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Comparison between I_{AD} and other maturity indices in nine commercially grown apple cultivars

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ABSTRACT

To maintain storage potential as long as possible, it is important to harvest fruit at optimal maturity. Different maturity indices have been developed, including flesh firmness, soluble solids content, starch degradation, ethylene production, and respiration rate. However, many of them are destructive, time consuming, and may be require some laboratory equipment to perform. The portable device DA-meter (measuring index of absorption difference; I_{AD}) can monitor the chlorophyll decline non-destructively in the field, and could potentially save time. To evaluate the I_{AD} in comparison with other maturity indices, nine common commercial cultivars of apple were investigated in a three-year trial. Correlations between I_{AD} and other maturity indices, especially starch degradation and ripening index by Streif were strong in most cultivars, though variation between years lead to weaker correlations were found last year of the trial. The strongest correlations were found between I_{AD} and harvest date showing that I_{AD} decreased with time in all investigated cultivars. Comparison between I_{AD} and ripening index by Streif showed in some cases that the two indices decreased at the same time, suggesting that I_{AD} could be used to monitor maturity when it is rapid. The suitability to use I_{AD} as a maturity index seems to be cultivar-dependent. For cultivars having a more consistent pattern between years in the decrease of I_{AD}, combined with relatively low variation in I_{AD} at any given time, it could be a good complement to other commonly used maturity indices.

1. Introduction

Losses of fruit occur all along the supply chain (Gustavsson et al., 2011). To reduce these losses is important, not only from an environmental, but also an economic point of view, as a lot of resources have been used to produce the fruit (Tahir, 2019). Losses occur both before harvest and after, and main causes are often unfavorable growing conditions and improper postharvest handling, leading to rotten and moldy fruit. Waste occurs later in the supply chain, i.e. at the retail and consumption level, and is caused by aesthetic defects and improper storage conditions (Gustavsson et al., 2011). To ensure that losses are as low as possible during storage, it is important to harvest at the pre-climacteric stage when ethylene production and respiration rate are at the lowest level and fruit shows the highest storage potential (Giovanelli et al., 2014). Fungal decay and physiological disorders can be substantial during storage and both are dependent on maturity at harvest (Tahir et al., 2015; Watkins et al., 2005). Apples harvested too early may have inferior quality traits related to maturity, such as deficient organoleptic characteristics, while a too late harvest may lead to increased storage losses (Tahir, 2019) and declining fruit quality (Peirs et al., 2001).

To ensure that fruit is harvested at the optimum date, a variety of maturity indices have been developed and used over the years. As a climacteric fruit apple has a typical pattern with a characteristic rise in respiration and ethylene production, that can be used to determine maturity (Song and Bangerth, 1996). Thus, fruit harvested at the climacteric minimum, when the respiration is at the lowest level, is known to store well, while apples harvested at a later stage might lose their quality quite rapidly (Blackman and Parija, 1928; Peirs et al., 2001). A trait that can be used as a maturity index already in the field and later during storage is skin color, from which a color index (CI) can be calculated (López Camelo and Gómez, 2004). However, in practice, it is more common to use firmness (Reid et al., 1982), SSC i.e. soluble solid concentration (expressed in Brix°) (Kingston, 1992), and starch degradation (Reid et al., 1982) as maturity indices, since they are convenient

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and fast to use. As apples ripen, enzymes break down compounds of the cell wall, such as pectin, making the fruit softer, and hence the changes in texture can be used to determine maturity (Korićanac et al., 2019; McGlone et al., 2002; Wei et al., 2010). The sugar/acid ratio is important for the development of taste (Bonany et al., 2013; Korićanac et al., 2019), and consequently the content at harvest is important. During ripening starch is degraded to sugars (Kovács and Eads, 1999), therefore changes in starch content can be used as a way to determine maturity. From firmness, sugar content and starch degradation, the so-called ripening index by Streif can be calculated (Streif, 1996). Ripening index by Streif is a commonly used maturity index in Europe; e.g. in Germany (Streif, 1996; Wood et al., 2022) and Sweden (Tahir and Nybom, 2013), and is used also in other parts of the world (DeLong et al., 1999). The ripening index by Streif decrease with increasing maturity and fruit with values of 0.18 and less were considered ripe for starting the harvest (Lv et al., 2016).

However, the maturity indices used have mainly been based on destructive measurements, which can be time consuming and limits the amounts of possible samples. In addition, the variability in the measured factors (color, SSC, firmness etc.) between different apples on the same tree, or between fruit on different trees, makes it more difficult to achieve a representative sampling, since the number of sampled apples by necessity is quite limited when using destructive measurements. In ripening fruit ethylene initiates many processes, and one of them being chlorophyll degradation by various enzymes (Gorfer et al., 2022; Hörtensteiner and Kräutler, 2011). In 2008 a new index for monitoring chlorophyll degradation under the skin called “Index of absorption difference” or I_{AD} was developed for peaches (Ziosi et al., 2008). A few years later a non-destructive portable device, called DA-meter, was introduced as a new instrument for measuring I_{AD} (Nyasordzi et al., 2013). By using spectroscopy, it calculates the difference in absorption between the wavelengths 670 nm, i.e. the chlorophyll a absorption peak, and 720 nm, which is the background spectrum. This gives an assessment of chlorophyll in the skin of the fruit called the “index of absorption difference” or I_{AD}, which has been shown to correlate with total soluble solids, acidity and firmness (Nyasordzi et al., 2013). In addition to being non-destructive, the measurements are fast, and the device can be used in the field, meaning that a larger number of apples can be tested and the ripening process of individual apples can be followed, which cannot be done when destructive maturity indices are used (DeLong et al., 2014). Both low and high I_{AD} values have been linked to an increased risk of physiological disorders and storage rots (Watkins et al., 2000). Unfortunately, optimal I_{AD} values at harvest for apples aimed for longer storage vary with cultivar and production area. Consequently, quite a lot of work has to be done to determine optimal values for each specific case (Nyasordzi et al., 2013).

The aim of this investigation was to evaluate how well I_{AD} values, measured by a DA-meter, correlated with different maturity indices during the maturity period around the estimated harvest time, in order to determine if I_{AD} could be a reliable substitute or a complement to the established maturity indices for commercially grown apple cultivars. In nine different apple cultivars, I_{AD} was measured as well as other maturity indices, i.e. SSC, firmness, starch degradation, and ripening index by Streif, before and after commercial harvest date. Correlations between I_{AD} and the other maturity indices were calculated to evaluate similarities or differences in the changes of these indices during the harvest period.

2. Materials and methods

Apples of nine cultivars, common in Swedish commercial production, were obtained from commercial orchards during three years; 2018, 2019 and 2020. The cultivars ‘Discovery’, ‘Aroma’, ‘Rubinola’, ‘Santana’, ‘Ingrid Marie’ and ‘Rubinstar’ were harvested in an orchard in western Scania (55°43′26.6″N 13°05′52.8″E) in southern Sweden. The cultivars ‘Saga’, ‘Frida’ and ‘Elise’ were harvested in another orchard in eastern Scania (55°37′35.6″N 14°16′21.9″E). The cultivars were harvested in the same orchards all three years.

Twenty-one trees per cultivar were chosen and care was taken to ensure that the trees were healthy and that they had an average crop load. Thinning was conducted during the growing season to ensure that for each fruit there were between 25 and 40 leaves. The first few trees in the row were not included and trees were chosen up to about 50 m into the row. The trees were between 8 and 15 years old at the start of the trial. To determine maturity, 21 apples in total from each cultivar were picked twice a week from the marked trees, starting from approximately two weeks before estimated optimal harvest (Table 1) and continuing up to completed starch degradation (value 10 on a scale from 1 to 10), meaning that for some cultivars fruit was harvested up to ten times. The estimation of optimal harvest date was based on a combination of days after full bloom and the advice from the local producer organization. The fruit was picked from the middle part of the tree, where it had been exposed to direct sunlight or semi-shade. After harvest the apples were immediately transported to the laboratory. Maturity tests were conducted the same day as the fruit was harvested, or the following day after storage in a cold room (2 °C, 95 % RH) over night.

The 21 apples were weighed, and the coloring of each fruit was measured by a colorimeter (Minolta Ltd., Osaka, Japan) on three points of the fruit and then an average was calculated. For each apple, an I_{AD} value was assessed on both the sunny and the shaded side of the fruit sides using a DA-meter (Sinteleia, Bologna, Italy). In addition, firmness tests with a penetrometer (Model FT 327; Effigy, Italy; plunger diameter of 11.1 mm, depth of 7.9 mm) in kg*cm^{-2} (conversion factor to N 9.81) on both the sunny and shaded side of the fruit after peeling and then an average was calculated for each apple. Measurements of soluble solids concentration (SSC) in percent was estimated as Brix° with a digital refractometer (RFM80, Bellingham + Stanley, Tunbridge Wells, UK) on the juice obtained by the firmness test. Starch degradation was measured by dipping a 0.5 cm thick slice, from across the core of the apple, in an iodine/potassium iodine solution (3 g/L I_2 and 12 g/L KI). After the slice had been colored by the iodine solution, starch degradation was assessed at the scale from 1 to 10 where 1 meant no starch degradation and 10 complete starch degradation which was also the methodology of (Lv et al., 2016). From the values of firmness, Brix° and starch degradation, the ripening index by Streif was calculated as: Firmness (kg cm^{-2})/ SSC (%) * Starch degradation stage (Streif, 1996).

The Pearson correlation coefficient was used to calculate the correlations between I_{AD} and other maturity indices (Minitab v 18.1; Minitab, Inc., USA). Correlations of 0.4–0.6 were considered as medium strong, 0.6–0.8 as strong and correlations between 0.8 and 1.0 as very strong. Coefficient of variation was calculated by dividing the standard deviation with the mean value, and expressed as %.

Table 1
Time of the first harvest each year for the nine apple cultivars. The first harvest was done approximately two weeks before the commercial harvest, estimated by a combination of days after full bloom and advice from the local producer organization.

Cultivar	2018	2019	2020
Discovery	Aug 6	Aug 1	Aug 4
Aroma	Aug 6	Aug 12	Aug 25
Saga	Aug 9	—	Aug 21
Rubinola	Aug 13	Aug 15	Aug 25
Santana	Sep 3	Aug 23	Aug 29
Rubinstar	Sep 3	Sep 10	Sep 18
Frida	Sep 10	Sep 2	Sep 4
Ingrid Marie	Aug 27	Sep 12	Sep 11
Elise	Sep 6	Sep 17	Sep 22

3. Results

3.1. Correlations

Negative, medium to very strong, correlations between I_{AD} and harvest time were found for all cultivars, which means that I_{AD} decreased with progressing maturity. In 2020, the correlations were the weakest of the three years in the cultivars 'Discovery', 'Aroma', 'Rubinola', 'Santana', 'Frida', 'Ingrid Marie' and 'Elise'. For 'Saga' the correlation was the weakest in 2020 of the two investigated years, while for 'Rubinstar' it was non-significant in 2020 (Table 2). Ripening index by Streif generally had medium to strong positive correlations with I_{AD} in 2018 and 2019, but correlations were weaker in 2020, especially in 'Discovery', 'Rubinstar', 'Frida' 'Ingrid Marie', and 'Elise'. As for firmness, correlations with I_{AD} were positive, and generally medium strong to strong, although there were also weak or non-significant correlations. The correlations between firmness and I_{AD} showed a high variability between years. For example, 'Frida' had a correlation of 0.828 in 2018, while the two following years the correlations were 0.215 and 0.231, respectively. For all cultivars, the strongest correlations were obtained either in 2018 or 2019. Starch degradation showed mostly strong, but varying correlations with I_{AD}, although correlations between −0.649 and −0.915 were found two years in a row in five out of the nine cultivars. For the other four cultivars correlations between −0.715 and −0.852 were found as the highest value of the investigated years. In fact, the average of the correlations for all the investigated cultivars and years taken together were higher between starch degradation and I_{AD} (−0.692), than between ripening index by Streif and I_{AD} (0.586). As was the case for ripening index by Streif, the same pattern with stronger correlations in 2018 and 2019 compared to 2020 was found for starch degradation, with eight cultivars having the weakest correlations in 2020, and in one cultivar a non-significant correlation. The correlation between color index and I_{AD} in 'Aroma', 'Elise', 'Rubinola' and 'Saga' had stronger negative correlation than the other cultivars, varying between −0.542 and −0.800 in the three years.

3.2. Changes in I_{AD} and ripening index by Streif over time

I_{AD} decline in the investigated cultivars showed different pattern during the three years. 'Aroma', 'Rubinola', 'Rubinstar' (only in 2018 and 2019), 'Ingrid Marie', and 'Elise' had a similar pattern between the years. 'Santana', showed a large difference between years in the average I_{AD} values for any given time (Fig. 1).

For 'Discovery', and 'Frida' no consistent pattern could be found. As shown regarding the correlations between I_{AD} and ripening index by Streif, the year 2020 differed from the other two years, and in five of the cultivars, the highest I_{AD} values were found in a majority of the investigated time points this year (Fig. 1).

There were big differences between cultivars regarding how large the variation in I_{AD} was at any given time among the apples, shown in the figure as standard deviation (Fig. 1). 'Aroma', 'Frida' and 'Elise' showed the lowest variation (average coefficient of variation (CV) for all years 13.0; 15.8 and 10.7 % respectively), while 'Discovery', and 'Rubinstar' had the highest variation (CV values were 88.1 and 30.1 %, respectively) (Table 3, average yearly values are shown). In general for I_{AD}, the highest CV was found at the later harvests, and the lowest CV at the first two harvests (values not shown).

Also in the ripening index by Streif there were differences between cultivars regarding how large the variation was at any given time among the apples, shown in the figure as standard deviation (Fig. 1), and in general the variation was higher in ripening index by Streif than for I_{AD} (CV average all years and all cultivars Streif: 35.7 %; I_{AD}: 25.5 %). 'Aroma', 'Santana' and 'Ingrid Marie' showed the largest variation (CV for all years 41.5; 41.0 and 46.7 %, respectively), while 'Frida' and

Table 2
Pearson correlations between I_{AD} and other maturity indices in all nine cultivars in 2018, 2019 and 2020. All values are significant ($P < 0.05$), ns instead of a value means that the correlation was not significant.

Cultivar	Year	Harvest time	Color index	Firmness	SSC	Starch degradation	Ripening index by Streif
Discovery	2018	−0.696	−0.405	0.308	−0.224	−0.492	0.536
	2019	−0.873	−0.748	0.637	−0.637	−0.790	0.804
	2020	−0.438	−0.403	ns	−0.274	−0.309	0.344
Aroma	2018	−0.879	−0.800	0.457	ns	−0.915	0.836
	2019	−0.819	−0.542	0.689	−0.602	−0.728	0.680
	2020	−0.636	−0.589	0.300	−0.171	−0.443	0.535
Saga	2018	−0.794	−0.650	0.767	−0.715	−0.852	0.857
	2020	−0.694	−0.711	0.430	−0.522	−0.584	0.555
Rubinola	2018	−0.765	−0.581	0.462	−0.239	−0.663	0.670
	2019	−0.861	−0.614	0.618	−0.298	−0.812	0.734
	2020	−0.703	−0.752	0.386	−0.283	−0.577	0.444
Santana	2018	−0.678	−0.195	0.330	−0.369	−0.559	0.548
	2019	−0.787	−0.421	0.399	−0.213	−0.678	0.632
	2020	−0.597	−0.416	ns	−0.184	−0.649	0.531
Rubinstar	2018	−0.945	−0.532	0.789	−0.796	−0.802	0.674
	2019	−0.751	−0.443	0.446	−0.534	−0.686	0.581
	2020	ns	−0.431	0.277	−0.357	ns	0.226
Frida	2018	−0.943	−0.299	0.828	−0.794	−0.900	0.776
	2019	−0.765	−0.401	0.215	−0.445	−0.650	0.603
	2020	−0.533	ns	0.231	ns	−0.501	0.373
Ingrid Marie	2018	−0.950	−0.397	0.808	ns	−0.819	0.879
	2019	−0.675	−0.392	0.377	−0.459	−0.305	0.535
	2020	−0.434	−0.311	0.467	ns	−0.257	0.275
Elise	2018	−0.918	−0.613	0.782	−0.654	−0.715	0.716
	2019	−0.645	−0.606	0.713	−0.183	−0.440	0.538
	2020	−0.599	−0.677	0.427	−0.229	−0.364	0.345

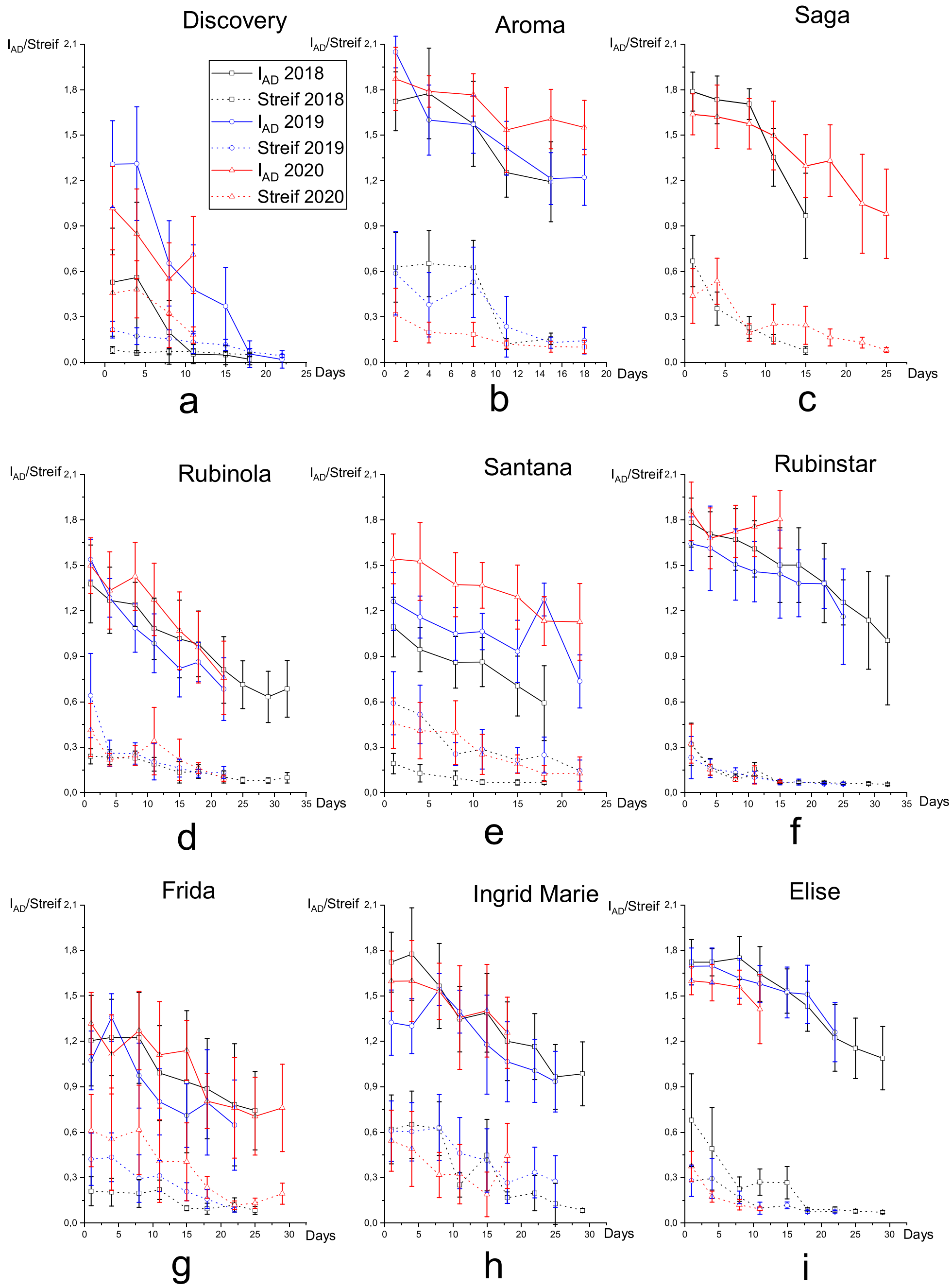

Fig. 1. Changes and standard deviations in I_{AD} and ripening index by Streif over time in 'Discovery', 'Aroma', 'Saga' 'Rubinola', 'Santana', 'Rubinstar', Frida', 'Ingrid Marie' and 'Elise'.

'Elise' had the lowest variation (CV 25.2 and 27.3 %, respectively). The three factors included in ripening index by Streif showed differences between cultivars in the variation at any given time. In average for all cultivars and all years SSC had the lowest variation (CV 8.4 %; average cultivar range 6.3–10.6), while firmness variation was almost as low (CV 8.6 %; average cultivar range 6.4–12.1), though starch degradation had higher variation (CV 32.9 %; average cultivar range 17.4–50.9) (Table 3; average yearly values are shown).

Comparing the difference between years in the ripening index by Streif for each cultivar, some cultivars; 'Discovery', 'Aroma', 'Santana', and 'Frida' had relatively large difference between years in the average values of ripening index by Streif at any given time, while other cultivars; 'Rubinola' and 'Rubinstar' showed less variation between years.

For the individual cultivars, different pattern in the changes of the maturity indices could be found. In 'Discovery', ripening index by Streif did not decrease very much in 2018 or in 2019 (Fig. 1a). There was a large variation among the apples in I_{AD} at any given time all three years, except at late harvests. In 2020 there was a simultaneous decrease in I_{AD} and ripening index by Streif from day 4, except for the fourth I_{AD} measurement. While ripening index by Streif continued to decrease there was an, albeit not significant, increase in I_{AD} at that point. The decline in I_{AD} was sharp all three years.

In 'Aroma', for both I_{AD} and ripening index by Streif the largest decreases were found between day 8 and 11 (Fig. 1b). I_{AD} decreased mostly slowly from the first harvest at day 1 to the third harvest at day 8, while ripening index by Streif was more stable during this time. After the decrease, mostly finished around day 11, though somewhat later in 2019, both indices leveled out as maturity at this point was very

Table 3

Average coefficient of variation (CV) for I_{AD}, ripening index by Streif, firmness, SCC and starch degradation in 'Discovery', 'Aroma', 'Saga', 'Rubinola', 'Santana', 'Rubinstar', 'Frida', 'Ingrid Marie' and 'Elise' in the years 2018, 2019 and 2020.

Cultivar	Year	I_{AD} %	Streif %	Firmness %	SSC %	Starch degradation %
Discovery	2018	113.8	26.2	14.81	10.57	14.18
	2019	96.1	34.0	11.34	8.11	19.88
	2020	35.4	48.5	10.26	7.79	35.57
Aroma	2018	16.2	30.4	10.22	9.38	58.16
	2019	12.2	53.5	8.82	6.99	36.56
	2020	11.1	38.8	8.70	9.24	31.00
Saga	2018	13.1	28.1	6.26	6.10	26.25
	2020	17.8	35.5	6.61	7.39	43.77
Rubinola	2018	21.1	28.5	7.23	18.36	23.91
	2019	17.3	35.6	7.12	8.34	29.89
	2020	20.9	37.5	7.58	5.26	24.32
Santana	2018	23.7	31.5	7.85	6.30	45.05
	2019	15.6	40.5	8.51	6.23	39.40
	2020	15.3	49.7	7.55	6.33	41.78
Frida	2018	17.6	20.4	8.90	8.89	29.40
	2019	16.6	29.8	6.97	8.86	30.67
	2020	10.9	27.3	6.86	8.07	41.01
Rubinstar	2018	34.5	36.6	9.85	8.79	14.79
	2019	28.3	35.8	8.41	9.09	18.49
	2020	27.7	43.8	6.30	6.49	18.94
Ingrid Marie	2018	18.4	43.3	11.31	9.25	47.07
	2019	17.8	45.5	9.55	7.65	50.39
	2020	17.8	53.6	11.94	8.54	55.14
Elise	2018	12.1	29.7	8.49	9.51	36.37
	2019	9.9	27.0	8.04	9.72	18.80
	2020	9.2	22.4	7.55	8.51	21.99

advanced.

In 'Saga' (Fig. 1c), there was a steeper decrease of I_{AD} in 2018 than in 2020, while the decrease in ripening index by Streif showed similar pattern both years with an initial fast decrease which then leveled out.

For 'Rubinola' (Fig. 1d), with the exception of day 1–4 2019 and 2020, the decrease in I_{AD} was more pronounced than the decrease of ripening index by Streif for all three years. Ripening index by Streif showed a rather even decline over the sampling period all three years.

'Santana' (Fig. 1e) had a similar development of maturity indices as 'Aroma' (Fig. 1) as both indices declined at a similar pace. In 2018 there was a slower decrease in ripening index by Streif compared to the other years.

In 'Rubinstar' the changes in I_{AD} differed in 2020, as compared with 2018 and 2019 (Fig. 1f). From day 1 to day 15 ripening index by Streif decreased, though not in 2020, but after day 15 the rate of decrease in ripening index by Streif waned as the average neared zero.

In 'Frida' (Fig. 1g) I_{AD} and ripening index by Streif showed a similar pattern each year at day 1–8, though the average values differed between years. Both I_{AD} and ripening index by Streif decreased rapidly between day 11 and 15 in 2018, between 4 and 7 in 2019 and day 15 and 18 in 2020.

'Ingrid Marie' (Fig. 1h) had an initial slow decrease in both I_{AD} and ripening index by Streif, with the exception of ripening index by Streif in 2020. The average values of I_{AD} was fairly similar between years after day 11. I_{AD} generally decreased fast once ripening started.

In 'Elise' ripening index by Streif had a steeper decrease than I_{AD} in 2018 and 2020 from harvest day 1 to day 7, though in 2019 these two maturity indices showed the same pattern of changes during this time (Fig. 1i). Ripening index by Streif had a sharp decrease from day 1 to day 7 in 2018, while the decrease in I_{AD} started after day 7 and continued until sampling stopped.

4. Discussion

In this investigation, comparison between I_{AD} values and other common maturity indices showed varying results between cultivars and between years. Unlike other studies, we investigated more cultivars and looked at more maturity indices making this a more in depth study compared to other studies on the subject. Variation in maturity level among apples in the same orchard makes decision about optimal harvest time more difficult. In this investigation, it was shown that different maturity indices had fluctuating coefficient of variation (CV), depending on time of harvest, cultivar and year. Interestingly, even though both ripening index by Streif and starch degradation had relatively large average CV, they both showed strong correlations with I_{AD} for many cultivars. Changes in I_{AD} values should reflect the changes in chlorophyll concentrations in the apple skin, as these two parameters have been found to correlate strongly (Betemps et al., 2012). Chlorophyll degradation during apple fruit maturity has since long been noticed, and suggested as a maturity index (Song et al., 1997). Degradation of chlorophyll is an important step in ripening of many fruits, where chloroplasts transition into chromoplasts as chlorophyll is degraded (Hörtensteiner and Kräutler, 2011). In climacteric fruit such as apples, chlorophyll degradation and other ripening processes are initiated by ethylene (Gorfer et al., 2022). However, as different processes related to maturation and ripening can be differently affected by the ethylene rise (Johnston et al., 2009), and environmental and production factors in the orchard also affect the changes related to maturation, the task of evaluating and comparing different maturity indices is complicated. The maturation indices have their weaknesses, depending on different factors, and may vary between years. Ideally, it should be possible to distinguish the environmental factors that make one maturation index less reliable a certain year, and to rely more on the other indices that year.

The correlation between the different maturity indices and chlorophyll decline was compared in this investigation. The strong correlation between I_{AD} and harvest time showed that I_{AD} was decreasing during the period before and during harvest time, though sometimes at varying pace. Even more important was the correlation with ripening index by Streif, which is a maturity index that is commonly used in Europe (Tahir and Nybom, 2013). The figure displaying changes with time in I_{AD} and ripening index by Streif illustrate that these two indices often decrease at the same time, showing medium to strong correlations. However, somewhat troublesome is the finding that there can be large variation between years in the correlation between I_{AD} and ripening index by Streif, and especially in some cultivars. The most pronounced difference in correlation between years was found for 'Ingrid Marie', displaying a difference between years of more than 0.6, with correlations ranging between 0.879 and 0.275. Still, this might only tell us that these maturity indices may not give the same indication in some years for some cultivars and not which one that gives the most accurate indication when to harvest. The big differences between cultivars found in this investigation regarding how large the variation in I_{AD} is between the years, together with the variation at any given time among the apples (in Fig. 1 shown as standard deviation), indicate that this maturity index is more suitable for some cultivars and less suitable for other cultivars. Previous investigations have pointed out the importance of correct sampling and avoiding misreading due to incorrect measuring technique when using the DA-meter (Toivonen et al., 2016; Musacchi and Serra, 2018). However, since all measurements were conducted with the same method and instrument, by the same person, in all years and in all cultivars in this investigation, the large variation found for some cultivars seems unlikely to be due to errors in the methodology, since there were also cultivars with relatively small variation. For cultivars with large variation in I_{AD} at any given time, together with no consistent pattern between years in the decrease of I_{AD}, such as 'Discovery' and 'Frida', I_{AD} as maturity index should be less reliable to use. On the other hand, for cultivars having less variation in I_{AD} at any given time, together with having a more consistent pattern between years in the decrease of I_{AD}, such as 'Aroma', 'Saga', and 'Elise', I_{AD} could be a good compliment to other commonly used maturity indices. This investigation found that there was less variation in I_{AD} at any given time at the first harvests, meaning that the measurements should be more reliable at an early maturity stage than at later stages.

In this investigation, the variation found in ripening index by Streif at any given time among the apples differed between the cultivars, and in general, the variation was higher for ripening index by Streif than for I_{AD}. The variation, CV, of starch degradation was higher than the other maturity indices (firmness, SSC and ripening index by Streif). This might possibly partly be due to that there is an element of subjectivity in the methodology for evaluation of the starch degradation, together with a non-continuous scale, but also that starch content and degradation are affected by environmental factors (Toivonen, 2015). In some cultivars; 'Rubinola' and 'Rubinstar', the decrease in ripening index by Streif was in general small during maturation, and possibly making decision of optimal harvest time harder, so I_{AD} could be used for these as a compliment to ripening index by Streif. If the grower makes the initial measurements in the orchard and notices a decline in I_{AD}, more extensive testing could then be done, in total saving some fruit from destructive maturity tests.

The year 2018 was an exceptionally warm year with high summer temperature peaks, and with average temperatures during the growing season of about 19 °C, as compared with 2019 and 2020 with 16 respectively 15 °C. 2018 had very little rain, 2019 had higher precipitation than 2018, and 2020 had less rain than 2019 (Sjöstrand et al., 2023). The diverse weather conditions during the three years in this investigation, and the differences found in the results between years, might illustrate that deciding optimal harvest time could be more challenging in the future, with more unpredictable and changing climate (Shivanna, 2022; Kazmi et al., 2023). It has been found that starch degradation is a factor that might be affected by night temperatures during fruit development (Toivonen, 2015). Further, warm night temperatures increase dark respiration in leaves, which can result in lower photosynthetic translocation to the fruits, and thereby resulting in lower starch accumulation (Richardson et al., 2004), and thus higher rate of starch degradation. Possibly this was the case in this investigation with the earliest harvested cultivar; 'Discovery', which showed initial unusually high values for starch degradation (values not shown). As for the correlation between I_{AD} and starch degradation in this investigation, no clear general tendency could be found for the warm year 2018 as compared with 2019 and 2020, though six out of the nine cultivars had the highest correlation between I_{AD} and starch degradation in 2018. Further, the average lowest temperatures during the growing season was lower for 2020 (Sjöstrand et al., 2023), which possibly might have affected the somewhat different result for 2020 as compared with the other two years. Decreasing night temperatures in the autumn have been suggested to increase the conversion of starch to sugars (Smith et al., 1979), which in this case especially could have affected the late harvested cultivars. Comparing the years, 2020 was found to have lower correlation than 2018 and 2019 between starch degradation and I_{AD} for some of the late cultivars ('Rubinstar', 'Frida', 'Ingrid Marie', 'Elise'), though lower night temperatures than the other two years were not found (values not shown).

I_{AD} can differ greatly even on different parts of one fruit depending on the sun exposure (Betemps et al., 2012). Sun exposure, or sun stress, can lower the I_{AD} value, as can also dark-induced chlorophyll loss (Toivonen et al., 2016). Another study showed that chlorophyll content is lower in sun scalded areas of a fruit (Felicetti and Schrader, 2009). Both temperature and intense light can cause sun burn and loss of chlorophyll (Schrader et al., 2008). The strong effect of sun exposure could, to some extent, explain the large variation in I_{AD} between years. Previous studies have suggested that microclimate and growing conditions play a large role in the accuracy of harvest prediction (DeLong et al., 2014, 2016). The quite diverse weather in the investigated three years during the growing seasons could have affected the I_{AD} values. For many of the earlier or medium late harvested cultivars, the I_{AD} values were mostly lower in 2018 than the other two years, which might have been due to the higher sun exposure during the warm and sunny summer of 2018.

Firmness followed a similar pattern as ripening index by Streif regarding the correlation with I_{AD}. Five of the nine cultivars showed the strongest correlation between I_{AD} and ripening index by Streif in 2018.

Color index in many cases had medium to strong correlation with $I_{AD,}$ though it did not follow the same pattern as ripening index by Streif concerning the yearly variation. Since the I_{AD} is based on wavelengths 670 and 720 nm, where the other pigments in the apples, the carotenoids and anthocyanins, have no or little absorbance (Xue et al., 2019), they should not be able to influence the measurements. On the other hand, it cannot be ruled out that there could be an indirect influence, e.g. possibly by the common precursor geranylgeranyl pyrophosphate in the biosynthesis for both chlorophylls and carotenoids (Quian-Ulloa and Stange, 2021), which might influence the concentration of the chlorophylls. A previous study, investigating correlations between chlorophyll concentrations and I_{AD} values in nine apple cultivars, found that more than half of the fruit in each cultivar had I_{AD} values that were higher in the blushed sides of apples compared with unblushed sides, with the exception of two cultivars (Shao et al., 2014). Therefore, we wanted to compare the cultivars with more cover color to those with less. In the marketing standards established by the European Union each apple cultivar is classified according to how much of its surface is covered by red color (Jordbruksverket, 2019). The apples in this trial can be grouped according to these standards. Group A, which 'Elise' belongs to, should have half of the fruit surface red. 'Rubinola', 'Santana', 'Saga' and 'Ingrid Marie' belong to Group B, which are expected to have 1/3 red coverage of the skin. 'Discovery', 'Aroma' and 'Rubinstar', belonging to Group C should have red coverage on at least 1/10 of the surface. Unfortunately, 'Frida' has not been classified under this system (Jordbruksverket, 2019), though visually it is obvious that the cultivar has more red cover color than group C. For all cultivars tested, the area that was not red was green in the most unripe fruit, and yellow/green in the ripe fruit. Our results do not show any consistent differences in I_{AD} between cultivars belonging to the different groups A, B, or C. Neither I_{AD} highest values, the rate of the decrease, the variation among apples at any given point, nor the variation between years could be found to be different between the groups. However, since only 'Elise' belonged to group A this limited the possibility to evaluate this group. The results suggest that there was no significant effect of cover color on I_{AD} in this trial.

5. Conclusions

I_{AD} decreases during fruit maturation and could be an acceptable non-destructive maturity index. The combination of three different indices in ripening index by Streif makes it a robust index, though in general with higher variation, CV, than I_{AD}. However, average I_{AD} in some cultivars decrease at the same time as ripening index by Streif and could therefore be used as a complement to monitor apples to indicate when to start a more intensive sampling before harvest. I_{AD} used as a maturity index seems to be more suitable for some cultivars and less suitable for other cultivars. I_{AD} should be less reliable to use for cultivars with large variation in I_{AD} at any given time, together with no consistent pattern between years in the decrease of I_{AD}. For cultivars having less variation in I_{AD} at any given time, together with having a more consistent pattern between years in the decrease of I_{AD}, it could be a good compliment to other commonly used maturity indices. I_{AD} showed lower variation at any given time at an earlier maturity stage, so it should be more reliable then than at later stages.

In this investigation, no influence of how much of a cultivar's surface that was covered by red color could be found regarding the I_{AD} values, or correlation between other maturity indices.

CRediT authorship contribution statement

Joakim Sjöstrand: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Methodology, Conceptualization. **Ibrahim Tahir:** Supervision, Writing – review & editing, Investigation, Formal analysis, Methodology, Conceptualization. **Helena Persson Hovmalm:** Supervision, Writing – review & editing, Methodology, Conceptualization. **Larisa Garkava-Gustavsson:** Supervision, Writing – review & editing. **Henrik Stridh:** Project administration, Supervision, Methodology, Conceptualization. **Marie E. Olsson:** Project administration, Writing – review & editing, Formal analysis, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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