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Effects of Harvest Maturity on Storability, Ripening Dynamics, and Fruit Quality of 'Geneva 3' Kiwiberries

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Abstract. **Maturity at harvest is an important determinant of fruit quality in kiwiberry [*Actinidia arguta* (Siebold & Zucc.) Planch. ex Miq.], a climacteric fruit that is harvested after reaching physiological maturity but not yet ready-to-eat ripeness. Although a recommended cultivar for commercial kiwiberry producers in the northeastern United States is 'Geneva 3', no published research exists regarding recommended harvest and postharvest practices for this variety. In this study, conducted across two seasons, 'Geneva 3' kiwiberries were harvested at a range of mean maturities (6.5, 8.0, and 10.0°Brix), held in cold storage for various durations (4, 6, and 8 weeks), and then ripened at room temperature. At regular time points during ripening (0, 3, 6, 9, and 12 days), visual quality was assessed, and measurements were taken of soluble solids content, dry matter content, and firmness as a means of characterizing fruit quality. Results show that berries harvested at 6.5°Brix largely became visually unacceptable under cold storage conditions and resulted in lower overall quality fruit. Harvesting at 8.0°Brix resulted in high-quality fruit amenable to cold storage, and such quality was not enhanced by delaying harvest to 10.0°Brix. Fruit harvested at 8.0°Brix after 4 weeks in cold storage was found to be acceptable for consumption for, on average, a 3-day window after ripening at room temperature for 4 days. After 6 weeks in cold storage, the consumability window shortened to ~2 days, starting after 3 days of ripening at room temperature. After 8 weeks in cold storage, the fruit were found to be largely visually unacceptable for fresh eating. In summary, the results indicate that harvesting 'Geneva 3' kiwiberries at 8.0°Brix produces berries with the greatest storability (at least 6 weeks in cold storage), the longest window of peak consumability, and the highest overall quality, while mitigating the risks associated with leaving physiologically mature fruit to ripen further in the field.**

Harvest maturity is one of the most important determinants of fruit quality and postharvest performance. *Actinidia arguta* (Siebold & Zucc.) Planch. ex Miq., commonly known as the kiwiberry, is an emerging commercial crop with a long history of individual use. As a climacteric fruit, kiwiberries are typically harvested when physiologically mature but not yet ripe (i.e., ready to eat). This practice has many advantages, including reducing mechanical damage to firmer fruit when harvesting and processing, minimizing exposure to late-season stressors in the field, and improving storability. Studies on optimal harvest time have been conducted for kiwiberries (Fisk et al. 2006; Han et al. 2019), but such studies are cultivar specific and their results do not necessarily transfer to other varieties, not to mention other production regions. General Goldilocks-type principles emerge from such studies, however, suggesting negative effects from harvesting either too early or too late. Harvesting too early can lead to fruit with suboptimal physiochemical profiles that lack sufficient aroma and taste (Mendes da Silva et al. 2020), not to mention susceptibility to physiological damage under cold storage (CS) conditions. Harvesting too late, on the other hand, risks fruit exposure to in-field stressors (e.g., spotted wing drosophila, wind) and significant reduction in storability (Latocha et al. 2021).

Green-skin kiwiberry varieties, even those that develop a visual "blush" under certain environmental conditions, display no reliable visual cues to signal their transition to physiological maturity in the field (Huang 2014). A method of monitoring the progression of ripeness destructively is therefore necessary for commercial producers, and this process typically begins with monitoring for transition to the so-called black-seed stage (BSS). As kiwiberries mature, their seedcoats transition from white to tan, then finally to a speckled dark brown or black. This color change is an easily observed sign that a fruit has reached physiological maturity, meaning its seeds are fully mature and capable of germination. Upon reaching BSS, growers undertake more intensive monitoring, usually based on either soluble solids content (SSC), a proxy for sugar content. and/or dry matter (DM) content. In practice, SSC is measured by analyzing the juice of individual berries with a handheld refractometer. Although SSC is a widely used metric for its convenience, some authors suggest DM to be a more accurate integrated indicator of kiwiberry ripeness (Fiorentini and Kay 2019), not least of all because it can be measured on groups of berries, thereby reducing sampling bias. Determining DM content is more time-consuming, however, and requires removing fruit from the field, desiccating it, and taking multiple mass measurements. For these reasons, it appears to be less used than SSC, especially among small producers. Other maturity indices include ethylene, titratable acidity, and flesh color (Mendes da Silva et al. 2020), but none are as convenient or reliable as SSC or DM and therefore are not often used.

As climacteric fruits, kiwiberries produce autocatalytic ethylene as they ripen, leading to acceleration of ripening even after harvest (Latocha et al. 2021; Pratt and Reid 1974). Ethylene is an important plant hormone with a variety of functions, including regulating genes involved in flavor production, color, texture, and softening (Atkinson et al. 2011). In climacteric fruits such as kiwiberries, tomatoes (*Solanum lycopersicum*), bananas (*Musa acuminata*), and many others, ethylene production is accompanied by a respiratory burst of carbon dioxide (CO_2) (Atkinson et al. 2011). In theory, if the respiration products of kiwiberries could be monitored in a cost-effective manner, the dynamics of ethylene and CO_2 production could be used to determine optimal harvest time. Ideally, for the sake of storability, harvest should occur after physiological maturity but before the onset of autocatalytic ethylene production (Latocha et al. 2021). Autocatalytic ethylene production triggers a hormone cascade that moves

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the fruit to ripeness, increasing sugar levels, developing flavor, and softening the skin and flesh to ready-to-eat firmness levels. Depending on ambient conditions (temperature and atmospheric composition), this process of ripening can take as long as several months (e.g., in CS) or as little as a few days, before further transitioning to a stage of overripeness that is no longer acceptable to consumers (Atkinson et al. 2011). Both ethylene and CO_2 can be measured via gas chromatography, but such technically demanding respiration data are not typically used to monitor the progression of ripening by producers.

In practice, the method used to determine harvest time depends, at least in part, on the size of the growing operation. Kiwiberries ripen erratically across vineyards and even within the canopies of individual vines (Giuggioli et al. 2017). In response to this erratic ripening, farms that can market fruit directly to consumers may conduct multiple harvests to bring successive batches of ripe fruit to local points of sale such as farm stands or farmer's markets (Latocha et al. 2021). Compared with larger operations, these smaller farms (usually ≤ 0.5 ha) can conduct multiple, selective harvests more feasibly because their overall yields are smaller and, with direct marketing, may not have the need for a highly storable crop (Latocha et al. 2021).

Multiple harvests may not be practical, however, for larger wholesale producers in need of a single harvest that maximizes both storability and overall yield of high-quality fruit for an entire vineyard. Although smaller scale operations may be able to conduct such a single-pass harvest for an entire vineyard over a matter of days, larger ones may require several weeks, during which time maturity would continue to advance. The rate of such advancement appears to be environmentally dependent, but an average increase of ∼1°Brix/week has been routinely observed in New Hampshire, particularly for physiologically mature SSC levels < 12°Brix. Certainly, for any given variety, shorter harvest windows are preferred to increase fruit uniformity and therefore simplify postharvest handling. Indeed, the logistical and labor demands of a rapid, well-timed harvest are one reason why a mixed cultivation of earlier- and later-maturing varieties is a typical practice in many horticultural crops, and likely kiwiberry operations will move in this direction as a wider range of economically viable cultivars becomes available (Latocha et al. 2021).

Although there have been previous studies on the effects of harvest maturity on kiwiberry quality, postharvest physiology is likely cultivar specific, and current recommendations may not apply to 'Geneva 3', a recommended cultivar for New England (Hastings and Hale 2019). Indeed, Latocha et al. (2014) found a significant interaction between SSC at harvest and cultivar when comparing the physiochemical properties of the two cultivars Ananasnaya and Bingo at three levels of maturity at harvest. General recommendations typically state that kiwiberries should be harvested between 6.5 and 8.0°Brix to attain high fruit quality (Hassall et al. 1998), but more recent studies have investigated specific cultivars to refine these recommendations. For example, Fisk et al. (2006) found that 'Ananasnaya' kiwiberries harvested after reaching 8.0°Brix attained high fruit quality after ripening in CS whereas fruit harvested at 6.5°Brix did not. Strik and Hummer (2006) also recommend 8.0°Brix as a minimum harvest threshold for 'Ananasnaya', and that harvest should occur between 8.0 and 14.0°Brix. Latocha et al. (2014), however, suggested 8°Brix as an upper limit for harvesting both 'Ananasnaya' and 'Bingo'. Their study recommended harvesting both cultivars between 6.5 and 8.0°Brix, as opposed to 8.0 and 9.5°Brix, for improved storability (Latocha et al. 2014). Another study, focusing on the South Korean cultivar Cheongsan, indicated that the berries should be harvested when the average SSC is > 8.0°Brix (Han et al. 2019). No study to date has investigated the optimal harvest time for 'Geneva 3'. Establishing best practices specific to 'Geneva 3' is needed to improve fruit quality and reduce postharvest losses for growers of this important cultivar. The aim of this study is to determine the optimal harvest time for 'Geneva 3' kiwiberries and to investigate the impact of harvest maturity on storability and ripening dynamics.

Materials and Methods

Study site. The study site was the Woodman Horticultural Research Farm, part of the New Hampshire Agricultural Experiment Station (NHAES) in Durham, NH, USA, on the western side of the University of New Hampshire campus (lat. 43°09'06"N, long. 70°56'43"W). The site has a temperate climate and an onsite weather station that records daily temperature and precipitation (https://rainwise.net/weather/StraffordNEWA). The soil type is Charlton fine sandy loam, and the research vineyard is located on a slight slope with a southern aspect, with rows running roughly east–west.

Plant materials. The kiwiberry plants used in this study were exclusively *Actinidia arguta* cv. Geneva 3, a recommended cultivar for Northeast US growers (Hastings and Hale 2019). As documented in Melo et al. (2017), 'Geneva 3' exists in the US Department of Agriculture (USDA) National Plant Germplasm System as Plant Introduction PI617133 (also CACT80 and DACT229) and can be found throughout the nursery trade under a range of names (e.g., 'Geneva 1', '74-49', 'Kuchta', 'Michigan State', and 'Passion Popper') as a result of historical misidentification and deliberate rebranding. A genetically verified commercial source of the 'Geneva 3' variety used in this study can be sourced through Hartmann's Plant Co., Lacota, MI, USA.

The six mature 'Geneva 3' vines used in this study were acquired from three different sources—namely, live plants from Tripple Brook Farm (Southampton, MA, USA), live plants from the University of Minnesota Horticultural Research Center (Excelsior, MN, USA), and dormant cuttings from the USDA National Plant Germplasm System—and transplanted to the NHAES vineyard in late May 2013. Since establishment, the vines have been grown on a T-bar trellis system, which aids in disease prevention and pollinator access (Strik and Hummer 2006). The T-bar system at the NHAES consists of support posts placed 9.75 m apart, with two mature vines growing between adjacent posts (Hastings and Hale 2019). The crossbars, placed horizontally over each support post to create a T shape, are 1.8 m long. An equally spaced set of five 12-guage wires running perpendicular to the crossbars supports the vines' permanent cordons and annually replaced fruiting laterals, which are fastened to the wires with clip-to-wire fasteners to create a Lincoln-type canopy (Jackson and Nguyen 1983). The vines are irrigated with microsprinklers mounted atop polyvinylchloride stakes and attached via spaghetti tubing to irrigation lines elevated ∼1.2 m off the ground via fastening to an in-row support wire (Hastings and Hale 2019).

The 'Geneva 3' vines are open-pollinated by a large and diverse collection of male, pollenizer cultivars growing in the NHAES research vineyard, the nearest males being cvs. Meader Male, 74-46, 74-52, and Smith 2 Male. For the two seasons of this study, fruit were harvested from 6 Sep to 3 Oct (season 1, 2020) and 6 Sep to 19 Oct (season 2, 2021).

Experimental design. The design of the experiment was a split-split plot randomized complete block design (RCBD) nested within season, with each of the three blocks consisting of two vines, paired based on both physical proximity within the vineyard and provenance (block 1, Tripple Brook Farm; block 2, Horticultural Research Center; block 3: USDA). In terms of treatments, harvest maturity served as the main plot (three levels: 6.5, 8.0, and 10.0 mean °Brix), weeks in CS as the subplot (0–1 °C, > 90% relative humidity), and days ripening at room temperature (RT) as the sub-subplot (20–22 °C). Fruit was held in CS for periods of either 4 or 6 weeks, as previous seasons indicated that fruit held for 8 weeks ripen in CS beyond consumer acceptability (data not shown). When fruit were removed from CS to ripen at RT, quality analysis was conducted at multiple time points (0, 3, 6, 9, and 12 d). The full quality analysis procedure is described in detail in the "Fruit Quality Assessment" subsection, and Supplemental Fig. S1 is provided as a schematic of the experimental design.

At the subplot level, the experimental units consisted of five 6-oz plastic, vented clamshells, each containing 14 berries (Supplemental Fig. S1). After removal from CS, the berries within each experimental unit were sorted for visual quality, and high-quality berries (i.e., no superficially visible damage) were condensed to three clamshells of 10 uniform berries each for subsequent quality analysis. Rare berries (< 0.5%) of outlying low quality were discarded at this point if they were nonrepresentative of their groups and therefore indicative of imperfect sorting (e.g., of cryptic injury) before CS. For quality analysis at each ripening time point, six berries were selected randomly for analysis, two from each clamshell. Each of the berries in the group of six was considered a subsample, and the six subsamples were

averaged for data analysis, as described in detail in the 'Fruit Quality Assessment' subsection.

Harvest maturity was determined based on mean degrees Brix, a common proxy for sugar content, and a popular and convenient metric for commercial growers. For each block, the first harvest occurred when the mean of the block reached 6.5°Brix. The second maturity level that triggered harvesting was a mean of 8.0°Brix, and the third maturity point was a mean of 10°Brix. These levels were chosen based on the common SSC recommendations for other kiwiberry cultivars. For example, 6.5°Brix is historically the recommendation for kiwifruit growers (Fisk et al. 2006) and is often reported as the minimum maturity threshold for kiwiberry growers in Europe (Debersaques et al. 2015). Recent studies such as those of Han et al. (2019) and Fisk et al. (2006) cite 8.0°Brix as the recommended harvest maturity level for their cultivars of interest, and the 10.0°Brix harvest was included because other researchers have recommended harvesting at levels as high as 14.0°Brix, particularly for small-scale growers (Strik and Hummer 2006). This study aimed to ascertain the minimum harvest maturity level that would result in quality 'Geneva 3' fruit and investigate whether any significant benefit was gained from allowing fruit to ripen further in the field.

Maturity monitoring. Data acquisition began each season with visual maturity monitoring, a practice kiwiberry growers typically undertake to track fruit development. Beginning 1 Sep of each season, vines were inspected systematically every 3 days for the transition to BSS (Supplemental Fig. S2). At each sampling time, six berries from each block (three from each vine) were cut in half to check visually for BSS, and the number of fruit at BSS was recorded. If a berry contained any seeds yet to transition to BSS, the berry was considered as a whole as yet-to-reach BSS. To ensure representative samples despite uneven ripening throughout the vine, the canopy of each vine was stratified into quadrants, based on trunk and cordon (i.e., center trellis wire) locations (Supplemental Fig. S3). For BSS monitoring, three quadrants were selected randomly per vine for sampling. Nonrepresentative fruit already soft to the touch (often physically damaged) were discarded and removed from the vine, as berries that are physiologically ripe release excess ethylene that can accelerate the ripening of nearby berries.

When four or more fruit in a set of six reached BSS within a given block, more frequent monitoring of SSC began, with data taken every other day (Latocha et al. 2014). Using destructive sampling, SSC was measured by squeezing juice from an individual berry into the sample cup of a digital refractometer (PAL-1; Atago Co., Ltd., Tokyo, Japan). As with BSS, SSC monitoring consisted of measurements made on a set of six random berries from each block. Unlike BSS, however, for SSC the berries were taken out of the field and measured in the laboratory after the fruit had reached RT.

The three average target SSC values used to time harvests in this study were 6.5, 8.0, and 10.0°Brix. When the average degrees Brix of a sample of six berries reached the target value, 12 additional berries (six from each vine) were sampled randomly from the block and measured to confirm the average with a larger sample. Harvest commenced after the average Brix level of this larger, random sample of 12 berries per block reached the target value and every individual berry tested had reached BSS.

Harvest and storage. Harvests were completed on a block-by-block basis, in each case following the protocol described in detail here. For each of the three harvest times (H1 = 6.5°Brix, H2 = 8.0°Brix, and H3 = 10.0°Brix), 105 kiwiberries were harvested from each of the two vines for a total of 210 berries per block. All berries per block were harvested within 1 h. These berries were harvested as randomly as field conditions allowed, with a quarter of the fruit coming from each quadrant of the canopy (Supplemental Fig. S3). Berries that were nonrepresentative by being soft to the touch or that displayed clear surface damage (e.g., scratches, mechanical damage, extensive scabbing, flyspeck) were not included in the harvest. Fruit were harvested by hand into a clean plastic bucket, washed immediately with running tap water, and air-dried thoroughly. Although it is not standard practice on commercial pack lines, fruit were washed in this study in an effort to standardize environmental conditions as much as possible. Any remaining stems were then removed to prevent mechanical damage during subsequent handling and storage. When dry, the berries were distributed among 15 plastic, vented clamshells (13 × 11 × 4 cm), with 14 berries per clamshell. At this point, five clamshells were assigned randomly to each of the CS treatment levels (4 or 6 weeks) and all were placed in CS.

To ensure even cooling, the clamshells were stacked inside vented harvest lugs that were placed in a cooling tunnel inside the larger CS room. The cooling tunnel consisted of stainless steel shelves draped with thick plastic sheets, through which air was pulled continually by a set of two box fans placed at one end to maintain stable air temperature and relative humidity across the set of experimental materials. The airflow was also intended to mitigate the buildup of ethylene gas in and around the bins of fruit, which could accelerate ripening and affect quality. No ethylene filters or absorbers were used during CS in this study.

Fruit quality assessment. After their designated durations in CS, the five clamshells per harvest maturity–CS duration combination were removed from CS and moved into the laboratory for ripening at RT. When in the laboratory, the fruit were pooled and condensed into three clamshells of 10 uniform berries each (Supplemental Fig. S2) via visual sorting and discarding of poor-quality, nonrepresentative fruit with any obvious bruising or blemishes. For each ripening time point (0, 3, 6, 9, and 12 d at RT), two berries from each clamshell, for a total of six berries, were selected randomly for full quality evaluation, as described next.

Throughout the study, various aspects of fruit quality were assessed, including fruit appearance (digital camera and imaging stand), firmness (analog penetrometer), SSC (digital refractometer), and DM content (low-temperature oven). Photographs were taken at the beginning of analysis for each set, before any destructive measurements were made. Every berry was included in the photograph, along with a scale (see Supplemental Fig. S4 for an example).

After photographing the sample, an analog penetrometer (FT 327; QA Supplies, Norfolk, VA, USA) was used to measure the firmness of the skin of each fruit. After recording skin firmness with an 8-mm probe, a handheld fruit peeler was used on the unpunctured side of each fruit to remove a section of skin. The 8-mm probe was then inserted through the skinned section to ascertain flesh firmness. After firmness assessment, Brix measurements were taken using a digital refractometer (PAL-1, Atago Co., Ltd.), calibrated with distilled water before each measurement to ensure accuracy. About one-third of each berry was removed with a razor for juice collection, and the remaining two-thirds was cut in half crosswise and placed on wax weighing paper for DM analysis. An initial weight measurement was taken of the fruit sections using a digital balance (AUY 220; Shimadzu, Kyoto, Japan; ±0.0001-g accuracy), and the fruit slices were then placed into a low-temperature oven for desiccation (6520, Precision Economy Oven; Thermo Fisher Scientific, Waltham, MA, USA). After a minimum of 24 h at 65 °C, a final weight measurement was taken and used to calculate percent DM. This process was repeated in the same order for each berry in the study.

Reference data. To develop benchmarks for identifying ready-to-eat fruit based on the quality metrics considered in this study, a reference dataset was developed using high-quality kiwiberries that had been divided into three maturity stages (slightly underripe, peak ripeness for consumption, and slightly overripe), as determined by a trained panel of two people, each with more than 6 years of experience working with and evaluating 'Geneva 3' kiwiberries for fresh eating. To establish this working reference set, the panelists relied on both the overall appearance of the berries as well as the feel of the resistance of the berries to gentle pressure applied between the thumb and the index and/or middle fingers. In this way, the panelists sought to replicate the method by which consumers are most likely to inspect berries visually and tactilely to ascertain their readiness for consumption. In addition to mimicking consumer behavior, this tactile approach to the fine discrimination of degrees of ripeness was deemed necessary because the analog penetrometer used in this study was found to be unable to measure firmness reliably after kiwiberries reach ~18.0°Brix, because berry softness was beyond the sensitivity of the instrument, even with a large (8-mm) probe.

The berries used for building the reference set were harvested from the study vines while still firm during Oct 2020 and were not exposed to CS conditions. Upon reaching RT, the fruit were monitored daily by the two panelists, who assessed and assigned the berries independently to the three different categories. Only those berries with assignments that were consistent between the panelists were retained and characterized immediately for both SSC and DM, thereby providing reference data to define the ranges of SSC and DM associated with peak consumability. Each day, a subsample of two berries from each reference category was tasted by each panelist to validate that day's assignments. Uniformly, kiwiberries in the slightly underripe category were confirmed to have an undeveloped aromatic profile, deficient sweetness, notes of starchiness, and hints of irritation (or "catch") in the back of the throat. In contrast, berries assigned to the slightly overripe category uniformly had inferior mouthfeel (less internal texture) and detectable "off" flavors, ranging from metallic aftertastes to those hinting of fermentation. Between these two categories, kiwiberries designated as being at peak ripeness, based on appearance and feel, had a fruity aroma, a tender but chewable texture, and a complex sweet–tart flavor with no starchiness or off flavors. In the end, the reference dataset consisted of 98 berries (30 slightly underripe, 39 at peak ripeness, and 29 slightly overripe). Mean Brix and DM data were calculated for each category, along with *SD*s, and these parameters were used to define a 95% confidence zone of peak consumability as a way of connecting the data in this experiment to the practical concerns of marketability, eating quality, and consumer experience (see "Results and Discussion").

Assessment of visual acceptability. Based on the photographs taken during fruit quality analysis, a visual assessment was made to determine the time point at which kiwiberries subjected to different combinations of harvest maturity and time in CS became visually unacceptable, thereby losing market viability. For this task, acceptability was assessed via two different 5-point visual quality scales, one characterizing extent of cold injury (Fig. 1A), observed primarily in low DM fruit, and the other characterizing degree of overripeness (Fig. 1B), as signaled by increasing desiccation/wrinkling.

Fig. 1A shows a scale for visible chilling injury (CI) in 'Geneva 3' kiwiberries, based on the extent of blackening under CS, likely resulting from oxidative reactions in less-mature fruit (Valenzuela et al. 2017). Using this scale, a score of 1 point corresponds to high-quality fruit with no visible CI. A score of 2 points is given to berries exhibiting the first signs of CI, as evidenced by darkened indentations (< 5% of surface area) and initial signs of a hardened appearance of the fruit's skin. A score of 3 points is given to fruit showing clear CI, including blackening that occupies as much as 40% of the fruit surface. A score of 4 points is associated with even more extensive damage (up to 80% of the surface), and a score of 5 points is assigned to berries exhibiting CI that covers more than 80% of the surface. Complementing the CI scale described here, Fig. 1B presents a visual scale for scoring the degree of overripening in 'Geneva 3' berries. Using this scale, a score of 1 point is assigned to perfect ready-to-eat berries.

For each group of six berries undergoing quality analysis at a given time, the group as a whole was determined to be visually unacceptable if at least four of the six berries scored ≥ 3 points on the CI scale (Fig. 1A) or ≥ 4 points on the ripening scale (Fig. 1B). In other words, if the surface of a berry was ≥ 5% blackened or excessively wrinkled, then that individual berry was marked as unacceptable. The majority of the berries in a group had to be unacceptable for the group to be marked as unacceptable as a whole. For a given combination of harvest time and CS duration, the representative time point at which the set of fruit became visually unacceptable was estimated by simply averaging across the three replicates (blocks). Similar to the reference data described earlier, the results of this visual analysis (acceptable or unacceptable, regardless of internal quality metrics) were used to provide an additional layer of overall fruit quality information in an effort to connect the data in this experiment to the practical concerns of marketability and eating quality, as experienced by the consumer (see "Results and Discussion").

Data analysis. To begin analysis of the fruit quality assessment data, outliers were first culled from the dataset by identifying all berries that had both Brix and DM values that deviated more than 3 *SD*s from the mean of their respective group of six berries. In each case, archived digital images (Supplemental Fig. S4) were then consulted to assess the visual condition of each potential outlier. If any visual anomalies were observed (e.g., surface damage, scratches, browning), providing independent evidence for being an outlier, that particular berry was culled from the dataset. In total, 49 outliers from season 1 and 26 outliers from season 2 were culled based on these criteria. After outlier analysis and culling, the measurements made on all remaining subsamples (i.e., individual berries) were averaged and an analysis of variance (ANOVA) was conducted to determine the effect of harvest maturity on berry quality, as well as its interactions with all other fixed factors (CS duration and ripening time).

When significant interactions among fixed factors were detected, the appropriate simple effects analyses were conducted and the R packages 'emmeans' and 'ggplot2' (R Foundation for Statistical Computing, Vienna, Austria) used to construct interaction plots (Lenth 2022; Wickham 2016). In an effort to integrate the information from the reference set as well as data pertaining to visual acceptability, all interaction plots were enhanced with additional layers of data—namely, 1) the range of Brix levels that corresponds to fruit at peak ripeness and 2) dashed lines denoting visually unacceptable fruit resulting from CS damage, overripening (wrinkling), or both.

Results and Discussion

Reference data. The Tukey honestly significant difference test revealed significant differences in Brix among the reference categories slightly underripe, peak ripeness, and slightly overripe, despite some overlap in their ranges (Table 1, Supplemental Fig. S5). Because of the complex organoleptic profiles of kiwiberries, it is important to note that berries with a high SSC do not necessarily possess superior eating quality. Indeed, overripe kiwiberries with greater degrees Brix

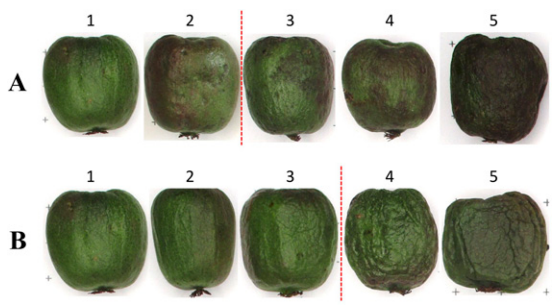

Fig. 1. Five-point visual scales, showing (**A**) cold injury and (**B**) ripening, used to describe acceptability thresholds for 'Geneva 3' kiwiberries. In addition to becoming deeply wrinkled, the skin of 'Geneva 3' berries can be seen to darken subtly and assume a more matte appearance as the fruit ripens (**B**). A berry scoring ≥ 3 points on the chilling injury scale (**A**) or ≥ 4 points on the ripening scale (**B**) is considered visually unacceptable/unmarketable.

Table 1. Summary statistics [Brix and dry matter (DM)] for the three reference set categories.

Reference category	°Brix		DM (%)	
	Mean	*SD*	Mean	*SD*
Slightly underripe (n = 30)	17.5 a[1]	2.3	22.9 a	1.0
Peak ripeness (n = 39)	21.2 b	1.9	24.4 b	1.6
Slightly overripe (n = 29)	23.8 c	2.5	26.6 c	2.7

[1] Means with different letters are significantly different (α = 0.05) as determined by Tukey's honestly significant difference test.

are less desirable to consumers than perfectly ripened ones, generally because of excessive softening, wrinkling, and discoloration associated with continued (over)ripening.

Summary results from the Brix reference data—namely, the mean of the peak ripeness category and its associated confidence interval—provide an interpretation framework for the fruit quality assessment results. In similar manner, percent DM was also analyzed for the reference set and generated similar results (Table 1, Supplemental Fig. S6). Compared with Brix, the *SD* for DM appears to increase as fruit ripens/softens. Although DM is supported by the literature as being the more robust metric for timing harvest (Fiorentini and Kay 2019), after fruit has been picked and is ripening off the vine, the reference data here suggest that Brix may be the more accurate metric for discriminating fruit quality at or near peak ripeness. Consequently, the following analysis focuses only on Brix.

Firmness data. Berry skin and flesh firmness were measured with an analog penetrometer (8-mm probe) to determine whether such metrics are useful in assessing quality at or near peak ripeness. Although results indicate that skin and flesh firmness are highly correlated for underripe fruit, both largely "zero-out" as berries reach ~20.0°Brix as a result of fruit softening beyond the limits of probe sensitivity (Fig. 2). For groups of six berries, the basic experimental unit (sub-subplot) in this study, the 95% confidence interval for mean peak ripeness ranges from 19.6–22.7°Brix, as indicated by the yellow zone in Fig. 2. Because both skin and flesh firmness become essentially undetectable in this zone, at least using an 8-mm probe on a standard analog penetrometer, firmness was found not to be a useful metric for distinguishing quality among berries near peak ripeness; therefore, firmness data were not analyzed further in this study.

Data analysis. Initial data analysis in the form of a full-factor ANOVA—namely, a split-split RCBD with blocks nested in random seasons—revealed strong interactions between harvest, CS, and ripening (Table 2). Because of the strong two-way interactions among the factors ($1e{-}6 < P < 0.007$), as well as their nearly significant three-way interaction ($P = 0.065$), subsequent analysis was of their simple effects, with interaction plots constructed to provide insightful visualizations of the data. The ripening dynamics for the three different harvest times are shown in Fig. 3, with Fig. 3A displaying data from fruit held in CS for 4 weeks and Fig. 3B displaying data from fruit held in CS for 6 weeks.

To facilitate a visual comparison of group means, all error bars in the interaction plots (Fig. 3) are ±1 *SE*, so that nonoverlapping error bars between groups indicate pairwise statistical differences between groups at about the 95% confidence level. As shown in Fig. 3A, fruit harvested at 8°Brix and held in CS for 4 weeks had a longer window of consumer acceptability in terms of Brix (~3 d) than that of fruit harvested at 6.5 or 10.0°Brix. Fruit harvested at 6.5°Brix was found to be visually unacceptable after only 3.5 d, at which point the berries had yet to develop sufficient sugar content. Fruit harvested at 10.0°Brix ripened the fastest and was in the zone of acceptability for ~2.5 d.

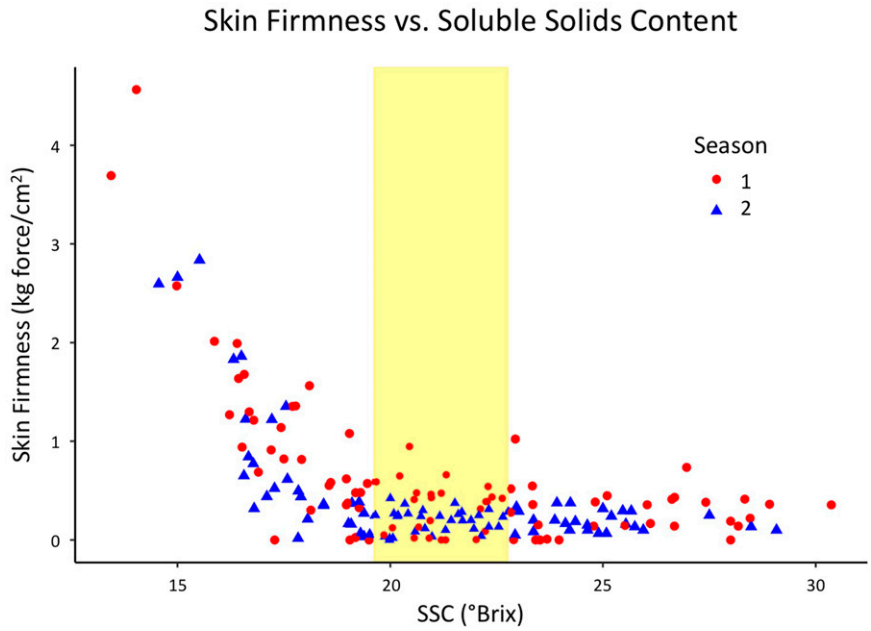

Fig. 2. Scatterplot of skin firmness vs. soluble solids content (SSC) of 'Geneva 3' kiwiberries ripening at room temperature across the two seasons of the study. Each point in the plot represents the average of six berries from a single clamshell. The yellow region demarcates the "zone of ripeness," a 95% confidence interval about the mean sugar content of kiwiberries at peak ripeness (n = 6), as informed by the reference set (Table 1).

A similar simple effects analysis was carried out for fruit held in CS for 6 weeks. As shown in Fig. 3B, there was an accelerated increase in Brix for all fruit held in CS for 6 weeks, compared with the 4-week CS fruit, as well as a shorter window of acceptability for the 8.0°Brix fruit (2 d). For 6-week CS fruit, the fruit harvested at 10.0°Brix had the longest window of consumer acceptability based on means (2.5 d), but the group mean error bars for 8 and 10°Brix fruit overlapped for every sample day—meaning, there was no statistically significant difference between groups at the 95% confidence level. The 6.5°Brix fruit, however, failed to develop an acceptable Brix content even after 6 weeks in CS. The effect of harvest maturity on the degrees Brix of ripening fruit was stronger for fruit held in CS for 4 weeks than 6 weeks. This may be an indication of how time in storage can increase uniformity among kiwiberries stored in close proximity.

Our study found accelerated ripening for fruit held for a longer duration in CS, as kiwiberries that had been in CS for 6 weeks ripened faster at RT than kiwiberries that had been in CS for only 4 weeks. Ripening time has been found to be related inversely to CS duration in other climacteric crops such as cherimoya or the custard apple (*Annona cherimola* Mill.) (Alique and Zamorano 2000). The relationship between CS duration and ripening time has direct relevance to the poststorage shelf life of kiwiberries. Refined CS conditions and improved technologies have the potential to delay the acceleration of ethylene production during CS, which may extend shelf life. For example, using controlled atmosphere with low oxygen concentrations, Latocha et al. (2014) were able to store *A. arguta* 'Ananasnaya' successfully for 8 weeks, and the application of an ethylene scrubber, edible coatings, controlled atmosphere, or refined storage temperatures may similarly be found to increase the long-term storability of 'Geneva 3' fruit. Until such research is carried out, and in the absence of such additional interventions, however, growers with CS

Table 2. Summary analysis of variance table of adjusted fixed-factor effects, with Brix as the response variable.

Factor	df	MS	*F* value	*P* value
Harvest	2	36.73	49.98	0.020
Cold storage	1	0.106	0.339	0.567
Ripening	4	287.3	416.4	< 1e–16
Harvest:cold storage	2	2.023	6.453	0.007
Harvest:ripening	8	2.784	4.036	0.0003
Cold storage:ripening	4	7.098	10.29	< 1e–6
Harvest:cold storage:ripening	8	1.323	1.917	0.065

df = degrees of freedom; MS = mean square.
Appropriate error terms were used to test the significance of each factor in the model according to a split-split randomized complete block design, with blocks nested within random seasons.

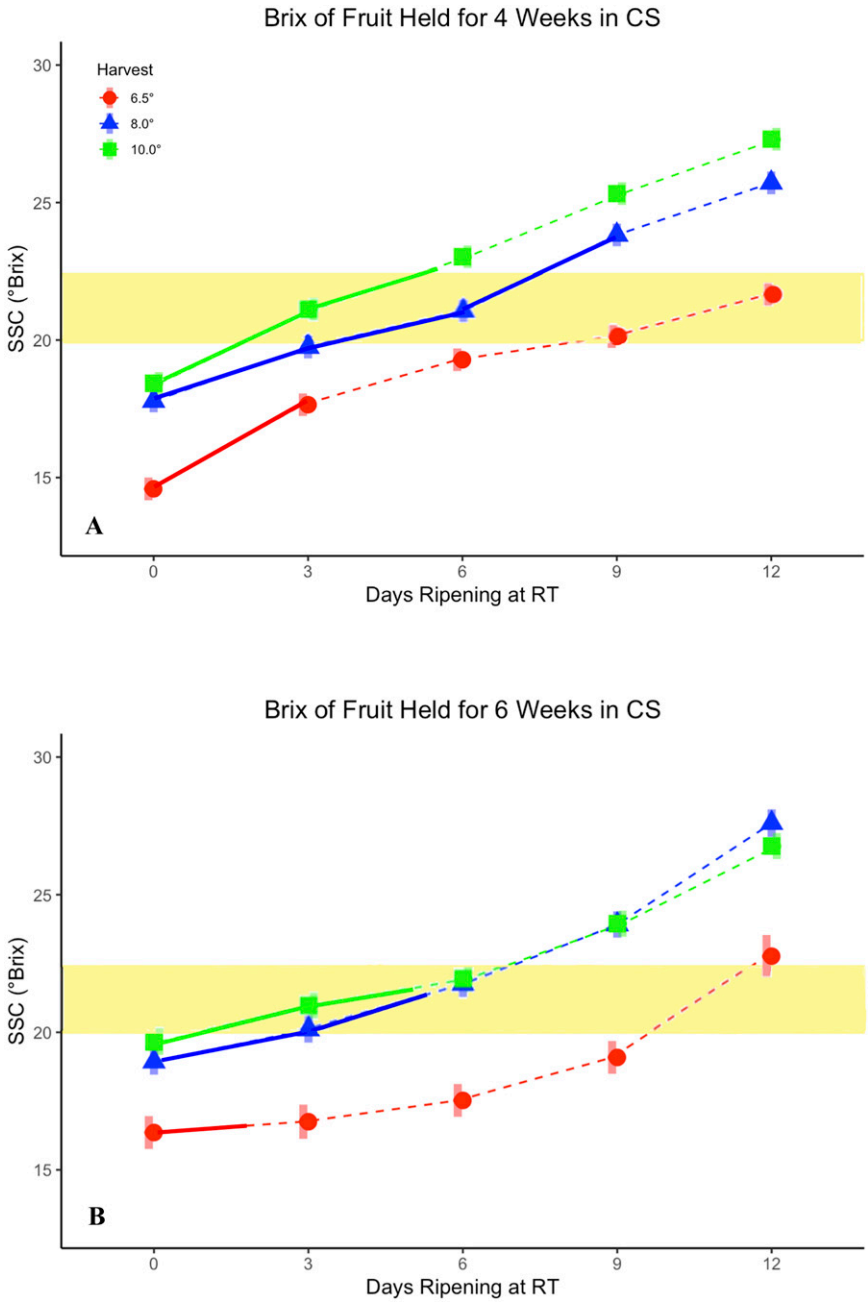

Fig. 3. Two-way interaction plots between mean Brix at harvest and days ripening at room temperature (RT) for berries held in cold storage (CS) for (**A**) 4 weeks and (**B**) 6 weeks, averaged across seasons. Yellow bands represent the zone of peak ripeness based on the reference data (mean ± 2 *SE*, n = 36 berries). In these plots, means that fall within this zone indicate combinations of harvest and ripening time that result in berries at peak, ready-to-eat ripeness. Bold lines represent visually acceptable fruit whereas dashed lines indicate combinations of harvest and ripening time that result in visually unacceptable/unmarketable fruit, regardless of Brix level.

conditions similar to those described in our study should store 'Geneva 3' fruit in CS for no more than about 6 weeks. Uneven ripening of kiwiberries within individual vines and across vineyards also continues to challenge producers, but the impact of uneven ripening on storability can be minimized by sorting berries by quality immediately after harvest and by ensuring soft fruit are not placed in CS.

The overall results of this study are consistent across seasons and CS durations—namely, harvesting 'Geneva 3' kiwiberries at 8.0°Brix results in fruit with the longest window of marketability after CS. The consistency across seasons implies that the patterns observed are relatively robust in the face of seasonal variability. For both lengths of the CS treatment, fruit harvested at 6.5°Brix failed to develop acceptable levels of Brix, in addition to becoming visually unacceptable during CS. Although fruit harvested at 10.0°Brix reached marketable quality after 4 and 6 weeks in CS, the window of peak ripeness was slightly shorter than that for fruit harvested at 8.0°Brix at 4 weeks in CS and was not significantly longer after 6 weeks in CS. Ultimately, the results of this study are consistent with the recommendations of Fisk et al. (2006) for cv. Ananasnaya and those of Han et al. (2019) for cv. Cheongsan, that kiwiberries should be harvested at a mean of 8°Brix. These results differ, however, from those of Latocha et al. (2014), who found stored fruit of cvs. Ananasnaya and Bingo to be of better quality if harvested at a mean Brix between 6.5 and 8.0°Brix. Such differences underscore the interactions between cultivars, postharvest physiology, and likely even regional growing conditions in kiwiberry, and the importance of cultivar- and place-specific research.

Conclusion

In our study, two seasons of fruit maturity data from cv. Geneva 3 kiwiberries harvested at different maturities and held in CS for varying durations were analyzed to develop practical harvest timing recommendations for producers. To connect the results to questions of marketability and consumer experience, analyses were anchored to a reference set of sensorially determined slightly underripe, perfectly ripe, and slightly overripe kiwiberries.

Based on the results of our study, it is recommended one harvest 'Geneva 3' kiwiberries when the average SSC reaches 8.0°Brix. Fruit harvested at 6.5°Brix failed to reach adequate SSC levels and quickly became visually unacceptable to consumers. When harvested at 8.0°Brix, fruit remained visually acceptable for the longest period of time while ripening at RT after CS conditions. This pattern was consistent across seasons, suggesting the findings may be generally applicable to 'Geneva 3'. Harvesting at an average of 8.0°Brix resulted in high-quality fruit amenable to CS, and there appears to be no benefit to either quality or shelf life by delaying harvest to 10.0°Brix. Fruit harvested at 8.0°Brix and held in CS for 4 weeks was found to be acceptable for consumption for a 3-day window after ripening at RT for 4 days, whereas after 6 weeks in CS, fruit were acceptable for 2 days after 3 days of ripening at RT. The 8.0°Brix harvest has the added advantage over later harvest times of removing fruit from the field sooner, reducing both pest pressure and the risk of damage from wind and late-season chilling events.

Unlike in our study, in which any given batch of fruit could be harvested within a very short period of time (< 1 h), large-scale commercial producers face the dual challenge of not only timing the beginning of harvest, but also completing the task while maturity continues to progress across a vineyard. Overall, our study finds 8.0°Brix to be an evidence-based threshold for starting the harvest of 'Geneva 3' kiwiberries—one that speeds the removal of fruit from the field while permitting development of marketable berries with a complex organoleptic profile and up to 6 weeks of simple CS. Even if complete harvest requires 2 weeks, harvest dates from our study suggest that the last-harvested berries would not exceed ~10°Brix and would still perform well in CS. Certainly, practical

challenges to growers such as uneven ripening within vines and across vineyards remain. Until further research and breeding efforts ameliorate such challenges, simple practices like thorough sorting before CS and managing bulk fruit according to harvest date are likely to improve fruit marketability.

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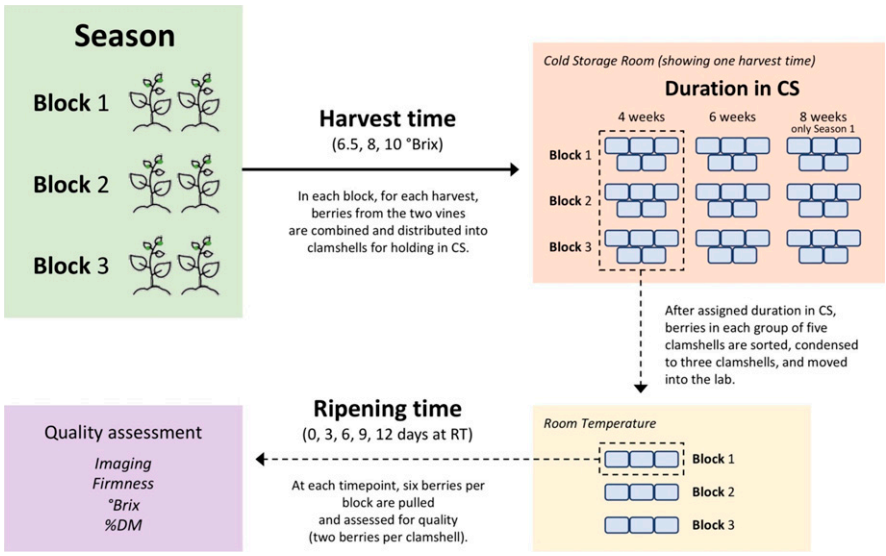
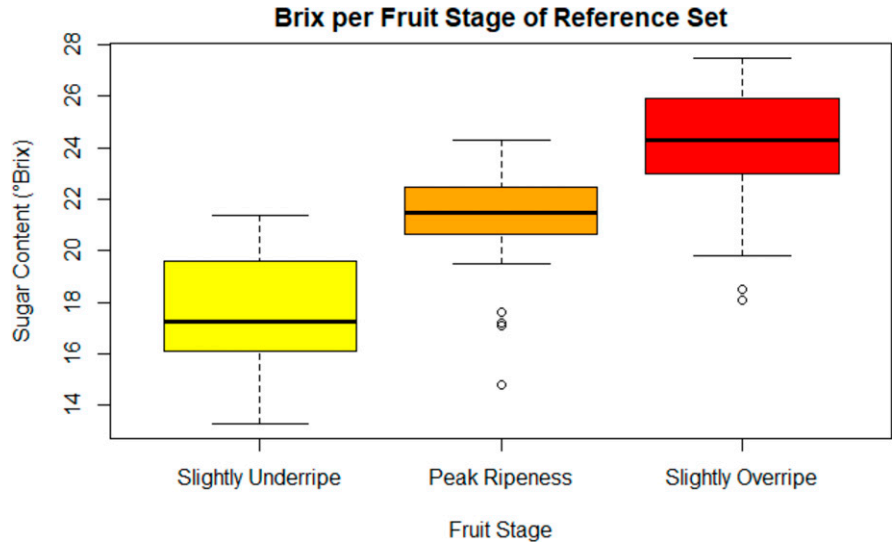


Supplemental Fig. S1. Schematic of experimental design depicting how fruit were harvested each season from the three blocks at three levels of harvest maturity and then held in a single cold storage (CS) room (1–3 °C, >90% relative humidity) for 4, 6, or 8 weeks. From CS, fruit were ripened at room temperature (RT) and assessed for quality at the indicated time points (0, 3, 6, 9, and 12 d at RT).

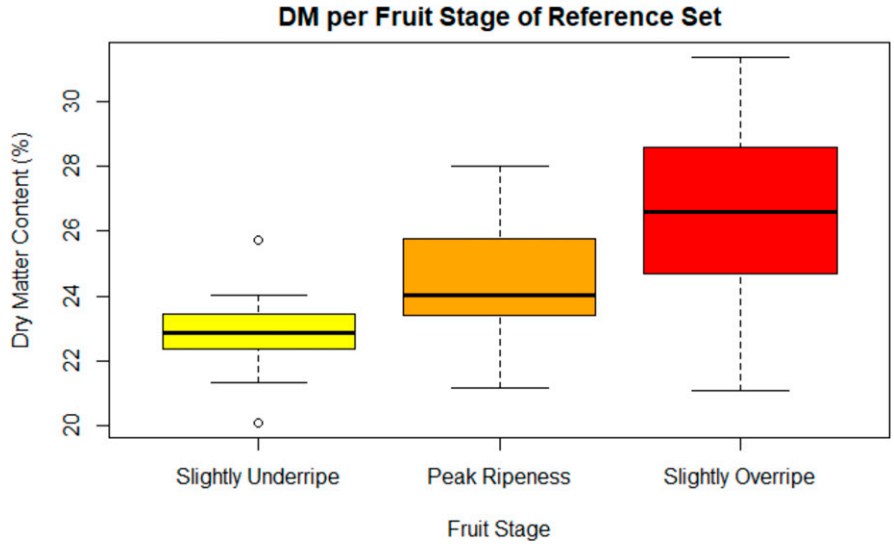
Supplemental Fig. S2. Comparison of an immature 'Geneva 3' kiwiberry (left) with one that has reached black-seed stage (BSS) (right), a commonly used visual indicator of physiological maturity.

Supplemental Fig. S3. Approximately isometric view of a mature kiwiberry vine, annotated to illustrate the protocol for random sampling in this study. The yellow dotted lines represent the axes used to divide the canopy into quadrants, each labeled with a Roman numeral (I–IV). When harvesting randomly, one-quarter of the total harvest per vine (~25 berries) was taken from each quadrant.

Supplemental Fig. S4. A representative photograph of a fruit sample. The label code designates this batch as belonging to block 2 (II). These berries were harvested at 8.0°Brix (maturity level 2), held in cold storage (CS) conditions for 4 weeks (4), and removed from CS on the day of the photograph (day 0).



Supplemental Fig. S5. Boxplot of measured Brix values for ‘Geneva 3’ kiwiberries by visually and tactilely determined reference categories.



Supplemental Fig. S6. Boxplot of measured dry matter values for ‘Geneva 3’ kiwiberries by visually and tactilely determined reference categories.