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# A mechanistic model to describe the effects of time, temperature and exogenous ethylene levels on softening of kiwifruit

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ABSTRACT

Early harvested kiwifruit (*Actinidia deliciosa* (A Chev) Liang et Ferguson cv 'Hayward'), from 14 growers and two seasons were stored under a wide range of storage temperatures (0–10 °C) and exogenous ethylene levels (0–200 μL $L^{-1}$) followed by an ethylene free shelf life period at 0–20 °C. Firmness levels were monitored using a non-destructive compression technique. A mechanistic model, based on a simplified representation of the physiology underlying fruit softening, explained 97% of the observed variation.

The kinetic model parameters appeared to be generic for the 14 grower lines studied. Differences between the grower lines could be explained based on differences in the initial firmness levels and the initial amounts of active enzyme system present.

The model was validated with independent experimental data on the softening of 70 batches of main harvest kiwifruit stored at 0 °C, with more than 99% of the variation explained for each of the 70 grower lines. A further validation was done using literature data on shipping of "Kiwistart" fruit under dynamic temperature and ethylene conditions.



## 1. Introduction

The New Zealand kiwifruit industry provides ready-to-eat kiwifruit (*Actinidia deliciosa* (A Chev) Liang et Ferguson cv 'Hayward') to overseas markets by harvesting early season kiwifruit, and ripening this fruit during shipping by applying ethylene at elevated temperatures (Lallu et al., 1989). A key criterion for consumers in their acceptance of this so-called "Kiwistart" fruit, is firmness, with an "eating window" of between 4 and 8 N (MacRae et al., 1990). Following long term storage of the "main harvest" fruit, kiwifruit lines intended for export by New Zealand kiwifruit industry must have a 'soft fractile' greater than 9.81 N. The soft fractile is defined as the 3rd percentile in a sample of 300 fruit, i.e. the 9th softest fruit of a sample of 300 must be greater than 9.81 N (Jabbar, 2014).

The rate of kiwifruit softening is affected by time, temperature, exogenous ethylene levels and maturity of the fruit (Burdon et al., 2014; Jabbar and East, 2016; Pranamornkith et al., 2012; Ritenour et al., 1999). Although the climacteric rise in ethylene production in kiwifruit only occurs after the fruit have undergone substantial softening, small amounts of exogenous ethylene can rapidly accelerate softening even at low temperatures. Generally, kiwifruit softening follows a triphasic curve with different enzymes responsible during the subsequent softening phases (Bonghi et al., 1996; Redgwell et al., 1992; Schröder and Atkinson, 2006). While considerable amount of research has been done to understand the mechanism of kiwifruit softening, most attempts to model softening of kiwifruit have been based on purely empirical models (Benge et al., 2000b; Jabbar et al., 2014). Although these models can be used to describe biological systems, their parameters have no obvious biological meaning, and as a result, their generic and predictive value is generally limited. Mechanistic, or kinetic-based, models have been used to describe softening in avocado (Hertog et al., 2003; Ochoa-Ascencio et al., 2009), apples (Gwanpua et al., 2013, 2012; Hertog et al., 2001), peaches (Tijskens et al., 1998), and tomatoes (Van Dijk et al., 2006). Hertog et al. (2004b) used a Michaelis-Menten type kinetics to model the impact of the rate of respiration on the rate of kiwifruit softening. While this approach focussed on a wide matrix of gas

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conditions at different temperatures the actual softening pattern was not monitored as they only measured the overall change in firmness over a fixed period of time. So far, no attempt has been made to extensively model the impact of ethylene on kiwifruit softening.

Our aim was to develop a robust mechanistic model, based on simplified physiological concepts, that would enhance the interpretation of kiwifruit softening behaviour under a wide range of storage and shelf-life situations combining the effects of time, temperature and exogenous ethylene. Such a model will enable the New Zealand kiwifruit industry to define storage requirements to reliably bring ready-to-eat "Kiwistart" fruit to the market.

## 2. Material and methods

### 2.1. "Kiwistart" storage trials

The storage trials with "Kiwistart" fruit were conducted at Massey University, Palmerstone North, New Zealand. The experimental work characterised in detail the effect of different ethylene applications at different temperatures on the softening of batches of "Kiwistart" fruit from two seasons (2000 and 2001) during both storage and subsequent shelflife. This enabled a robust calibration of the model. The storage period of four weeks reflected the time required to ship "Kiwistart" fruit from New Zealand to Europe.

#### 2.1.1. Fruit

Export quality "Kiwistart" fruit (*Actinidia deliciosa* (A Chev) Liang et Ferguson cv Hayward) were obtained from growers from Te Puke, New Zealand. In 2000 fruit from four growers were harvested on April 17th. In 2001 fruit obtained from ten growers were harvested on April 25th–26th. After harvest fruit were graded, packed and couriered overnight to Massey University. On arrival, fruit were randomised, individually labelled, and initial fruit measurements were taken. Samples of 30 fruit each were assigned to each of the storage treatments for non-destructive firmness monitoring.

#### 2.1.2. Fruit measurements

Throughout the experiments fruit firmness was measured non-destructively by recording the maximum compression force required to compress tissue for 1.5 mm using the standard penetrometer cylinder probe (7.9 mm diameter) used for destructive firmness measurements in the kiwifruit industry. The probe was mounted on a TA-XT2 texture analyser (Stable Micro Systems Ltd.). The compression test was run using a pre-test speed of 2 mm $s^{-1}$, a test speed of 1 mm $s^{-1}$, and a trigger force of 0.0015 N. A compression test begins when the probe travels to the fruit's surface at pre-test speed and detects an initial resistance of a given value (the trigger force) as it begins to make contact with the fruit after which it continues to compress the fruit at the test speed. All fruit were tested at weekly intervals at their respective storage or shelf life temperatures. Fruit were measured until they reached a firmness of about 5 N. After each measurement, the measured spots were marked with a felt-tip pen to prevent subsequent measurements from being taken at the same spot.

Only during the 2000 season destructive firmness measurements were taken at certain stages to compare to the non-destructive measurements. At the start of the experiment, and at the end of the ethylene treatment destructive firmness readings were taken on a separate batch of 30 fruit. At the end of shelf life, firmness of all remaining fruit was destructively measured as well. Destructive firmness readings were taken using the standard penetrometer cylinder probe (7.9 mm diameter) mounted on a TA-XT2 texture analyser (Stable Micro Systems Ltd.). A piece of skin about 2 mm thick was removed using a cutting device with a fixed blade. The test was run using a pre-test and a test speed of both 10 mm $s^{-1}$, a trigger force of 0.0015 N, and allowing the probe to travel 9 mm deep into the tissue, measuring the maximum force encountered.

#### 2.1.3. Storage conditions

A flow-through system using 75 L barrels located in temperature-controlled rooms was used to generate the intended conditions and to prevent contamination from other potential ethylene sources. Before entering the barrels, the gas stream was humidified by bubbling through jars with water. Depending on temperature, flow rates were controlled at 0.6–1.9 L $min^{-1}$ to prevent accumulation of $CO_2$ and depletion of $O_2$.

During the 2000 season, fruit from each of the four growers were stored for 4 weeks at one of 16 temperature-ethylene combinations generated by continuously applying ethylene levels of 0, 0.1, 10 or 200 μL $L^{-1}$ at temperatures of 0, 2, 5 or 10 °C. After these ethylene treatments, fruit were stored for up to 6 weeks shelf life at 0, 5, 10 or 20 °C under ethylene free air. The factor grower was used as a blocking factor assigning each of the 64 possible storage temperature × ethylene level × grower combinations to one of the 4 shelf life temperatures in such a way that the 4 growers together covered all possible storage temperature × ethylene level × shelf life temperature combinations, making sure that these main factors were equally represented per grower (Table 1).

During the 2001 season, fruit from each of the ten growers were stored for 5 weeks at one of 6 temperature-ethylene combinations generated by continuously applying ethylene levels of 0, 2 or 100 μL $L^{-1}$ at temperatures of 0 or 2 °C. After these ethylene treatments, fruit were stored for up to 8 weeks shelf life at 0, 10 or 20 °C under ethylene free air in such a way that all possible storage temperature × ethylene level × shelf life temperature combinations were covered. Similar to the 2000 season the possible storage combinations were blocked over three groups of growers. (Table 1). The term shelf life is used to indicate the storage period under ethylene free air although the temperatures applied are not necessarily typical 'shelf life' temperatures.

In both years a flow-through system was used to generate the different levels of ethylene by mixing ethylene standard gases with air. Ethylene concentrations were regularly checked using gas chromatography (Varian 3400, USA, fitted with flame ionisation

**Table 1**
Shelf life temperatures (in °C) applied to the different grower batches after storage at the temperature × ethylene level combinations indicated. ($T_{stor}$: storage temperature in °C); $C_2H_4$: exogenous applied ethylene level in μL $L^{-1}$).

2000 season

| | | Grower 1 | | | | | | Grower 2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_2H_4$ | $T_{stor}$ | 0 | 2 | 5 | 10 | $C_2H_4$ | $T_{stor}$ | 0 | 2 | 5 | 10 |
| 0 | | 20 | 0 | 5 | 10 | 0 | | 0 | 5 | 10 | 20 |
| 0.1 | | 0 | 5 | 10 | 20 | 0.1 | | 20 | 0 | 5 | 10 |
| 10 | | 10 | 20 | 0 | 5 | 10 | | 5 | 10 | 20 | 0 |
| 200 | | 5 | 10 | 20 | 0 | 200 | | 10 | 20 | 0 | 5 |
| | | Grower 3 | | | | | | Grower 4 | | | |
| $C_2H_4$ | $T_{stor}$ | 0 | 2 | 5 | 10 | $C_2H_4$ | $T_{stor}$ | 0 | 2 | 5 | 10 |
| 0 | | 5 | 10 | 20 | 0 | 0 | | 10 | 20 | 0 | 5 |
| 0.1 | | 10 | 20 | 0 | 5 | 0.1 | | 5 | 10 | 20 | 0 |
| 10 | | 0 | 5 | 10 | 20 | 10 | | 20 | 0 | 5 | 10 |
| 200 | | 20 | 0 | 5 | 10 | 200 | | 0 | 5 | 10 | 20 |

2001 season

| | Growers 1–4 | | | | Growers 5–7 | | | | Grower 8–10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_2H_4$ | $T_{stor}$ | 0 | 2 | $C_2H_4$ | $T_{stor}$ | 0 | 2 | $C_2H_4$ | $T_{stor}$ | 0 | 2 |
| 0 | | 20 | 0 | 0 | | 10 | 20 | 0 | | 0 | 10 |
| 2 | | 0 | 10 | 2 | | 20 | 0 | 2 | | 10 | 20 |
| 100 | | 10 | 20 | 100 | | 0 | 10 | 100 | | 20 | 0 |