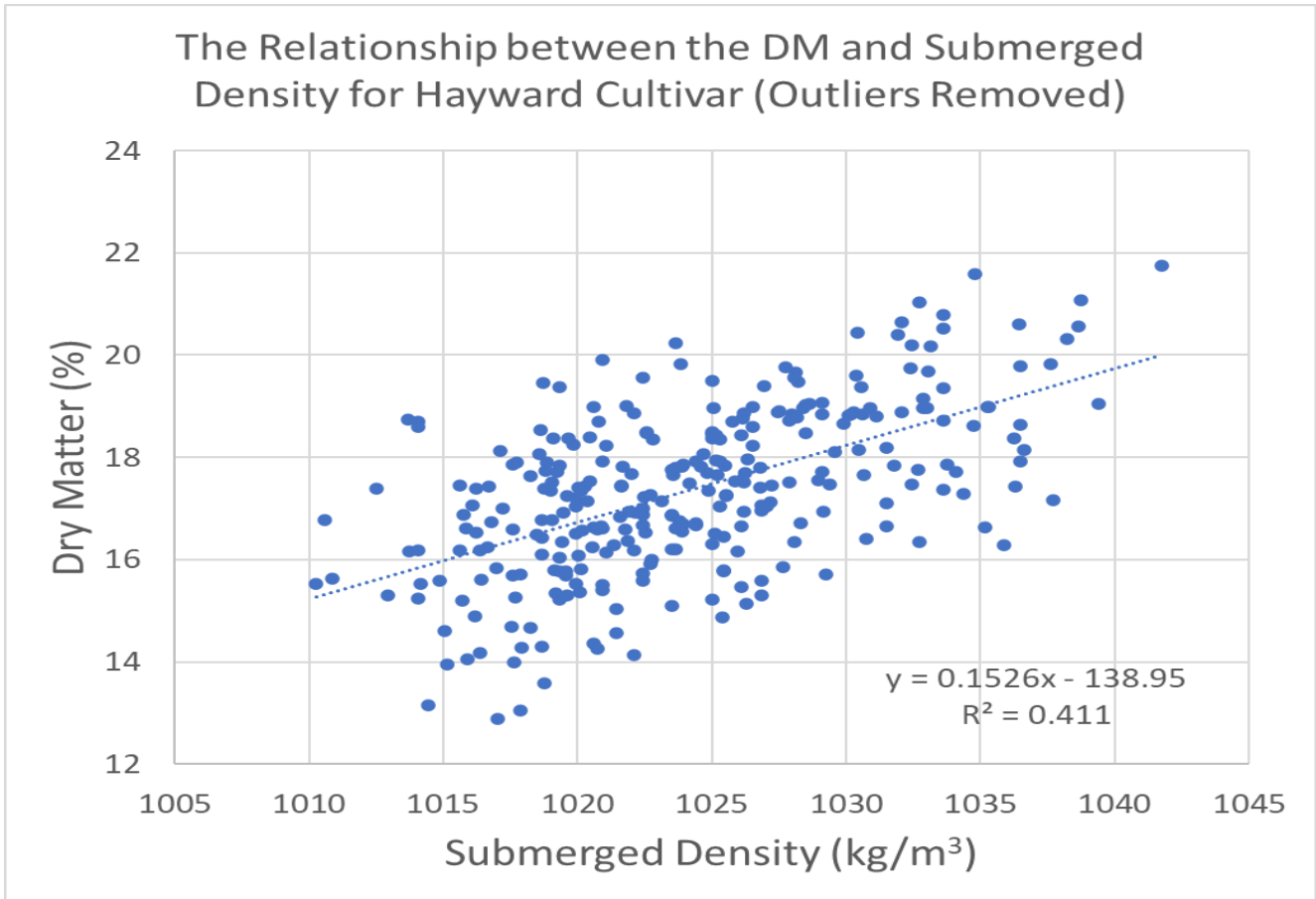


Figure 52. Graph showing the relationship between DM and submerged density for Hayward with outliers removed.

This graph (Figure 52) is similar to the graph above in Figure 51, the only difference is observing the submerged density in relation to dry matter with the removal of outliers. It can be observed that the relationship is slightly weaker with a lower R value.

Relationship between total Soluble Solids Content and Density

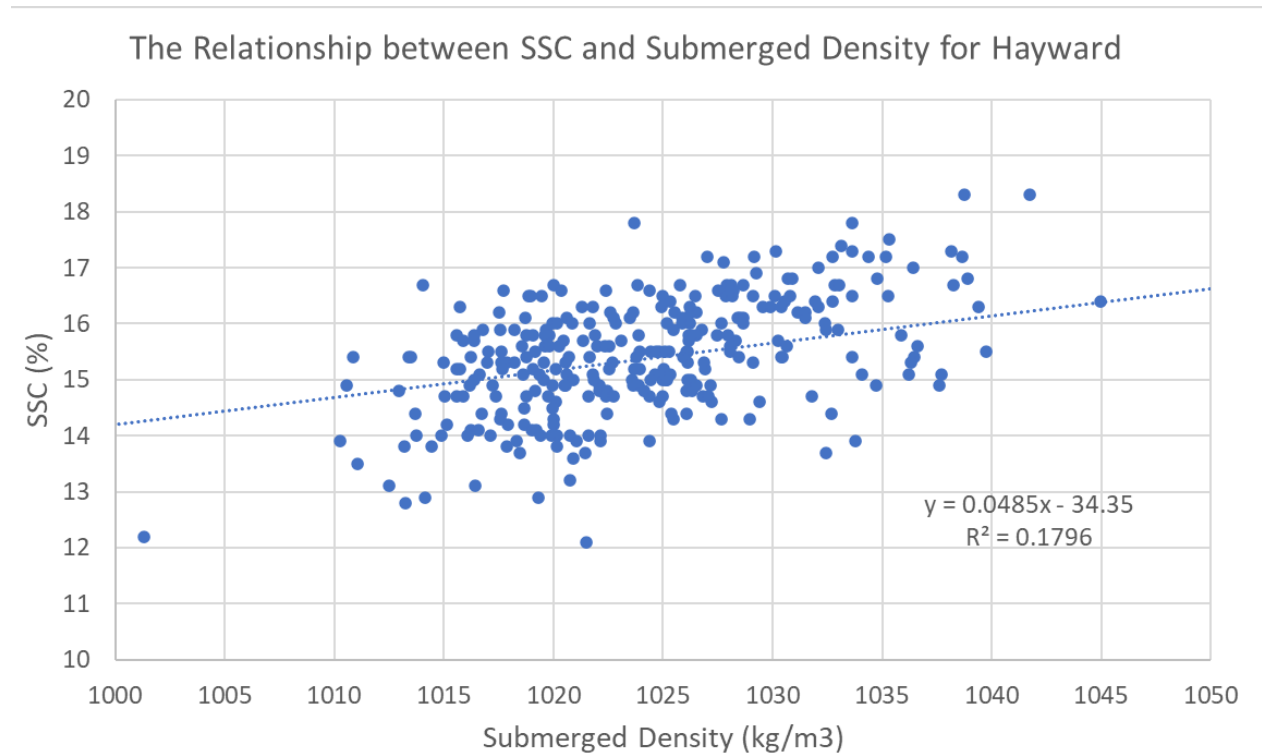


Figure 53. Graph representing the Relationship between SSC and Submerged Density for Hayward.

The above graph (Figure 53) shows that there is no correlation between the SSC and submerged density for Hayward. The graph and data points outline that the R value of 0.18 is very low, revealing further there is no relationship between the two parameters. It can also be observed that the data points are scattered around with no specific trend line detailing no significant relationship between SSC and the submerged density for hayward. The values for SSC range approximately between 13% and 18%.

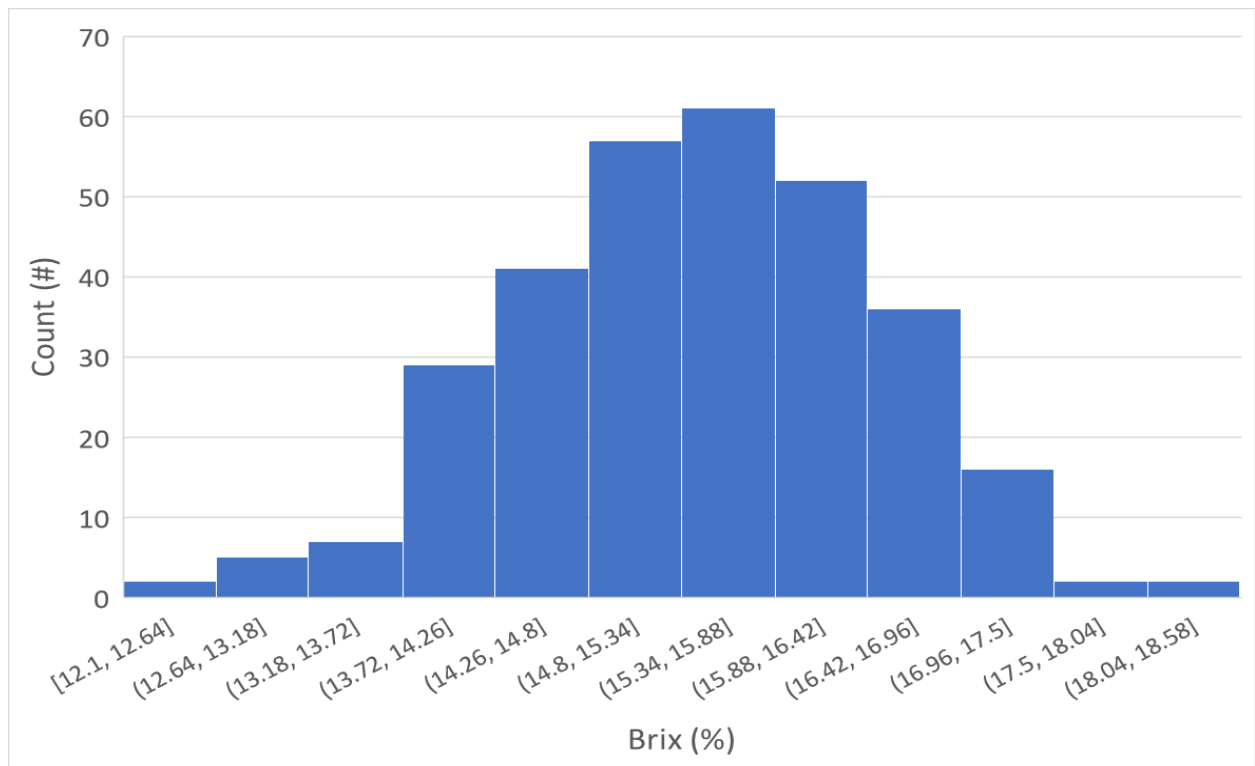


Figure 54. Histogram of Brix for the Hayward Cultivar.

Figure 54 above shows another histogram, observing the brix for Hayward where it follows the bell curve nature, being centred on within the data range. The peak of the data points lies between the brix range of 15.34% and 15.88%.

4.4 Comparison between RubyRed, SunGold and Hayward Cultivars

Surface Area, Mass and Volume

The surface area of fruit is an important attribute to quantify to help determine the different phenological stages and maturity of the fruit. However, direct measurement of this attribute is difficult, destructive and not very precise. Bovi, M. L., & Spiering, S. H. (2002) used image digitalization and edition methodology, which was then compared with the traditional gravimetric method. It was determined that the image digitization was twice as fast compared to the gravimetric method. The graphs in section 4.1, 4.2 and 4.3 above show the relationship between surface area and mass for the different kiwifruit cultivars.

In figure 26, the relationship between the volume and mass for RubyRed shows similarities to the graph for SunGold (figure 36). Where the majority of the data follows the line of best fit with 99% of the data being accounted for. This shows a positive relationship between the volume and mass for SunGold which was to be expected. As the volume of the fruit increases as does the mass of the fruit.

Relationship between Submerged and Digital Volume

The validation of the digital volume is important for further correlations between DM and SSC. The traditional golden standard using submergence-based volume measurement is used to calibrate digital volume. It is important to relate the water displacement method with the new digital novel method to enable comparability of the results. Ensuring the resulting measurements are efficient and correct.

The linear regression between the submerged volume (x-axis) and digital volume (y-axis) for each cultivar showed varying degrees of strong coefficient determination (R^2). It was observed for RubyRed ($R^2 = 98\%$, Fig 27), SunGold ($R^2 = 99\%$, Fig 37) and Hayward ($R^2 = 98\%$, Fig 47). A high R^2 value reveals a strong relationship and therefore both the submerged and digital are very similar and they agree with each other.

Figures 28, 38 and 48 are histograms for the density of the three kiwifruit cultivars. These represent the frequency in which the data is placed within a specified data range. All the figures (Fig. 28, 38 and 48) show a similar trend, with each showing a normal distribution (having one main peak). The “bell curve” is most predominant for the SunGold cultivar. Whereas, both RubyRed and Hayward have one peak with other high peaks surrounding this main peak. For SunGold (Figure 37), the data is skewed to the left while for Hayward (Figure 48) the data is skewed to the right.

Relationship between Dry Matter and Density

The fruit density has previously been observed to be highly correlated with dry matter content for some produce such as Mango (Saranwongab, S., 2004). The regression analysis of DM allows for better estimation of the fruit quality and harvest time. The experimental results from the different kiwifruit cultivars present potential correlations in relation to the literature found previously.

Table 6. *Upper and Lower limits for the different cultivar densities.*

Density	Hayward	RubyRed	SunGold
Std	10.458	10.055	7.817
Average	1024.9	1043.238	1057.34
Sample Size	311	312	312
Upper Limit	1056.274	1073.403	1080.791
Lower Limit	993.526	1013.088	1033.889

The table above shows important values to have a higher accuracy when evaluating the data sets below. The standard deviation shows how spread out the values are in a given dataset. The smaller the standard deviation the less variability of the data. Using standard deviation and the average, the coefficient of variation (CV) can be calculated to make comparisons.

$$\text{CV (coefficient of variation)} = \frac{\text{std}}{\text{avg}} \times 100$$

The following coefficient variations were obtained: Hayward (1.02%), RubyRed (0.96%) and SunGold (0.74%). The CV of the predicted density is the ratio of the standard deviation to the mean. The lower the CV value, the lower the variability around the mean. The higher the CV, there is a higher dispersion of data around the mean. Hayward has the highest CV and thus more variability around the mean while RubyRed and SunGold have lower CV values showing lower variability. Meaning the density does not vary by much between the kiwifruit (for SunGold and RubyRed). Having the upper and lower limits identified for each of the cultivars helped to justifiably remove any outliers outside of these limits.

The upper limit is representative of the largest data value that can be reached within the dataset while the lower limit is representative of the smallest data value that can be reached. SunGold has the highest upper and lower limit value, while Hayward has the lowest upper and lower limits. Reflecting the SunGold kiwifruits fall within a higher density data set range compared to both RubyRed and especially Hayward. The average values for the three cultivars should be close to the median values, representing the centre area of the data set, with SunGold having the highest average value, then RubyRed with Hayward having the lowest average density value. Correlating to the upper and lower limits.

The Hayward cultivar was expected to have a stronger relationship between DM and density compared to RubyRed based on prior literature obtained and the graph from Jordan. R. et al., (2000). The Hayward cultivar has been around since the 1920's (Zespri, 2021), the research conducted by Jordan et al. identifies that there is a strong relationship between DM and submerged density. The data and graph in the research paper by Jordan et al. (2000) shows the Hayward DM and submerged initial density had an R value of 96.2%. RubyRed, like previous studies conducted on Hayward, shows a strong relationship, but weaker in comparison to the Hayward cultivar. However, this may be due to smaller data sets and slight differences in how experiments were conducted. Jordan et al.'s data set had 812 Hayward kiwifruit whereas approximately 312 kiwifruit of each cultivar was used in this experiment. A significantly smaller data set in comparison to Jordan et al. (2000). The difference in submergence volume method can be noted, with Jordan et al., using magnesium sulphate solution and tanks. While the submerged volume measurement in this project were done on a smaller scale, each kiwifruit individually with no magnesium sulphate solution.

The DM range can be observed to be between 15 - 25% which is quite a wide spread of values. With the majority of the DM values lying between 18 - 22%. Studies conducted by Beever and Hopkirk., (1990)

and Burdon et al., (2004) have identified that for Hayward the DM range is approximately 12 - 20% of fresh weight at harvest, with most kiwifruit having an at-harvest DM range between 14 - 17%. When comparing RubyRed results in this study compared to previous literature for the Hayward cultivar, the general DM ranges overlap. However, the majority DM ranges vary significantly between the two cultivars with RubyRed having the majority of DM values at a higher DM %. The higher the DM the sweeter the taste and stronger the flavour.

In section 4.2, the graph for SunGold in Figure 39 is showing a similar trend compared to figure 41, looking at the relationship between the submerged density. However, the R value on this graph is slightly lower. It still rounds to 80% of the data being accounted for. This reveals that digital density has the potential to be used for the estimation of DM. This graph observing the correlation between the digital density (Figure 40) is similar to the graph above (Figure 41) looking at the submerged density. This was to be expected as both the submerged and digital densities are potentially interchangeable. Which was also noted for RubyRed (Figure 30), but SunGold results were highly interchangeable in comparison, likely due to increased human accuracy when carrying out the experiments. However, the digital density has a slightly lower R value, showing a slightly weaker relationship compared to the submerged density and DM.

Relationship between the Total Soluble Solids Content, DM and Density

The total soluble solids and harvest density has a direct relationship, according to literature by Jordan. R., et al., (2000), the harvest DM is highly correlated with SSC. DM is a strong taste indicator and thus an important property of kiwifruit in the consumer taste experience. The total soluble sugar content helps to measure the fruit's maturity, determining how far through the kiwifruit is in the ripening process. The higher the DM at harvest, the higher the SSC when sold to consumers. The following graphs in 4.1, 4.2 and 4.3 investigate the relationship between DM and SSC for the different kiwifruit cultivars.

In previous literature conducted by Jordan. R., et al., (2000), the SSC range was found to be between 10 - 16% (refer to Figure 1). This was found to be a similar range to previous studies by Beever and Hopkirk (1990) and Paterson et al. (1991). Typically, the kiwifruit arrives at the packhouse (at harvest maturity) with SSC values between 6.5 - 10.5% brix. As these values increase, it indicates the process of starch hydrolysis. Jordans paper notes that the kiwifruit with higher density and DM, correlated to higher SSC

values. However, the results of SSC and density obtained for SunGold show no relationship. Instead, the SSC range is consistently spread between 10-20%, despite increase or decrease in density.

The results for the relationship between SSC and Density across all cultivars showed no correlation. RubyRed had a weak relationship while SunGold and Hayward had no correlation. The data was majorly dispersed. This may be due to error in handling the raw data correctly or human error when taking measurements. However, this could be an accurate representation showing a weak or non-existent relationship between kiwifruit once the kiwifruit starts to mature and undergo senescence. However, these results do not align with the findings in literature.

Potential of Implementing Digital Density Commercially

The implementation of digital density for commercial kiwifruit is worth doing due to the positive results obtained from the RubyRed and SunGold cultivars. From the results, it can be observed that between the key parameters like DM and density (traditional and digital) strong relationships were formed. This provides a positive basis for further experimentation of digital density, to determine stronger relationships with higher efficiencies and lower error. The digital density can be implemented within the packhouse where existing equipment is in place to take photos for kiwifruit grading. It also has potential to be implemented out in the kiwifruit orchard, in the form of a 3D scanner gun, similar to existing NIR guns used for quality parameters of the fruit. The advantages of digital density include:

- Being a non-destructive technique.
- This technique is not limited to kiwifruit, can be used for other fruit like mangos.
- The volume measured is not subject to errors like air bubbles.
- Can be used along with correlations to estimate dry matter and brix anywhere within the supply chain.
- The digital volume estimation can be carried out on a grader using photogrammetry via existing images which are captured and provide an additional estimate of DM and brix which would then be combined with existing estimates of these parameters. Providing estimates that are more robust.

- More time efficient methods of image-based volume measurement could be developed. An example of this would be, using methods which have previously been developed which only require partial scanning (Olatunji, J. R., Redding, G. P., Rowe, C. L., & East, A. R., 2020)).
- Potentially other data driven techniques could be developed for rapid volume estimation of produce in the future.

Some limitations surrounding digital density could be the training of the equipment to get the correct data. Can be time consuming initially, however, with advances in the technology and coding this limitation will be overcome. Potentially may not be cost-effective for some growers depending on the size of their crop and existing equipment they may have in place. A limitation would be the lighting and rotation of the fruit has an influence on the 3D image. Further study is required to gain more in-depth knowledge around the feasibility of implementing this method commercially on a larger scale. Whether it would be better suited within the packhouse or out in the orchard as a handheld device. Further study is recommended around the experimentation, to be done with more data points to gain more insight between the different parameter relationships, especially for Hayward.

Chapter 5: Conclusion and Recommendations

5.1 Conclusions

In conclusion, this project was conducted in part to assess the industrial opportunity for the exploitation of imaging technologies as a means to measure key parameters for kiwifruit quality, the density, DM and SSC. It is important to the kiwifruit industry for accurate estimation of the DM. This report identified literature pertaining to the current methods for measuring the DM. Commonly, physical drying, NIR and submerged volume methods are used in industry. NIR is a direct competitor for 3D scanning, with NIR results showing high efficiency. However, it is a less feasible method to implement due to cost and limitations like specific lighting conditions, fruit orientations and calibration set up. Literature identified key methods to use in the duration of the project including physical drying in duplicate (for higher accuracy), 3D scanning and submerged volume by Jordan, R. B. et. al (2000).

Literature identified key correlations between quality parameters. Jordan, R. B. et. al (2000), identified a strong correlation between density and dry matter (and SSC). However, this key relationship has been impractical to exploit industrially due to the cumbersome and time-consuming nature of accurately measuring the volume using submergence-based techniques. Thus, identifying the viability of digital volume to implement industrially will be a huge asset for the kiwifruit industry. It will eliminate the amount of time taken, increase efficiency and minimise waste. The results have shown positive correlations between submerged and digital densities and DM for RubyRed (98%), SunGold (99%) and Hayward (98%).

For RubyRed and SunGold it was observed that volume, DM and density had good correlations with 72% for RubyRed and 77% for SunGold. In comparison Hayward had the weakest correlation with an R^2 value of 42%. This is likely due to the inconsistency of lab work and measurements due to COVID lockdown. As well as human error, due to limited access and equipment, the efficiency was not at its optimal. For all cultivars, the relationship between density and SSC was weak with R^2 values of 45% (RubyRed), 20% (Hayward) and no correlation for SunGold. The positive results for RubyRed and SunGold (for digital density and DM) provide a good base for extended research of this project, as it shows potential for the industry.

5.2 Recommendations

Based on the findings in literature and the results from the project, a few recommendations can be made:

- Notably, the DM and density (submerged and digital) relationships showed positive relationships with R^2 of 73% for submerged and 65% for digital. This is a good base for further research to allow growers to incorporate digital non-destructive methods to help determine the optimal period to harvest the kiwifruit.
- Potentially extend this research project on a larger scale with more data and people involved, so the time to complete measurements is shorter and thus the results will be more efficient as the fruit will not be stored for prolonged periods of time. Minimising the effect that kiwifruit maturation and water loss may have on the kiwifruits and thus the results.
- This method has the potential to be an additional non-destructive method for determining dry matter. It can be used both on orchard and in the packhouse. If combined with existing methods, it could result in improved accuracy or segregation in dry matter estimation.
- To further this research with a larger number of kiwifruits (and raw data), now that the method has been identified to work. It can be carried out on a larger scale to identify potential relationships and correlations that were weak (give example of kiwifruit correlation that could have been stronger).
- Digital scanning for the digital density is relatively inexpensive since it could be achieved with a load cell and a standard RGB sensor. In addition, the large number of images taken by current graders can also be used to measure volume and can therefore be used to estimate dry matter and brix when combined with the mass measurements already made by graders. These additional estimates could serve as supplements to bolster the reliability of the existing estimates graders make of dry matter and brix, or even replacements should they prove more accurate.
- Further optimisation of the 3D scanning method. Ensuring in-depth knowledge about the methodology required to obtain an accurate data set. This method has the potential for rapid estimation of dry matter as an alternative to current sampling. During the packhouse process, hundreds of photos are taken of the kiwifruit which can be utilised for forming digital kiwifruits. This eliminates the time (15-20 minutes) taken to scan individual kiwifruits.

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7.0 Appendix

7.1 Coding Script

For the determination of digital volume and surface area from .stl files

```
import bpy

import math

import random

import numpy as np

import os

from math import radians

from mathutils import Matrix

from mathutils import Vector

import bmesh

import csv

import statistics

import object_print3d_utils

print("Script x")

#Delete all objects

bpy.ops.object.select_by_type(type='MESH') #select all meshes

bpy.ops.object.delete(use_global=False) #delete all meshes (start blank)
```

```
#set the directory which we will ouput the results too

output_dir = bpy.path.abspath("//")

output_dir = output_dir + "output/"

#get all the file names of the stl files we will be processing

stl_dir = bpy.path.abspath("//")

stl_dir = stl_dir + "orig_stl/"

stl_filenames = []

for file in os.listdir(stl_dir):

    if file.endswith(".stl"):

        stl_filenames.append(file)

print("the length of the file list is " + str(len(stl_filenames)))

##fruit loop starts here

volume_list = []

surface_area_list = []

for fruit in range(0, len(stl_filenames)):

    #get rid of all previous files (all scene objects)

    bpy.ops.object.select_all(action='DESELECT')
```

```
bpy.ops.object.select_all()
```

```
bpy.ops.object.delete()
```

```
#load in the stl file
```

```
fpath = stl_dir + stl_filenames[fruit]
```

```
bpy.ops.import_mesh.stl(filepath=fpath)
```

```
    #set the center of mass of the object (can do this either by volume or area)
```

```
bpy.ops.object.origin_set(type='ORIGIN_CENTER_OF_VOLUME')
```

```
#scale the geometry
```

```
bpy.context.object.location[0] = 0
```

```
bpy.context.object.location[1] = 0
```

```
bpy.context.object.location[2] = 0
```

```
bpy.context.object.scale[0] = 0.001
```

```
bpy.context.object.scale[1] = 0.001
```

```
bpy.context.object.scale[2] = 0.001
```

```
#apply the transformation to stop it being combined with any subsequent ones
```

```
bpy.ops.object.transform_apply(location=True, rotation=False, scale=True)
```

```

#measure the volume and surface area of this fruit

    #Get the active mesh

mesh = bpy.context.object.data

    # Get a BMesh representation

    bm = bmesh.new() # create an empty BMesh

bm.from_mesh(mesh) # fill it in from a Mesh

    # Modify the BMesh, can do anything here...

volume = bm.calc_volume()

print("volume is " + str(volume))

#surface_area = sum(f.calc_area() for f in bm.faces)

surface_area = object_print3d_utils.mesh_helpers.bmesh_calc_area(bm)

print("surface area is " + str(surface_area))

volume_list.append(volume * 1000 * 1000) #ml

surface_area_list.append(surface_area * 10000) #cm^2

    # Finish up, write the bmesh back to the mesh

bm.to_mesh(mesh)

bm.free() # free and prevent further access

```

```

#and save the collected information to file

output_filepath = output_dir + "output.csv"

with open(output_filepath, 'w', newline='') as f:

   thewriter = csv.writer(f)

#Grower, Count, Harvest

header = []

header.append('Filename')

header.append('Volume (ml)')

header.append('Surface area (cm^2)')

thewriter.writerow(header)

    for fruit in range(0, len(stl_filenames)):

data = []

data.append(stl_filenames[fruit])

data.append(volume_list[fruit])

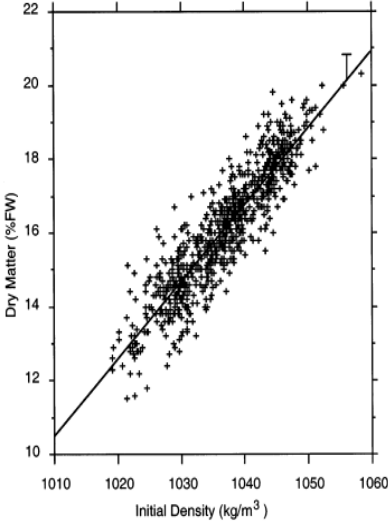
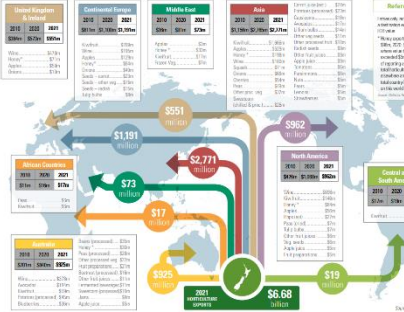
data.append(surface_area_list[fruit])

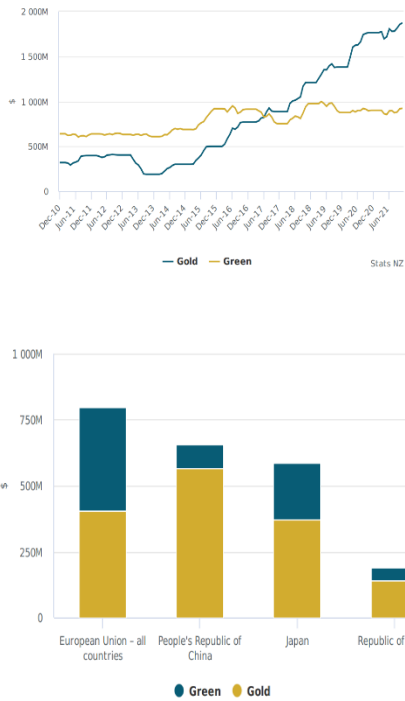
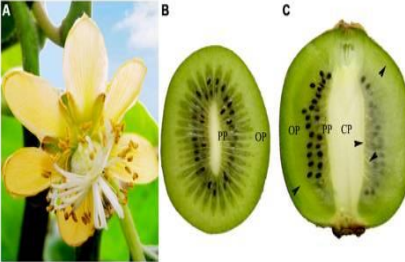
thewriter.writerow(data)

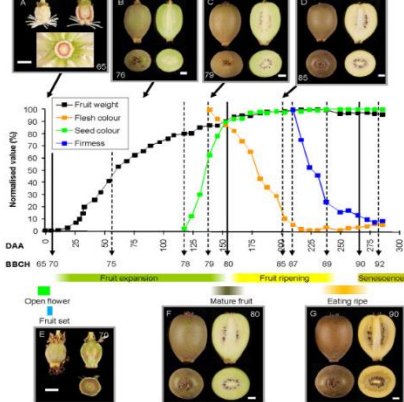
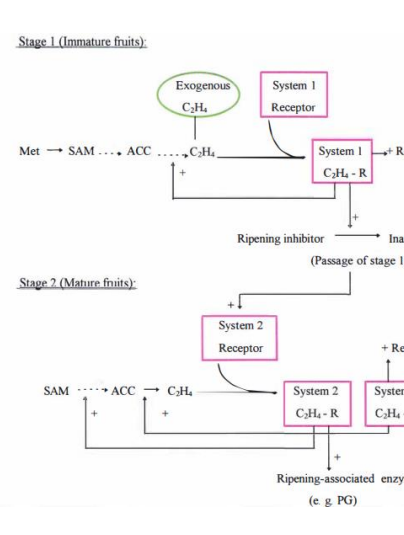
```

```
print("Finished")
```

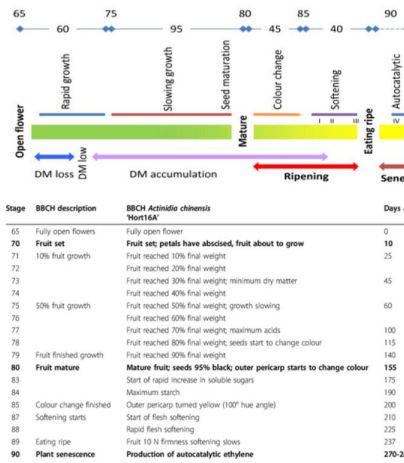
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