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Evaluating Maturity Index I_{AD} for Storability Potential in Mid-Season and Late-Season Apple Cultivars in the Light of Climate Change

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Abstract: Reducing food losses in apple production is becoming increasingly important, as the effects of climate change constitute a challenge to food production. Improving methods for determining fruit maturity at harvest leading to the longest storability is crucial, thereby facing more unpredictable seasonal weather conditions. In addition, the increasing temperature is affecting common maturity indices differently; thus, present practice may not be valid. In this study, a non-destructive, time-efficient method was used, tentatively indicating maturity. This study was performed during three climate-diverse years, reflecting more irregular climate conditions. Mid- to late-season cultivars 'Frida', 'Ingrid Marie', 'Rubinstar', and 'Elise' were harvested at different pre-determined I_{AD} (index of absorbance difference) intervals and stored for five months. Correlations between I_{AD} values at harvest and total losses after storage were found for all cultivars and years, while only a few correlations related to firmness after storage were found. Although a strong effect of year was related to correlations between I_{AD} and different quality parameters, no noticeably general differences could be found between the exceptionally warm year in comparison to the other investigated years. I_{AD}, as a maturity index, thus, seems to be resilient to changing temperatures and can be used as a complementary maturity index.

Keywords: apple (*Malus domestica*); chlorophyll absorbance index (I_{AD}); late cultivars; storability; fruit losses; firmness

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1. Introduction

Reducing food losses and waste is one of the key factors to obtain food security for future global demand. In addition, food losses and waste account for 7–10% of global greenhouse gas emissions [1,2]. Climate change has increased events of unfavorable agricultural conditions in recent decades [3]. Drought, heatwaves, and heavy rainfall have caused a reduction in the production of certain crops [4,5]. Fruit and vegetables are important crops for nutrition and health [6], though their perishable nature makes it crucial to optimize pre- and postharvest practices to reduce losses. In recent years, several studies have dealt with the consequences of climate change for apple production. The onset dates for several phenology stages, including flowering, resulting in 10.7 days earlier onset of flowering during the investigated 50 years and were found to be inversely correlated with daily mean, maximum, and minimum temperature from January to May [7]. In addition, an increasing risk of frost damage during springtime has been observed due to warmer winters, resulting in earlier blossoming of fruit trees and fewer chilling hours during wintertime [8]. Also, signs of an increasing risk of pathogen attacks with a changing climate have been presented, while data from 56 years of recordings in England showed that fungi doubled the length of their reproductive season from 33 days to 75 days, and some reproduced twice instead of once a year [9]. As for postharvest apple quality, textural and taste attributes were found to have changed as a result of global warming, based on 30–40 years of measurements in Japan [10]. A summary of different indicators is shown in Table 1.

Long-term storage of fruit is critical in regulating the flow of produce to the market, meeting off-season demand [11], and ensuring self-sufficiency, so thereby contributing to food supply and food security even in times of trade disruption [12]. Storage potential is known to vary between cultivars and to be affected by various factors. Cultivars that matured late in the season have been found to produce ethylene less rapidly and have lower production than early-season cultivars [13,14]. It has also been found that maturation time during the season is correlated with firmness at harvest, with late-season cultivars having a lower softening rate and greater firmness at harvest than early-season cultivars [15,16]. Further, the composition and thickness of cuticle and skin differ between early- and late-season cultivars [17,18]. Together, these traits in late cultivars are likely to result in longer storability for late-season cultivars.

Irrespective of whether the maturation time of an apple cultivar is early or late in the season, if the fruit is not harvested within the correct window of time for that cultivar, the risk of diseases and disorders increases, leading to increased losses in storage [19,20]. This is especially important to consider with respect to late- and mid-season cultivars, since their fruit is intended for long-term storage. Physiological disorders, such as soft scald and soggy breakdown, are, in some cases, also affected by the time of harvest, as their incidence may increase with late harvest for the cultivar [20–22]. However, studies investigating the effects of climate change on fruit ripening and, consequently, optimal harvest time are scarce.

To ensure that apples are harvested at the optimal time, many different maturity indices, both non-destructive and destructive, have been developed. Non-destructive indices include measurements of ethylene production and respiration [23,24]. Destructive indices include measurements of soluble solids concentration (SSC), firmness, and starch degradation [25–27]. From the values of these three parameters, the Streif index can be calculated [28]. In recent years, a non-destructive maturity index has been used, in which a DA (difference in absorbance) meter is used to measure chlorophyll content under the peel of the apple and produce an index of absorbance difference (I_{AD}) value. Unlike some previous maturity assessment methods, the I_{AD} approach is more convenient, with a portable device suitable for field testing, enabling faster maturity evaluation and a larger and more reliable sample size [29,30]. The optimal I_{AD} value for long-term storage of apples varies, both with cultivar and growing region, so specific values need to be determined for each case [29,31]. I_{AD} has previously been shown to decrease during the harvesting period, showing that chlorophyll content under the peel of the apple continuously decreases with maturation [21]. While additional non-destructive methods are under development [32,33], no other cost- and time-efficient device has so far entered a broader market, though the changing climate conditions will require a re-evaluation of the methods for estimate maturity before harvest.

Different maturity indices have been found to be more suitable for different apple cultivars and regions, but often, a combination of several is used [34,35]. However, with more often occurring high-temperature incidence during the season due to climate change, which might affect the maturity indices to a different extent, the present-day practice might not be valid for the future. The aim of the present three-year study was to evaluate how harvesting at different harvest I_{AD} values affected the storage potential of four mid-season and late cultivars of apple ('Frida', 'Ingrid Marie', 'Rubinstar', and 'Elise'), indicating the applicability of the I_{AD} values as maturity indices. For each cultivar, up to four different I_{AD} intervals were used. After storage, quality parameters were recorded, as well as fungal decay and physiological disorders. In addition, given the diverse environmental conditions between the investigated seasons, the study also aimed to evaluate how a more extreme weather season affected the suitability for using harvest I_{AD} as a maturity index.

Table 1. Environmental conditions affecting growth and quality of apple, which might be affected by climate change. Some quality attributes are used in maturity indices.

Cultivar	Indicator	Observed Effect	Conditions	Reference Number
'Golden Delicious'	Onset dates of phenology stages	Significant linear relationships between higher air temperature and earlier onset dates	Higher air temperature	[7]
No specific	Risk of frost damage	Frequency of relatively rare frost events after blossom	Higher air temperature	[8]
No specific	Fungal fruiting date and frequency	First fungal fruiting date is earlier, last fruiting date is later. Increased frequency of reproduction twice per year	Increase in late summer temperatures and autumnal rains	[9]
'Fuji', 'Tsugaru'	Quality attributes	Decreases in fruit firmness and acid concentration. Some cases of higher soluble solids concentration	Higher air temperatures	[10]
'Cox' Orange Pippin', 'Granny Smith'	Chlorophyll concentration in apple skin	Higher temperatures up to ca 25 °C gave faster chlorophyll degradation, but above ca 30 °C the rate went down.	Higher air temperatures	[36]
'Gala', 'Fuji'	Red skin color	More red skin area in cooler sites than in warmer	Air temperatures	[37]
'Galaxy', 'Cripps Pink', 'Braeburn'	Red skin color	More red skin area in cooler sites than in warmer	Air temperatures	[38]
'Mondial Gala'	Anthocyanin concentration Gene expression	Higher anthocyanin concentration in a cooler climatic area than in a warmer. Changes in gene expression	Air temperatures above 20 °C	[39]
'Iwai', 'Sansa', 'Tsugaru', 'Homei-Tsugaru', 'Akane'	Anthocyanin accumulation Gene expression	Higher anthocyanin concentrations and increase in gene expression at low temperatures	Air temperatures	[40]
Various cv.	Firmness	Higher temperatures led to lower firmness in some cultivars but not for all	Higher air temperatures	[37,38]
'Delicious', 'Northern Spy', 'Macintosh'	Starch degradation	Low temperatures favored the conversion of starch to sugar, and high temperatures the reverse	Higher air temperatures	[41]

2. Materials and Methods

The study was performed during three consecutive years: 2018, 2019, and 2020. Healthy trees were chosen after fruit set of the cultivars 'Ingrid Marie' and 'Rubinstar' grown in a commercial orchard in western Scania, southern Sweden (55°43′26.6″ N 13°05′52.8″ E) and of the cultivars 'Frida' and 'Elise' grown in another commercial orchard in eastern Scania (55°37′35.6″ N 14°16′21.9″ E). All cultivars selected for the study were grafted on M9 rootstock, and the trees were between 8 and 15 years old at the start of the study. All trees were managed according to commercial practices, including integrated pest management (IPM) practices with regard to pesticides and fungicides. Twenty-one trees per cultivar were marked to exclude them from commercial harvest in the orchard. Apples were picked from the same rows of trees in all three years. Harvesting started two weeks before the optimal harvest time, as estimated by a local producer organization based on a combination of the Streif index and weather conditions. The first harvest date in 2018, 2019, and 2020, respectively, was 10, 2, and 4 September for 'Frida'; 27 August, 12 September and 11 September for 'Ingrid Marie'; 3, 10, and 18 September for 'Rubinstar'; and 6, 17, and 22 September for 'Elise'. The apples of each cultivar were harvested 3–4 times each year according to I_{AD} intervals, as described below.

Apples were scanned at harvest with a DA meter on both the sunny and shaded side of each fruit, and an average for the fruit was calculated (Sinteleia, Bologna, Italy) and 120 apples within specific pre-determined I_{AD} intervals based on earlier studies and previous information on cultivar storability [42] were selected for analysis. In 2018, I_{AD} was measured in 'Frida' and 'Elise' after harvest, and an average was calculated, while 'Ingrid Marie' and 'Rubinstar' were harvested at pre-determined I_{AD} intervals. In 2019 and 2020, all cultivars were picked at pre-determined I_{AD} intervals. Each cultivar was harvested up to four times in total, where the pre-determined I_{AD} interval decreased with each subsequent harvest. The harvested apples were stored in cold storage (2 °C, 95% relative humidity (RH), ambient atmosphere) for 119 days, after which the measurements were conducted. In addition to the harvest of the apples for storage, apples for measurements of firmness at harvest were picked from each cultivar and from the same rows of trees. This harvest started approximately two weeks before the estimated optimal harvest and continued up to completed starch degradation (value 10 on a scale from 1 to 10). Firmness at harvest was measured in four replicates on both the sunny and shaded side of the fruit after peeling with a penetrometer (Model FT 327; **FACCHINI srl**, Alfonsine, Italy; plunger diameter of 11.1 mm, depth of 7.9 mm), and an average was calculated for each apple.

Sampling after storage took place on day 119 and an additional three times with ten days apart for each sampling, so storage time was in total 149 days. At each sampling for assessments during storage, fruit affected by diseases and disorders were removed from the boxes, and the number of apples affected and the disease/disorder were recorded. Total losses were calculated as the sum of apples affected by physiological disorders and disease. All measurements of quality traits, respiration, and ethylene were performed with four replicates. For these measurements, from the remaining healthy apples, 12 were chosen randomly and taken to the laboratory, where firmness was measured by penetrometer (Model FT 327; **FACCHINI srl, Alfonsine,** Italy; plunger diameter 11.1 mm, depth 7.9 mm) and expressed as N cm^{-2}, SSC (Brix°) was measured by digital refractometer (RFM80, Bellingham + Stanley, Tunbridge Wells, UK) and I_{AD} was measured by DA meter (Sinteleia, Bologna, Italy). In 2019 and 2020, respiration was measured with a "Sidor" gas analyser (Sick Maihak GmbH, Reute, Germany) in apples sealed in individual 0.5 L air-tight jars for one hour and expressed as volume percent (vol%) per hour. At the same time, ethylene production was measured with an ethylene analyser and expressed as ppm h^{-1} (Ethylene Spy ES100, FCE, Milan, Italy). A total of four measurements were made for each I_{AD} interval, with 10 days between measurements, and averages per week were then calculated. Weather data (average daily temperature, average daily maximal temperature, relative humidity, and rainfall) was collected by weather stations (Vantage Pro, Davis Instruments Corp., Hayward, CA, USA) located in the orchards.

One-way analysis of variance (ANOVA) followed by Tukey's test was used to determine significant differences in quality parameters post-storage depending on I_{AD} value at harvest. Pearson correlations between I_{AD} at harvest and respiration, ethylene production, firmness, SSC, fungal decay, physiological disorders, and total losses after the storage period were calculated using Minitab software v 18.1 (Minitab Inc., State Collage, PA, USA). Correlations below 0.4 were considered to indicate weak correlations, 0.4–0.6 as medium strong correlations, >0.6–0.8 as strong correlations, and >0.8–1.0 as very strong correlations.

3. Results

3.1. *I_{AD} and Firmness at Harvest Related to Other Parameters After Storage*

Firmness at harvest varied between cultivars and harvest I_{AD}, and the range in firmness at harvest for the years 2018, 2019, and 2020, respectively, was for 'Frida' (92–87), (101–87), (100–92) Ncm^{-2}, for 'Ingrid-Marie' (88–78), (83–71), (78–71) Ncm^{-2}, for 'Rubinstar' (94–82), (88–78), (87–79) Ncm^{-2}, and for 'Elise' (102–92), (89–80), (92–88) Ncm^{-2}.

Firmness after storage was, in some cases, related to harvest I_{AD} interval, although the results varied both between cultivars and between years (Figure 1). The range in firmness for the years 2018, 2019, and 2020, respectively, was for 'Frida' (55–52), (59–51), (57–53) Ncm^{-2}, for 'Ingrid-Marie' (45–40), (44–40), (42–39) Ncm^{-2}, for 'Rubinstar' (51–46), (52–45), (47–46) Ncm^{-2}, and for 'Elise' (61–59), (55–54), (58–55) Ncm^{-2}. In 'Frida' in 2019 and 2020, 'Ingrid Marie' in 2018 and 2019, and 'Rubinstar' in 2018, higher I_{AD} interval at harvest resulted in higher firmness values after storage, but in the other cases, no clear pattern could be found. 'Ingrid Marie' showed lower firmness after storage than the other cultivars (Figure 1).

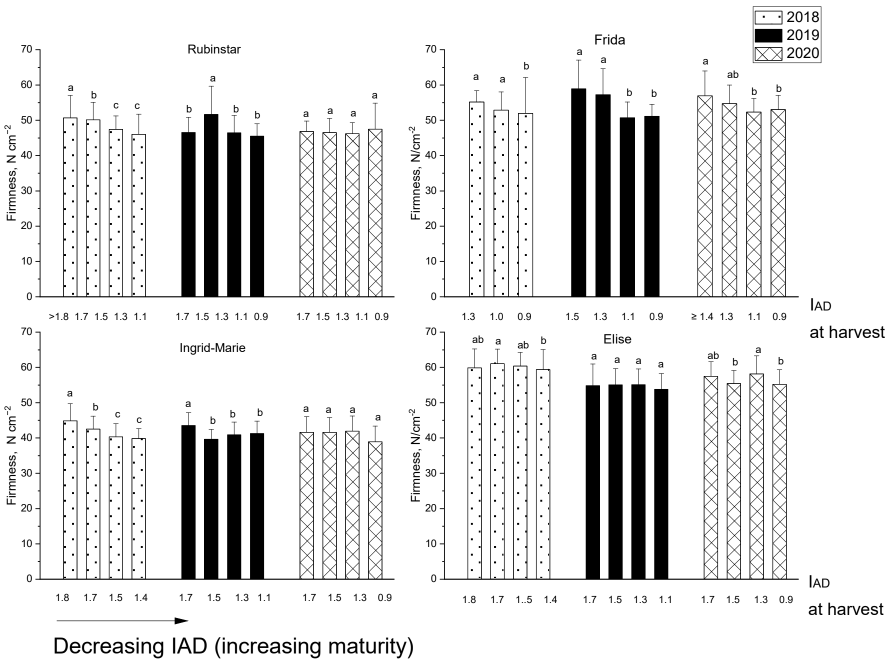

Figure 1. Firmness after storage and I_{AD} values at harvest in the four apple cultivars studied. Values are averages calculated from the four tests during the storage period ± standard deviation. Fruit was harvested in different I_{AD} intervals, average values of which are shown on the x-axis. Values for a cultivar in a specific year followed by different letters are significantly different at $p \leq 0.05$.

Respiration rate after storage tended to be the lowest or next lowest, for apples in the highest harvest I_{AD} interval, which were harvested earliest, i.e., were least mature at harvest. Respiration rates were within a similar range for all four cultivars investigated, with a range of 0.13–0.20 vol% h^{-1} (mean 0.17) for 'Frida', 0.15–0.30 (mean 0.23) for 'Ingrid Marie', 0.14–0.22 (mean 0.19) for 'Rubinstar' and 0.12–0.20 (mean 0.16) for 'Elise'. However, when all I_{AD} intervals were included, all cultivars except 'Rubinstar' showed lower average respiration rates after storage in 2019 than in 2020. With all I_{AD} included, the lowest average respiration rate (0.15 vol% h^{-1}) was found for 'Elise' in 2019, while the highest average respiration rate (0.26 vol% h^{-1}) was found for 'Ingrid Marie' in 2020 (Tables 2 and 3).

Table 2. I_{AD} values at harvest and soluble solids content (SSC), respiration, and ethylene production after storage in 'Frida' and 'Ingrid-Marie'. Values are averages calculated from the four tests during the storage period ± standard deviation. Physiological disorders and fungal decay after the last storage measurements are also shown. N/A = no measurements for that parameter. Values for a cultivar in a specific year followed by different letters are significantly different at $p \leq 0.05$.

Cultivar	Year	Harvest I_{AD}	SSC °Brix	Respiration, vol% h^{-1}	Ethylene Production, ppm h^{-1}	Physiological Disorders, %	Fungal Decay, %
Frida	2018	1.27	13.18 ± 0.96 a	N/A	N/A	6.6	0
		0.99	13.41 ± 0.93 a	N/A	N/A	8.3	0.8
		0.89	13.54 ± 0.78 a	N/A	N/A	2.5	0
	2019	1.4–1.6	12.34 ± 1.48 b	0.13 ± 0.05 b	6.16 ± 2.04 c	1.7	0
		1.2–1.4	12.39 ± 1.04 b	0.14 ± 0.02 b	6.79 ± 1.06 bc	1.7	3.3
		1.0–1.2	12.74 ± 0.94 ab	0.18 ± 0.05 a	8.27 ± 1.72 b	0.8	3.3
		0.8–1.0	12.99 ± 0.84 a	0.18 ± 0.06 a	7.24 ± 1.85 b	3.3	0.8
	2020	1.4–1.7	12.44 ± 1.04 b	0.17 ± 0.03 b	8.54 ± 1.69 a	0	0
		1.2–1.4	13.08 ± 0.84 a	0.20 ± 0.04 a	8.30 ± 2.11 a	4.2	0.8
		1.0–1.2	12.74 ± 0.80 ab	0.18 ± 0.03 ab	8.35 ± 1.60 a	8.3	0
		0.8–1.0	12.72 ± 0.65 ab	0.19 ± 0.06 ab	8.52 ± 4.32 a	4.2	0
Ingrid Marie	2018	1.5–2.0	14.05 ± 1.19 a	N/A	N/A	2.5	9.2
		1.5–1.8	13.22 ± 1.03 b	N/A	N/A	0	5.8
		1.2–1.4	14.43 ± 1.05 a	N/A	N/A	2.5	19.2
		1.0–1.2	13.98 ± 0.70 a	N/A	N/A	0.8	15.8
	2019	1.6–1.8	12.95 ± 1.27 a	0.15 ± 0.03 b	6.97 ± 1.43 b	0	1.7
		1.4–1.6	13.13 ± 1.04 a	0.19 ± 0.06 a	7.46 ± 2.17 b	0	2.5
		1.2–1.4	13.07 ± 1.22 a	0.20 ± 0.04 a	11.33 ± 4.40 a	0	0.8
		1.0–1.2	13.46 ± 1.07 a	0.22 ± 0.12 a	9.99 ± 5.46 a	0	9.2
	2020	1.6–1.8	13.41 ± 1.30 a	0.18 ± 0.04 c	7.86 ± 1.68 b	0	4.2
		1.4–1.6	13.81 ± 1.00 a	0.29 ± 0.08 ab	10.62 ± 4.90 a	0	4.2
		1.2–1.4	13.96 ± 1.24 a	0.30 ± 0.05 a	11.89 ± 4.70 a	1.7	14.2
		1.0–1.2	13.40 ± 1.34 a	0.26 ± 0.07 b	9.81 ± 3.14 a	0	8.3

Ethylene production after storage in 2019 was highest for apples of 'Frida', 'Ingrid Marie', and 'Rubinstar' in the lowest harvest I_{AD} intervals (i.e., apples harvested at a later stage with higher maturity) (Tables 2 and 3). A similar pattern was not found for 2020 or in either year for 'Elise'. Ethylene production varied between cultivars and, on average for both years, it was 7.8 ppm h^{-1} for 'Frida', 9.5 ppm h^{-1} for 'Ingrid Marie', 12.7 ppm h^{-1} for 'Rubinstar' and 4.3 ppm h^{-1} for 'Elise' when all I_{AD} intervals were included. All cultivars, except 'Rubinstar', had lower ethylene production after storage in 2019 than in 2020. SSC °Brix increased with maturity, as measured by $I_{AD,}$ in 'Rubinstar' and 'Elise' in 2020 and in 'Frida' and 'Elise' in 2019. In 'Ingrid Marie', no consistent effect of maturity on SSC could be found in any of the years. The other results regarding SSC were either inconsistent or not significantly different (Tables 2 and 3).

Total losses (sum of physiological disorders and fungal decay; Tables 2 and 3) were generally highest in 2018, though for 'Frida' and 'Ingrid Marie' in 2020, some higher losses were found as compared with 2019. The losses in this investigation were more often due to fungal decay than to physiological disorders, though exceptions with higher losses due to physiological disorders occurred, such as in 'Frida' and 'Rubinstar'. In 'Frida', losses were generally lower at the highest I_{AD} values (≥1.3) in all years, while at values below

1.3, the losses were higher, though there were some differences between years. In ‘Ingrid Marie’, the losses in some I_{AD} intervals and years were higher than in the other cultivars studied, reaching 22% in 2018 and 16% in 2020, although the losses were low at the highest I_{AD} values in 2019. Although there were great differences between years, the breakpoint for ‘Ingrid-Marie’ could also be set for the I_{AD} value of $\geq$1.3. The losses were generally low in ‘Rubinstar’, with the exception of apples harvested at an I_{AD} value of 1.3 in 2018, where the losses were 14%. The losses were also generally low in ‘Elise’. The physiological decay was caused by soft scald in all cultivars, with one exception: in ‘Elise’ 2018 it was caused by soft scald and also by chilling injury.

Table 3. I_{AD} values at harvest and soluble solids content (SSC), respiration, and ethylene production after storage in ‘Rubinstar’ and ‘Elise’. Values are averages calculated from the four tests during the storage period ± standard deviation. Physiological disorders (Phys. disorders) and fungal decay after the last storage measurements are also shown. N/A = no measurements for that parameter. Values for a cultivar in a specific year followed by different letters are significantly different at $p \leq 0.05$.

Cultivar	Year	Harvest I_{AD}	SSC °Brix	Respiration, vol% h^{-1}	Ethylene Production, ppm h^{-1}	Phys. Disorders, %	Fungal Decay, %
Rubinstar	2018	>1.8	14.30 ± 0.90 a	N/A	N/A	0.8	3.3
		1.6–1.8	13.99 ± 0.94 a	N/A	N/A	0	1.7
		1.4–1.6	13.28 ± 1.05 b	N/A	N/A	0	0.8
		1.2–1.4	13.31 ± 0.78 b	N/A	N/A	11.7	0
	2019	1.6–1.8	12.72 ± 0.90 b	0.14 ± 0.06 b	10.01 ± 3.83 b	0	0.8
		1.4–1.6	14.00 ± 1.16 a	0.22 ± 0.08 a	12.63 ± 6.45 b	0	0.8
		1.2–1.4	12.81 ± 1.01 b	0.20 ± 0.07 a	13.01 ± 5.81 b	0	1.7
		1.0–1.2	13.05 ± 0.65 b	0.21 ± 0.09 a	20.28 ± 10.73 a	0.8	0
	2020	1.6–1.8	13.00 ± 0.77 b	0.17 ± 0.04 c	11.15 ± 3.64 a	0	0
		1.4–1.6	12.63 ± 1.60 b	0.22 ± 0.04 a	11.44 ± 2.07 a	0	0.8
		1.2–1.4	13.60 ± 0.75 a	0.19 ± 0.04 b	11.60 ± 3.79 a	0	0.8
		1.0–1.2	13.93 ± 1.18 a	0.20 ± 0.06 b	11.24 ± 3.2 a	0	0.8
Elise	2018	1.72	13.14 ± 0.83 a	N/A	N/A	0.8	0
		1.74	12.96 ± 1.19 a	N/A	N/A	0	2.5
		1.53	13.02 ± 1.34 a	N/A	N/A	0	0.8
		1.43	12.70 ± 1.47 a	N/A	N/A	1.7	0.8
	2019	1.6–1.8	11.90 ± 1.10 c	0.15 ± 0.04 a	3.40 ± 0.74 b	0	2.5
		1.4–1.6	12.16 ± 1.25 bc	0.17 ± 0.05 a	4.51 ± 1.20 a	0	0.8
		1.2–1.4	12.57 ± 0.92 ab	0.12 ± 0.04 b	3.71 ± 1.06 b	0	0.8
		1.0–1.2	13.11 ± 1.37 a	0.15 ± 0.03 a	3.96 ± 0.89 ab	0	1.7
	2020	1.6–1.8	11.83 ± 1.02 c	0.17 ± 0.05 b	5.20 ± 2.53 ab	0	0.8
		1.4–1.6	12.60 ± 1.46 b	0.18 ± 0.03 b	5.71 ± 3.25 a	0	0.8
		1.2–1.4	13.69 ± 1.62 a	0.18 ± 0.04 ab	3.51 ± 1.12 c	0	0.8
		1.0–1.2	13.33 ± 1.27 a	0.20 ± 0.04 a	4.49 ± 1.13 bc	0	2.5

3.2. Correlations Between I_{AD} and Other Maturity Indices and Parameters

Total losses showed the highest and the most frequently occurring significant negative correlations with I_{AD} values, ranging from weak to strong (Table 4). No year stood out as generally having the highest or lowest correlation between I_{AD} values and total losses for the investigated four cultivars. In contrast to total losses, firmness after storage had only a few positive weak to medium strong significant correlations with I_{AD} values, namely in ‘Frida’ in 2019 and 2020, ‘Ingrid Marie’ in 2018 and 2019, and ‘Rubinstar’ in 2018. In the other cases, correlations were not significant. Significant weak negative correlations were found between I_{AD} values at harvest and ethylene production and respiration in a few cases. Correlations between I_{AD} values at harvest and SSC were generally weak, but ‘Elise’ and ‘Rubinstar’ both had medium strong negative correlations in 2020.

Table 4. Correlations between I_{AD} and different quality parameters in the apple cultivars 'Frida, 'Ingrid-Marie', 'Rubinstar', and 'Elise' after storage for 119 days in ambient atmosphere at 2 °C and 95% RH. N/A= not available; ns = non-significant, *, **, *** = significant at $p \leq 0.05$, 0.01, and 0.001, respectively.

Cultivar	Year	Respiration	Ethylene Production	Firmness	Soluble Solids Conc.	Total Losses
Frida	2018	N/A	N/A	ns	−0.154 *	0.248 ***
	2019	−0.320 ***	−0.170*	0.479 ***	−0.159 *	−0.168 *
	2020	−0.285 ***	ns	0.273 ***	−0.181 **	−0.455 ***
Ingrid Marie	2018	N/A	N/A	0.412 ***	−0.135 *	−0.372 ***
	2019	−0.222 **	−0.363 ***	0.151*	−0.142 *	−0.540 ***
	2020	−0.386 ***	−0.210 **	ns	ns	−0.592 ***
Rubinstar	2018	N/A	N/A	0.426 ***	0.398 ***	−0.699 ***
	2019	−0.394 ***	−0.386 ***	ns	ns	−0.215 **
	2020	ns	ns	ns	−0.405 ***	−0.302 ***
Elise	2018	N/A	N/A	ns	ns	−0.267 ***
	2019	ns	ns	ns	−0.362 ***	−0.280 ***
	2020	−0.321 ***	0.208 *	ns	−0.401 ***	−0.665 ***

Solar radiation and temperature were high in 2018, and this year had more than double the number of days with the maximum temperature above 25 °C for 'Ingrid Marie' and 'Rubinstar', and about 3–5 times more days for 'Frida' and 'Elise' with the maximum temperature above 25 °C, as compared with 2019 and 2020. The highest rainfall and highest relative humidity were found in 2019. Moreover, 2020 had a similar temperature as 2019, though with more peaks in temperature but lower relative humidity and rainfall (Table 5).

Table 5. Weather conditions during the growing seasons, from flowering to harvest, in 2018, 2019, and 2020. Number of days with maximum day temperature above 25 °C was calculated from the approximate start of bloom time until harvest at the latest I_{AD} interval each year.

Cultivar	Year	Daily Min. Temp. °C	Daily Aver. Temp. °C	No Days Max. Temp. ≥ 25 °C	Relative Humidity %	Rainfall (Total) L/m^2	Solar Radiation MJ/m^2
Frida	2018	12.78	17.58	38	79.62	188	23.44
	2019	12.50	16.15	7	87.91	398	16.51
	2020	13.21	15.67	13	81.00	175	20.75
Ingrid Marie	2018	12.30	18.84	52	71.46	125	29.62
	2019	11.75	16.10	26	81.7	326	21.41
	2020	11.12	15.91	21	77.03	160	20.91
Rubinstar	2018	12.78	17.58	52	79.62	188	23.44
	2019	11.32	15.59	26	82.08	335	20.70
	2020	11.45	15.57	21	81.54	192	20.17
Elise	2018	11.47	17.58	38	79.62	188	23.44
	2019	11.89	15.29	7	86.21	398	19.22
	2020	11.47	15.59	13	81.45	187	20.27

4. Discussion

Between-year variation influenced many of the quality parameters investigated in this study, and results of correlation calculations showed variation between years. In Sweden, the summer of 2018 was exceptionally warm, with several periods of hot temperatures, while rainfall levels were higher in 2019 than in the other years (Table 5) [21]. However, when evaluating the influence of different weather factors on the ability of maturity index I_{AD} to predict storability and correlating these with the quality traits after storage studied in this investigation, in general, no clear difference was found between the climate-diverse years. Nonetheless, the year 2018, with the highest average temperature and most incidences of temperatures above 25 °C, showed the highest values of soluble solids content for all four cultivars after storage when all I_{AD} values per year were considered. These results are in agreement with another study that found increasing soluble solids content coinciding with increasing temperature over 20 years when investigating two apple cultivars in a high-latitude region [43].

Late-season apple cultivars have a number of traits that are beneficial for long-term storability. This study investigated some key factors known to be associated with long storage ability and correlations between these and I_{AD} values at harvest in order to examine whether this maturity index can accurately predict storability related to the decision of optimal harvest time. Losses due to physiological disorders and fungal decay during storage are among the main factors that can limit storage potential. Common storage pathogens include *Neofabraea* spp., *Colletotrichum* spp., *Penicillium expansum*, *Botrytis cinerea*, and *Monilinia* spp. [44,45]. Attacks by *Monilinia* spp., *P. expansum*, and *Colletotrichum* spp. are known to be aggravated by inappropriate harvesting time [19,46]. In this study, significant negative correlations between I_{AD} values at harvest and losses during storage were found at all years and in all cultivars, with the exception of 'Frida' in 2018, so losses were generally higher at a lower I_{AD} value, indicating a more advanced maturity. The losses in this investigation were more often due to fungal decay than to physiological disorders. Previous studies have found that higher harvest I_{AD} can lead to lower pathogen incidence during storage [47,48] and reduce storage losses of fruit due to physiological disorders and fungal decay [48], and the results in this investigation corroborate those conclusions.

Apart from more unpredictable weather, including occasionally occurring high rainfall levels, further temperature increases and heat waves due to climate change seem to be inevitable [49,50]. The diverse weather conditions during the three years in this investigation might illustrate that predictions of optimal harvest time can be an even greater challenge in the future, since many weather factors can affect different quality traits, which are the basis of different maturity indices. In another investigation during the same years and at the same places, the variation in harvest I_{AD} values (calculated as the average coefficient of variation) was higher in 2018, which was the year with the highest average temperature and most days with temperatures above 25 °C. However, Streif index and starch degradation values showed most often higher variability between years than I_{AD} values. Assessing the results in that study, if one cultivar was excluded ('Frida', which showed a different pattern), the calculation of averages of the other eight cultivars showed that I_{AD} had an average coefficient of variation (CV) of 17.6%, while Streif index had a CV of 35.9%, and starch degradation a CV of 34.0% if all years were included [51]. Temperature is maybe the most important factor related to climate change and the consequences for optimizing harvest dates. A previous investigation showed that the rate of chlorophyll degradation in the skin of apple fruit is affected by temperature. The chlorophyll degradation rate increased with temperature, with the highest rate at 25 °C, and decreased at 30 °C, though having approximately the same rate constant (k) at 30 °C as at 20 °C [36]. In this investigation, the year 2018, having more episodes with high temperatures, did not differ from the other years regarding significant correlation values between harvest I_{AD} and total losses during storage. Hence, the temperature did not seem to affect the results for I_{AD} as predicting storability, possibly due to the fact that the temperature was in a range not affecting chlorophyll degradation to any notable extent. However, even though experiencing more incidences with higher temperatures and increasing average temperatures, Sweden is among the apple-producing countries with a cooler climate, with an average temperature in July at 17–18 °C in the southernmost part [52]. On the other hand, the climate can be warmer in other apple-producing regions. For example, an investigation in the fruit-growing region of

Leida in Spain reported maximum mean temperatures of 29–34 °C (over 10-day intervals), and temperatures above 30 °C were reported as frequently occurring [39]. In addition, increasingly occurring heat waves in apple-producing regions in Northern Italy have been reported, as well as in regions in the United States [53,54]. Such high temperatures could then affect the chlorophyll degradation, and possibly the predictability of the I_{AD} measurements for apple maturity, though this needs further investigations.

As for other parameters used as maturity indices, the color of the fruit has been found to be affected by the temperature during the growing season, giving less red-colored fruit with a higher temperature [37,38]. A high-temperature climate was found to reduce anthocyanin content, and a reduction in gene expression related to anthocyanin formation was found, connected to the maintenance of temperatures above 20 °C [39]. Firmness at harvest did not show any clear pattern of differences between cooler and warmer sites for 'Gala', nor for 'Fuji' [37], though in another investigation, cooler conditions lead to higher firmness at harvest for some cultivars [38]. Also, the absence of cooler night temperatures during the growing season might affect the maturity indices used, as even moderately lower night temperatures have been found to accelerate the starch degradation process [41]. Further, for anthocyanin accumulation in apple fruit skin, low temperature was found to be an important factor in promoting anthocyanin biosynthetic genes [39,40]. In general, the suitable value of each maturity index is determined specifically for each cultivar for the determination of optimal harvest time, and practice may vary between regions [34,55,56]. The results found in this investigation showed that there could be great variability between years in the quality traits after storage but that using I_{AD} values as a complemental maturity index can be suitable, though with better accuracy for some cultivars.

To ensure the long-term storage ability of apples, high firmness is important as it decreases the severity of rot [19]. Changes in firmness leading to softening and mealiness during storage can also limit the marketability of apples due to market demands and consumer preferences for firm and not mealy fruit [57,58]. In general, late-season cultivars are firmer and show a slower decline in firmness than early-season cultivars [15]. In the present study, there were some weak to medium-strong, significant correlations between I_{AD} and firmness in three of the cultivars. Firmness was consistently high in 'Elise' during storage, independently of harvest I_{AD} value, and together with the lowest ethylene production of the investigated cultivars, this could explain why no significant correlation between firmness and harvest I_{AD} was found for this cultivar. In a previous study, no relationship was found between higher firmness and later harvest time when comparing only within the group of late-season cultivars [15]. Thus, our results are consistent with the finding that there can be variation within cultivar groups. There are also adaptations, such as thicker skin [17] and differences in the cuticle [18], that might indirectly affect firmness during storage. In a previous one-year trial, firmness after storage was found to be strongly correlated with harvest I_{AD} when measured under controlled conditions at a research station but much weaker when assessed at a commercial storage facility, leading to the conclusion that I_{AD} is not a suitable predictor of firmness after storage of apples in commercial facilities [59]. In another study, correlations with harvest I_{AD} were found to be lower for firmness than for total soluble solids and titratable acids [30]. From the results of this study, it can be concluded that for some cultivars and some years, I_{AD} at harvest could predict how firmness is retained during storage, though, in general, it cannot be used as a reliable index for firmness retention during storage.

Although all investigated cultivars were harvested, as commercial practice, at midseason- and late-season, there were some profound differences between them after storage. 'Elise' stood out as seemingly being the cultivar affected the least by storage, with the lowest ethylene production, highest range of firmness after storage, and, together with

'Rubinstar', the lowest total losses. 'Ingrid-Marie', on the other hand, had the lowest range of firmness and, in general, more total losses, which also was the case for 'Frida', though not reaching the highest incidences of losses as 'Ingrid-Marie'. Evaluating the significance of harvesting at a specific I_{AD} value, or interval, in relation to their performance during this storage time, for 'Frida', an I_{AD} value of 1.3 could be seen as the recommended harvest value, while for 'Ingrid Marie' a value of 1.4 could be recommended, mainly based on their total losses during storage, although variation between years seems to occur. However, for 'Rubinstar', no specific breakpoint could be found, and considering the previous report of this cultivar having the second highest average coefficient of variation (CV) for I_{AD} values among nine investigated cultivars (51) using I_{AD} values as maturity indices for harvest time determination is not recommended for this cultivar. As for 'Elise', even though there were significant correlations found between total losses and I_{AD} values, the total losses were low, making comparisons between the effects of harvest at different I_{AD} values more difficult. Aiming at a middle-range I_{AD} value of 1.3–1.4 but relying more on other maturity indices for harvest time determination could be a good strategy.

Among cultivars compared, 'Rubinstar' showed higher ethylene production than the other cultivars, especially in 2019. There was no indication that high ethylene production benefited pathogen attack, as fruit losses during storage were generally low in 'Rubinstar', and no major differences were found between apples in different harvest I_{AD} intervals regarding rot or physiological disorders. 'Elise' had lower ethylene production than 'Rubinstar' and was also firmer, which is in line with previous findings [60]. On average, for all harvest I_{AD} intervals, 'Ingrid Marie' suffered more fungal decay than the other cultivars, possibly because pathogens benefited from the softer fruit of that cultivar, which is in agreement with previous findings [19]. Pathogenic fungi benefit from wet weather in many cases. Rain and wetter conditions can spread these pathogens [61], and high humidity helps conidia from fungal pathogens to adhere and infect the fruit [62,63]. However, no consistent differences between years in fungal decay that could be linked to the more humid weather during the season of 2019 were found in this study.

The involvement of ethylene in the softening of apple flesh tissue during ripening and post-harvest storage has long been studied, and it has been suggested that the presence of ethylene induces softening by regulating the expression of cell wall-modifying enzymes [16]. Late-season cultivars may show better storability because they produce less ethylene and have a lower respiration rate [13]. The rate of loss of flesh firmness can be driven at least partly by ethylene, although late-season cultivars are not as sensitive as early cultivars to low ethylene concentrations [60]. However, ethylene production and concentration do not always seem to be linked to changes in firmness during post-harvest storage [64,65]. In the present study, ethylene production was lower in the late-season 'Elise' in 2019 than in 2020, although measured firmness was similar in both years. In 'Rubinstar', the lowest harvest I_{AD} values resulted in much higher ethylene production in 2019 than in 2020, although firmness was similar in both years. Earlier studies have shown that ethylene production may increase flesh softening in high concentrations [60]. However, in the present study no association between high ethylene production and softer fruit was found when comparing different I_{AD} intervals within cultivar and year. Recent studies showed that differences in genotype regarding ethylene production do not solely explain differences in fruit ripening rates and that differences in ethylene perception and downstream signaling are also important [15,66,67].

5. Conclusions

Correlations between I_{AD} at harvest and losses due to fungal decay and physiological diseases after storage were frequent in all four cultivars and years, indicating that I_{AD} at harvest can be used as a complementary maturity index for predicting storability regarding storage losses. In contrast, only a few significant results were found for I_{AD} at harvest and fruit firmness after harvest, so, in general, it cannot be used as a reliable index for how firmness will be retained during storage.

Between-year variations in factors that are used as maturity indices, together with variability between apples within the same orchard, make it difficult to establish a basis for decision-making on the optimal time to harvest apples of different cultivars in order to maximize storability. It seems reasonable to assume that using a combination of indices is a more reliable method for determining the optimal time of harvest. Since I_{AD} values were correlated with losses after storage, I_{AD} measurement could be used as a complement to other maturity indices, though it is not suitable as a replacement for other maturity indices. It has many benefits over the other methods, such as speed, simplicity, and non-destructive measurements. These features also make it possible to use in the apple orchards to follow the progression of maturity non-destructively.

Regarding the investigated cultivars in this study, for 'Frida', an I_{AD} value of 1.3 could be seen as the recommended harvest value, while for 'Ingrid Marie', a value of 1.4 could be recommended, mainly based on their total losses during storage, although variation between years seems to occur. However, for 'Rubinstar', no specific breakpoint could be found. For 'Elise', with very low losses after storage found in this study, aiming at a middle range I_{AD} value of 1.3–1.4 but relying more on other maturity indices for harvest time determination could be a good strategy.

The exceptionally warm year 2018 did not differ noticeably in comparison to the other years in relation to I_{AD}'s use as a maturity index and prediction of storage potential. This indicates that $I_{AD,}$ as a maturity index, is resilient to changing temperatures, at least at warmer episodes up to 30 °C. Further research is needed to evaluate the influence of climate change on other maturity indices.

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Abbreviations

The following abbreviations are used in this manuscript:

I_{AD}	Index of adsorption difference

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