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Improving and predicting storability of Swedish apples with I_{AD} and improved storage conditions

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Abstract

Only around 30% of the apples consumed in Sweden are produced within the country, even though many customers prefer locally produced fruit. One way to increase the availability of Swedish fruit is to reduce post-harvest losses to pathogens and disorders, which increase if fruit is not harvested at optimal maturity. This thesis examined ways of improving the storability of Swedish apples by reducing losses due to fungal decay and to the physiological disorder soft scald, and by using different measures for establishing optimal harvesting time for mid- and late-season cultivars.

Weather conditions were found to have an effect on the incidence of soft scald, with humidity and rain increasing the incidence in some cases. Rainy weather also increased fungal decay. Absorbance difference index (I_{AD}) was shown to be correlated with harvest time, apple firmness and Streif index before harvest. The strength of correlations showed high between-cultivar and between-year variations. I_{AD} was found to be a possible complement to existing maturity indices, but causes of variation in the accuracy of I_{AD} as a predictor of maturity need to be identified.

Controlled storage atmosphere was found to be the most effective measure to control soft scald, while delayed cooling had little effect. Fruit maturity had a significant effect on soft scald incidence in some cases, but not every year. A strong effect of year was seen in most measurements, *e.g.* for strength of correlations, soft scald incidence and fungal decay.

Keywords: Apple, storability, I_{AD}, soft scald, ULO, maturity index,

Förbättring och bestämning av lagringsduglighet för svenska äpplen med IAD och förbättrade lagringsförhållanden

Abstract

Endast cirka 30 % av äpplen som konsumeras i Sverige är odlade här trots att många konsumenter föredrar lokalt producerad frukt. För att förbättra tillgängligheten för svenska äpplen så bör förlusterna på grund av lagringssjukdomar och fysiologiska skador under lagring minskas. Lagringsförluster ökar om frukten inte plockas vid optimal mognad. I denna avhandling var målet att öka kunskapen om den fysiologiska skadan mjuk skalbränna, samt hitta metoder att minska förekomsten av mjuk skalbränna. Vidare jämfördes olika mognadstest och deras förmåga att hitta den optimala skördetidpunkten. I denna avhandling var målet att minska förlusterna under lagring genom att undersöka ett sätt att mäta mognad som är nytt för Sverige kallat DA-mätaren. Dessutom undersöktes den fysiologiska skadan mjuk skalbränna, vilken kan orsaka stora förluster under lagring.

Väderförhållanden under odlingen ökade förekomsten av mjuk skalbränna i vissa fall. Regnigt väder ökade även förekomsten av lagringssjukdomar. I_{AD} före skörd korrelerade med skördetidpunkt, fasthet samt Streif index men det förkom skillnader i korrelationernas styrka både mellan sorterna samt från år till år. I_{AD} visade sig vara ett möjligt komplement till andra mognadsindex, men på grund av variabiliteten i noggrannhet behöver I_{AD} undersökas vidare.

Mjuk skalbränna kontrollerades bäst med lagring i kontrollerad atmosfär. Fördröjd nedkylning hade dålig effekt på mjuk skalbränna, medan mognadsgrad i vissa fall hade en effekt på mjuk skalbränna, men inte varje år. År hade stor betydelse på flera delprojekt både för styrkan på korrelationer, förekomsten av mjuk skalbränna och lagringssjukdomar.

Keywords: Äpple, lagringsduglighet, I_{AD}, mjuk skalbränna, ULO, mognadsindex

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Joakim Sjöstrand, Ibrahim Tahir, Helena Persson Hovmalm, Henrik Stridh & Marie E. Olsson (2023). Multiple factors affecting soft scald and fungal decay in apples. *Postharvest Biology and Technology* 201,112344.

II. Joakim Sjöstrand, Ibrahim Tahir, Helena Persson Hovmalm, Larisa Garkava-Gustavsson, Henrik Stridh & Marie E. Olsson (2023). Comparison between I_{AD} and other maturity indices in nine commercially grown apple cultivars. Scientia Horticulturae (Accepted)

III. Joakim Sjöstrand, Marie E. Olsson Ibrahim Tahir, Larisa Garkava-Gustavsson, Henrik Stridh, Helena Persson Hovmalm (2023). Determination of optimal harvest maturity for apple cultivars using a DA meter – can I_{AD} predict storage potential? (manuscript)

IV. Joakim Sjöstrand, Ibrahim Tahir, Helena Persson Hovmalm, Larisa Garkava-Gustavsson, Henrik Stridh & Marie E. Olsson (2023). Maturity indices and predictability of storage potential in four mid-season and late-season apple cultivars (manuscript).

Paper I-II are reproduced with the permission of the publishers.

The contribution of Joakim Sjöstrand to the work in Papers I-IV was as follows:

I — Participated in the design of the study together with the co-authors. Carried out experimental work, data collection and data analysis. Wrote the manuscript with input from the co-authors.

II — Participated in the design of the study together with the co-authors. Carried out experimental work, data collection and data analysis. Wrote the manuscript with input from the co-authors.

III — Participated in the design of the study together with the co-authors. Carried out experimental work, data collection and data analysis. Wrote the first draft of the manuscript with input from the co-authors.

IV — Participated in the design of the study together with the co-authors. Carried out experimental work, data collection and data analysis. Wrote the first draft of the manuscript with input from the co-authors.

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Abbreviations

1-MCP	1-Methylcyclopropane
DCA	Dynamic controlled atmosphere
DA	Delta absorbance
DAFB	Days after full bloom
I_{AD}	Index of absorbance difference
SSC	Soluble solids concentration
ULO	Ultra-low oxygen

1. Introduction

This thesis is part of an industry PhD programme, LivsID, initiated by the Swedish government, comprising 10 projects examining different aspects of Swedish food security, both in the sense of safe food and increased productivity. The PhD students were employed at different companies, but performed joint activities to create connections between academia and industry (Lithell, 2023). The part of the programme reported in this thesis focused on Swedish apples and ways to increase the quality of stored fruit, thereby enabling longer storage time and lower losses, so that a higher level of self-sufficiency can be reached.

1.1 Apples in Sweden

Over the past 20 years, apple production in Sweden has increased from around 16,000 tons to 30,000 tons per year (FAOstat, 2023). A modern, high-yielding orchard in Sweden can produce on average 40 tons/ha (Nybom, 2019). In comparison, the neighbouring countries of Finland and Latvia produce around 10 tons/ha (FAOstat, 2023). Swedish commercial apple orchards are concentrated in the southern part of the country (Nybom, 2019).

In recent years, the market share of domestically produced apples in Sweden has remained at around 30%, meaning that the remaining 70% of the apples sold in Sweden need to be imported, mainly from Italy, Poland, Germany, Chile and Argentina (Jordbruksverket, 2022). To increase the proportion of locally produced fruit, losses and waste need to be reduced, especially in the post-harvest stage (Gustavsson *et al*., 2011). Apples grown in Sweden are increasingly being stored in ultra-low oxygen (ULO) conditions to extend the season (Nybom, 2019).

Popular cultivars in Sweden include 'Ingrid Marie', 'Aroma', 'Discovery', 'Rubinola' and 'Santana' (Tahir, 2019). The growing conditions in northern Europe, with long summer days and a relatively short, cool growing season, mean that cultivars need to be adapted to these special conditions (Ikase, 2015). Flavour and colour have been shown to be increased by low night temperatures (Blankenship, 1987; Wicklund *et al*., 2021). Locally produced fruit is in demand among many consumers in Sweden (Denver & Jensen, 2014), and with increased productivity and higher self-sufficiency this demand could be fulfilled to a greater extent.

1.2 Apple quality

The characteristics of apples that constitute good quality are not necessarily the same for different stakeholders in the production and distribution chain from grower to consumer (Shewfelt, 1999). Internal quality parameters such as soluble solids content (SSC), firmness, starch degradation, acidity and antioxidants are important quality parameters for consumers, while breeding and commercial stakeholders require good storage potential, high yield, good appearance and resistance to pathogens and physiological disorders (Evans, 2013; Musacchi & Serra, 2018). To researchers, quality often refers to parameters that can be measured and monitored to predict the storability of fruit, while for consumers it refers to parameters that the consumer either likes or dislikes, influencing acceptability (Shewfelt, 1999).

There are also quality traits linked to trade norms between countries, for example in the European Union. These norms state that the fruit should be intact, free from pests, disorders and pathogens, and free from excessive moisture and unusual odours. For apples, there are also cultivar-specific norms, such as that the fruit should not have the physiological disorder water core and should follow cultivar-specific appearance norms in terms of ground/cover colour and russeting (Jordbruksverket, 2019). Many pre-harvest factors, such as weather conditions (Jones *et al*., 1996), nutrient status (DeLong, 1936) and maturity at harvest (Holthusen & Weber, 2021), can affect fruit quality and the storability of fruit.

After harvest, fruit will sooner or later enter senescence, an active programmed degeneration of the fruit, which will lead to quality loss (Qin *et* *al*., 2009). For apples, there are several ways to delay this process and prolong the post-harvest lifetime of the fruit.

1.3 Destructive and non-destructive maturity indices

One of the most important measures to increase the long-term storage ability of apples is to harvest at the optimal time (Tahir, 2019). Many different maturity indices have been developed for apples. One of the simplest ways of predicting optimum harvest date is to calculate days after full bloom (DAFB) (Luton & Hamer, 1983; Musacchi & Serra, 2018). However, maturity varies greatly depending on weather and growing conditions, making DAFB an unreliable index (Narasimham *et al*., 1988). Apple is a climacteric fruit, which means that there are specific patterns of change in respiration and ethylene production, with minimal values just before the so-called "climacteric rise", after which rapid changes in quality occurs which lead to ripening (Blackman & Parija, 1928; Peirs *et al*., 2001). The characteristic development pathways of ethylene production and respiration can therefore be used as maturity indices (Song & Bangerth, 1996). Soluble solids content, or Brix, which can be measured by spectroscopy, is another quality parameter that can be used as a maturity index (Jannok *et al*., 2014). Firmness is traditionally measured by penetrometer, often on two sides of the fruit after it has been peeled (Blankenship *et al*., 1997). In ripening apples starch is degraded, meaning that it can be used as a maturity index if iodine is used to stain starch (to a dark blue colour) (Menesatti *et al*., 2009). From firmness (F), SSC and starch degradation (SD) can be used to calculate the so-called Streif index (Streif, 1996), as:

$$\text{Streif} = F * (SSC * SD)^{-2}$$

Streif index is the most commonly used maturity index in Sweden today (Tahir & Nybom, 2013).

Figure 1. Destructive measurement of firmness in the apple cultivar 'Ingrid Marie' using a penetrometer. photo: J. Sjöstrand .

1.4 Apple storage

Controlled storage is designed to decrease quality loss by reducing respiration rate, maturation rate and the senescence process. This is achieved by controlling storage temperature, humidity and atmosphere (Fiddler & North, 1968; Watkins & Nock, 2012). The simplest form of storage is a cold room in which only the temperature is regulated, generally to around 2-4 °C. Better storability can be achieved in controlled atmosphere and dynamic controlled atmosphere (DCA), systems, where lower oxygen (O_2) levels and increased levels of carbon dioxide (CO_2) work synergistically with the low temperature to further increase storability compared with cold rooms (Brizzolara *et al*., 2017). The main difference between controlled atmosphere and DCA is that fruit stored in a DCA system is monitored by sensors and the O_2 and CO_2 levels are changed dynamically if the sensors indicate fruit stress. This means that DCA-stored fruit can usually be kept at lower O_2 and higher CO_2 levels than under the static gas levels of controlled atmosphere storage, thereby reducing respiration and in turn the ripening and senescence rate (Lafer, 2009). Too low oxygen levels lead to anaerobic metabolism, which produces compounds with an unpleasant taste and odour and ultimately leads to damage such as flesh breakdown (Thewes *et al*., 2021).

1.5 Physiological disorders

Apples can develop a number of different disorders, many of which are induced by pre-harvest factors such as temperature, time of harvest or weather conditions (Ferguson *et al*., 1999). For example, the disorders known as bitter pit and soggy breakdown occur at a higher rate in mature fruit and decrease with earlier harvesting date, while senescent breakdown increases with later harvest (Watkins *et al*., 2005; Prange *et al*., 2011). Superficial scald is another physiological disorder that can increase with premature harvesting (Erkan & Pekmezci, 2004). Low temperatures increase the incidence of soggy breakdown (Watkins *et al*., 2005). Lastly, nutrient status may also affect some physiological disorders, such as bitter pit and soft scald (Al Shoffe *et al*., 2020).

1.5.1 Soft scald

Soft scald is a physiological disorder that can lead to high losses in stored apples (DeLong *et al*., 2004). Affected fruit develop band or ribbon-like areas of soft, discoloured skin. The aetiology of soft scald is still somewhat unclear, but many factors have been shown to increase the incidence of the disorder (Watkins *et al*., 2004). As soft scald is affected by ethylene blockers, such as 1-methylcyclopropane (1-MCP), it is most likely a metabolic condition (Fan *et al*., 1999). Storage conditions, weather, nutrient status and harvest time have all been linked to soft scald (Tong *et al*., 2003; Watkins *et al*., 2005; Al Shoffe *et al*., 2020). Some apple cultivars are more prone to develop soft scald and these differences are genetically determined (McClure *et al*., 2016; Howard *et al*., 2017).

Figure 2. Apple affected by the physiological disorder soft scald. photo: J. Sjöstrand .

1.6 Fungal diseases

The most common storage pathogens in Sweden are *Penicillium expansum, Neofabraea* spp., *Colletotrichum* spp., *Monilinia* spp. and *Botrytis cinerea* (Nybom *et al*., 2020). Apples tend to become more sensitive to pathogens as they ripen, partly because of softening (Ahmadi-Afzadi *et al*., 2013). Breakdown of acids during senescence and the resulting increase in pH also benefit many fungal diseases (Sharma & Kulshrestha, 2015). Lastly, storage conditions have a considerable effect on pathogens. Room temperature (18-25 °C) during shelf-life is close to the optimal growing temperature of *e.g. Neofabraea* spp. and *Colletotrichum gloesporides*, meaning that pathogen growth is rapid under these conditions (Baert *et al*., 2007; Hortova *et al*., 2014; Sharma & Kulshrestha, 2015).

2. Aims and objectives

2.1 Objectives of the thesis

The overall aim of the work in this thesis was to increase storability and quality in Swedish apples so that they could be stored for longer. The following specific objectives were investigated in three-year trials:

- To investigate the aetiology of soft scald and fungal decay. Weather conditions during the growing period, maturity, gradual cooling before storage and storage conditions (temperature and atmosphere) were factors investigated as possible causes of soft scald and fungal decay (Paper I).

- To investigate changes in I_{AD} values in relation to other maturity indices. I_{AD} was compared with other, more established, maturity indices such as SSC, firmness, starch degradation, respiration, ethylene production and Streif index. Sampling was performed during the period from before optimal harvest time until after optimal harvest time (Paper II).

- To assess I_{AD} as a predictor of storability. Apples within different I_{AD} intervals were picked and then stored. After storage, losses were calculated and quality parameters (SSC, firmness) were measured. Each I_{AD} interval was sampled up to four times during storage and then again after one week of simulated shelf-life. The aim was to find which I_{AD} intervals at harvest resulted in the best storage outcome (Papers III and IV).

3. Results and Discussion

3.1 Maturity, I_{AD} and their effect on storability

In Paper I, in most cases no connection could be found between later harvest and increased soft scald incidence or fungal decay, possibly because of the short sampling period. However, Papers III and IV showed that advanced maturity at harvest (low I_{AD}) sometimes led to increased losses, especially after one week of simulated shelf-life (Paper III). Firmness also tended to decrease more with low $I_{AD.}$ However, this was not generally the case for apples in the lowest I_{AD} intervals, probably because firmness was so low in those to begin with that a large percentage decrease was not possible. Other studies have also shown that advanced maturity leads to greater losses (Kviklienė *et al*., 2011). Maturation processes, such as fruit softening (Johnston *et al*., 2009) and chlorophyll degradation (Gorfer *et al*., 2022), have been indicated to be accelerated by ethylene production. Therefore, changes in firmness and chlorophyll degradation mainly occur after the rise in respiration and ethylene production. However, fruit softening is to some extent cultivar-specific (Nybom *et al*., 2013) and SSC is not affected by ethylene (Pre-Aymard *et al*., 2003), meaning there is a more steady change in SSC compared with firmness. In Paper II, the correlations between starch degradation and I_{AD} were often strong, meaning that changes in these variables seem to be associated. If I_{AD} could be used to predict starch degradation, or at least indicate when it is starting, many apples could be saved from destructive maturity tests. Apple is a climacteric fruit, so ripening continues after harvest (Seppä *et al*., 2013). During senescence, many compounds in the fruit are degraded, such as chlorophyll (Mir *et al*., 1996), polysaccharides, some connected to the occurrence of mealiness (Li *et al*.,

2020) and malic acid (Defilippi *et al*., 2004). Growth of *Penicillium expansum* is promoted by an acidic environment and this organism excretes acids to lower the pH, while growth of *Colletotrichum acutatum* is instead promoted by higher pH and it releases ammonia to enhance its pathogenicity (Prusky *et al*., 2001; Prusky *et al*., 2004). In the stored apples analysed in Papers III and IV, the losses due to pathogens in more mature fruit may have been partly due to changes in acid content, but also firmness loss, as pathogens tend to grow better in softer fruit (Ahmadi-Afzadi *et al*., 2013). Long-term storage of fruit depends on many factors to keep the fruit healthy. As mentioned above, pH, firmness and ethylene production all affect the resistance of apples to pathogens. I_{AD} can probably not provide as accurate predictions as all of these indices, so it cannot replace them but could work well as a complement.

Figure 3. Meter for measuring difference in absorbance (DA meter), with a disc for calibration to the left. photo: J. Sjöstrand

3.2 Between-year variation and climate change

Table 1. *Weather conditions from flowering to harvest, 2018-2020. Values for temperatures and humidity are averages for the whole growing season, while rainfall is accumulated value for the whole season*

Year	Average daily temperature ° C	Maximal daily temperature ° C	Minimal daily temperature ° C	Humidity, %	Rainfall mm
2018	19.3	25.0	13.2	73.1	100
	19.2	24.7	13.2	73.8	125
	19.0	24.5	13.2	74.8	139
2019	16.5	21.2	11.9	80.1	207
	16.6	21.3	11.9	80.3	219
	16.5	21.1	12.0	80.8	287
2020	16.2	21.1	11.2	75.6	152
	16.1	21.0	11.2	75.9	154
	16.1	20.9	11.3	76.2	157

A large effect of year on losses was observed in Paper I, and also in Papers III and IV. The year 2019 was an exception in all experiments, with higher losses than in 2018 and 2020 (Paper I). Some other factors, such as weather conditions during the growing period, also seemed to have an effect on fruit susceptibility to fungal attack. The summer of 2018 was exceptionally hot with little rainfall, while 2019 had more rain than the other two years and 2020 had similar temperatures to 2019 and more rain than 2018 (Table 1). In Papers III and IV, there was a tendency for more fungal decay to occur in 2019 than in the other years in some cultivars. The same was true for low I_{AD} values, which in some cases were associated with increased losses, but not always. In Paper I too, more fungal decay was found in 2019. Since the apples were harvested from the same orchard, some post-harvest factor was probably the cause of these differences in losses of apples during storage. One possible reason for the differences between studies could be that the apples in Paper I were subjected to different treatments and storage conditions than the apples in Papers III and IV.

A warmer climate can also cause more frost damage, as blossoming in apples trees is triggered by a warm period after a certain degree of chilling (Pfleiderer *et al.*, 2019). Further, pathogens new to areas have emerged, and will continue to emerge, while a more humid and wetter future climate, will favour canker formation and increasing inoculum levels of certain pathogens (Weber, 2009). A warmer climate will also affect pests such as codling moth (*Cydia pomonella*), which will arrive earlier, cause more damage and possibly produce an additional generation in each season (Samietz *et al*., 2015).

During the work presented in Papers I-IV in this thesis, there were very different weather conditions in the three study years (Table 1). This may indicate that there are no longer any "normal" years and could actually be considered a strength of the research, as it allowed the responses of maturity indices and pathogens to different weather conditions to be assessed. The results showed *e.g*. that fungal decay in stored apples was higher in some cultivars in the rainy year 2019 (Papers III and IV). Climate change will affect the cultivars that can be grown at a certain latitude in future (Kaukoranta *et al*., 2010), *e.g*. old cultivars may react with stress responses and signs of damage. In the future, knowledge of optimal harvesting time for old apple cultivars could become obsolete if extreme weather damages the fruit or alters the rate of change in maturity indices. More research is needed to determine how maturity indices react to climate change and how different cultivars, old and new, react.

3.3 What constitutes a "good" maturity index?

Sun scald, darkness-induced chlorophyll loss and high temperatures have been shown to decrease I_{AD} (Schrader *et al*., 2011; Felicetti & Schrader, 2009; Toivonen *et al*., 2016). This is a problem in terms of maturity assessment, as measuring I_{AD} in such apples will give an indication that the fruit is riper than it really is. Further, differences between years in weather conditions can have a major effect on chlorophyll degradation. A warm sunny summer might result in different optimal I_{AD} values for storability than a cloudier growing season, as sun scald could reduce the average I_{AD}. Therefore, it is important to know how each cultivar reacts to weather conditions and plan sampling for maturity tests accordingly. Weather not only affects I_{AD}, but also starch degradation as a maturity index, as both degradation of chlorophyll and translocation of photosynthate are affected (Richardson *et al*., 2004; Toivonen *et al*., 2016). Other quality parameters such as firmness, sugar content, colour, weight and size also vary from one growing season to another (Musacchi & Serra, 2018). This means that any maturity index value must be interpreted in relation to the growing conditions in a particular year. Using harvest boundaries that are based on multiple indices could be a more robust approach, compensating for cases where one index is abnormal.

Maturity indices such SSC, fruit size, firmness, starch content and fruit colour often give different values depending on fruit position on the tree (Barritt *et al.*, 1987; Tustin *et al.*, 1988). These differences based on weather and on position on the tree are likely to result in some variation in maturity indices. This was seen in Paper II, where the coefficient of variation for the different indices compared was calculated (Table 3 in Paper II). Firmness and SSC showed the smallest differences between years of all indices investigated in Paper II, while Streif index and starch degradation varied widely from one year to another and had the highest coefficient of variation. Starch degradation is used to calculate Streif index (see section 1.3), which explains why the values of these two parameters were often high in the same year. Comparing the coefficients of variation for I_{AD} and Streif (Table 3 in Paper II) revealed that the variation was always lower for I_{AD}, with cv. 'Discovery' and 'Rubinstar' as exceptions. Uniformity of I_{AD} value may seem desirable, but it will not show the variation actually present in the fruit in terms of SSC, firmness and starch degradation, which are important parameters for storability and fruit quality. The relationship between I_{AD} and Streif index was found to vary between cultivars and years. If these two indices were to decrease at the same time, I_{AD} would be a good predictor of Streif index. However, in Paper II there was some variation in the strength of the correlation between Streif index and I_{AD}. The strongest correlations were most often found in 2018 (6 out of 9 cultivars), and the weakest in 2020 (Table 2 in Paper II).

The I_{AD} approach has the benefit of enabling larger sample size, which reduces the risk of outliers skewing the average. Measurements with the DA meter are easy to perform with little training without laboratory equipment. A downside with I_{AD} is that it is not as transparent as many of the conventional indices. Indices such as SSC give an indication of how sweet the fruit is, which is important to the consumer. Firmness gives an indication of the maturity of the fruit, but also eating quality and to some extent storability. Another benefit of the conventional maturity indices is that there is much more experience and knowledge of how these react to pre-harvest conditions. However, they require some training in their use, so that *e.g.*

firmness tests are performed consistently in the same way. For starch degradation, there is also a subjective factor in the assessment, which means that ideally the same person should perform all assessments for consistency. There are machines available now which can evaluate starch degradation, but these are expensive and have to be trained (Figure 4). The best-case scenario would be an index that is easy to use and produces results that are easy interpret and are consistent from year to year. In reality, all indices available to date have their benefits and drawbacks, meaning that they should be used to complement each other and not as a sole approach.

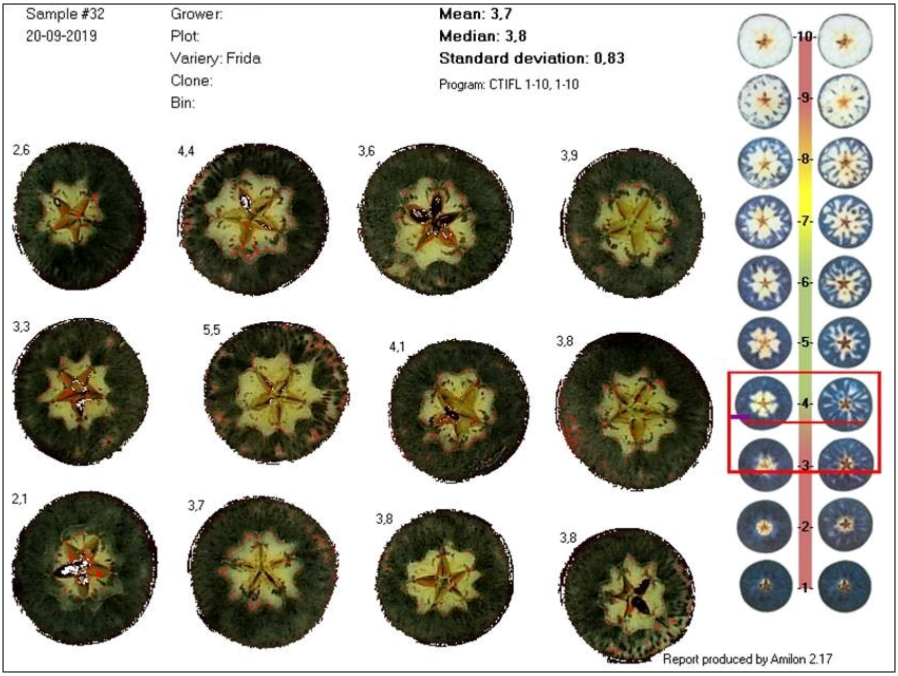

Figure 4. Starch degradation (scale of 1-10) in apple cultivar ‘Frida’ as measured by an Amilon device (Isolcell, Laives, Italy). Using a machine to perform the evaluation reduces the subjectivity, but the machine has to be trained for each cultivar. Photo Äppelriket.

3.4 Differences in storability and correlations between maturity indices in late- and midseason cultivars

In the early- and midseason apple cultivars analysed in Paper I, there were high losses due to physiological disorders, with *e.g*. cv. 'Santana' suffering exceptionally high losses to soft scald in some years (Paper 3). Early-season apples have been found to have a higher rate of metabolism and therefore deteriorate faster (Singh *et al*., 2017). The mid-season cultivars 'Aroma' and 'Santana' analysed in Paper III and cv. 'Ingrid Marie' in Paper IV lost firmness to a greater degree, while the other cultivars analysed in Paper IV, *i.e*. 'Rubinstar', 'Elise' and 'Frida', were generally firmer.

Table 2. *Total losses (%) during storage of apples from mid-season and late-season cultivars. Cultivars 'Aroma' and 'Rubinola' were stored for 111 days, 'Santana' for 118 days and 'Elise', 'Frida' 'Ingrid Marie' and 'Rubinstar' for 119 days*

	Cultivar	**2018**	**2019**	**2020**	**Average losses %, all years**
Mid-season cultivars	Santana	72.73	21.83	8.00	34.19
	Rubinola	1.67	2.67	2.17	2.17
	Aroma	12.33	10.83	11.66	11.61
	Average losses %, year	28.91	11.78	7.28	15.99
Mid- and late-season cultivars	Elise	7.29	3.33	1.67	4.10
	Frida	49.04	3.50	5.34	19.29
	Ingrid Marie	26.25	9.17	7.17	14.19
	Rubinstar	23.75	1.50	1.00	8.75
	Average losses %, year	26.58	4.37	3.79	11.58

Table 2 shows total losses in midseason and late cultivars stored in cold rooms in ambient atmosphere. Losses were higher in 2018 and the combined losses over all three years in the mid-season cultivars (15.99%) were almost 30% higher than the combined losses in the midseason and late cultivars (11.58%). Firmness was low after storage, both in the mid-season cultivars in Paper III and the late-season cultivars in Paper IV, although it varied between cultivars. This is probably because the apples were stored in cold rooms in ambient atmosphere. Comparing firmness values for cv. 'Frida' and 'Aroma' apples stored in ULO storage in Paper I showed that, as expected, these apples were firmer than the corresponding apples stored in cold rooms in ambient atmosphere. Storing the fruit in cold rooms in ambient atmosphere was a 'worst-case scenario' without the positive effect of ULO on storability. Interestingly, the late-season varieties analysed in Paper II showed weak correlations between I_{AD} and Streif index in 2020. It is a concerning finding that cultivars expected to have the greatest storability show such weak correlations in some years. The correlation between I_{AD} and DAFB for the late-season cultivars was also weak in 2020, indicating that I_{AD} was not accurate in estimating apple maturity in that year.

3.5 Soft scald

Physiological disorders can develop for a number of reasons. Soft scald has been linked to a number of different factors, such as pre-harvest conditions, storage atmosphere, storage temperature and many more. Multiple factors seemed to influence soft scald incidence in the apple cultivars analysed in Paper I, one of which was climate during the growing season. The most effective way to reduce soft scald incidence is to use 1-MCP to block ethylene production (Fan *et al*., 1999), but this substance is not used in Sweden, presumably due to Swedish consumers having high environmental awareness and disliking any form of chemical treatment (Diagourtas *et al*., 2023).

The results in Paper I indicated that multiple factors affect the incidence of soft scald and that different cultivars do not necessarily react in the same way to a certain factor. This was also seen in Paper III, where in 2018 the cultivar 'Santana' was severely affected by soft scald when harvested in the I_{AD} interval 1.0-1.2, with up to 93% losses (shown in Table 2 in Paper III only as losses due to 'physiological disorders', though only soft scald occurred in this case). In the following years, apples harvested in the same I_{AD} interval did not develop nearly as much soft scald (0.8% losses in 2019 and 8.3% in 2020), indicating that some other factor/s also influenced soft scald incidence.

Unlike in Paper I, where 2019 had the highest soft scald incidence, in Paper III and IV 2018 was the year with the highest soft scald incidence for 'Frida' and 'Aroma'. This indicates that cultivars may develop soft scald for different reasons, since cv. ‘Aroma’ in Paper I and cv. ‘Santana’ in Paper III were harvested from the same orchard and only a few hundred metres from each other. In Paper I, inconclusive results were obtained when different ULO conditions were compared. No ULO condition consistently and significantly lowered soft scald incidence and fungal decay more than any other ULO condition (Paper I). However, in most cases ULO conditions lowered the incidence of soft scald compared with cold room storage in ambient atmosphere, both in cv. ‘Aroma’ (with 2018 as an exception) and cv. ‘Frida’. Different cooling regimes in Paper I also gave inconclusive results, but ULO storage instead of cold room storage had a greater effect on soft scald incidence and fungal decay, as shown in Figure 5.

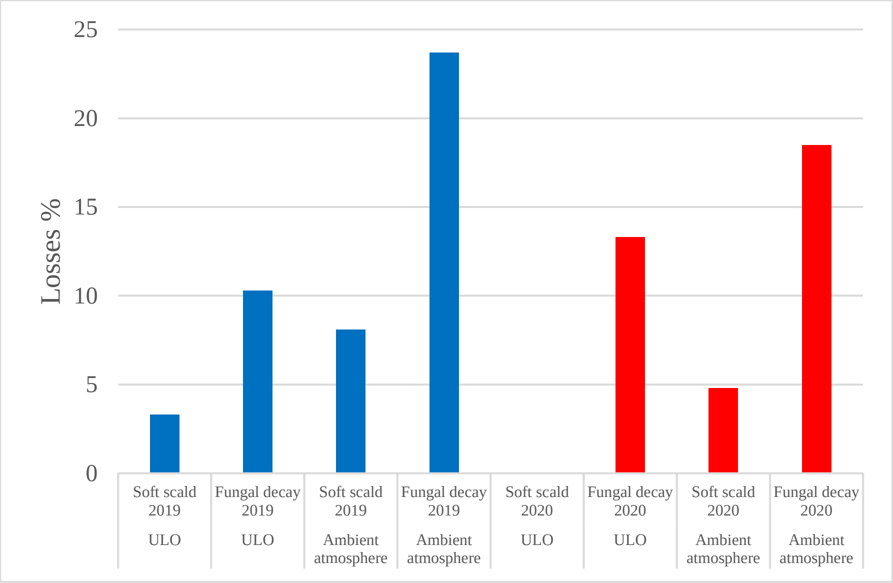

Figure 5. Losses to soft scald and fungal decay during storage in 2019 and 2020 of apples from cultivar 'Frida' depending on storage atmosphere (Paper I).

4. Conclusions

- During the work presented in this thesis, there was great variation in weather conditions between years. In 2018 there was a very hot summer, while 2019 was rainy. This appeared to affect the storability of the apples, with *e.g*. more fungal decay in 2019. Ripening was affected by the earlier start of harvesting in 2018.

- Among the different maturity indices compared, the coefficient of variation varied most from year to year for starch degradation and Streif index, while it was lower and more stable for I_{AD} and SSC.

- I_{AD} cannot be recommended to be used as a sole maturity index, replacing the indices currently used, but it could be a valuable complement to existing approaches. Using a DA meter enables a larger number of measurements, so it would be possible to check for differences between parts of the orchard and identify where to start harvesting. The accuracy of the DA meter values as an assessment method for estimating optimal harvest time seem to vary from year to year, possibly due to seasonal weather conditions affecting the maturation of apples.

- The DA meter has the advantages that more fruit can be evaluated faster with minimal training. However, I_{AD} has lower accuracy in predicting storability in some apple cultivars compared with other maturity indices and supply chain stakeholders have much more experience of using *e.g*. Streif index.

- Several different factors affect the incidence of soft scald and fungal decay in stored apples, with many showing a strong effect of year. Humidity was found to be the factor that probably contributed most to development of soft scald. The most consistent measure for lowering the incidence of soft scald and fungal decay was to store the fruit in a controlled atmosphere.

5. Directions for future research

- The results in this thesis confirmed that optimal I_{AD} values for storage need to be identified for each apple variety. More research into when chlorophyll degradation occurs in apples (in general and in different cultivars) could help in interpretation of I_{AD} values.

- The accuracy of the DA meter varies between years. Better knowledge of the causes of this variation would improve the usefulness of I_{AD} as a maturity index.

- Reducing respiration and lowering ethylene production are the most effective measures against soft scald, which indicates that soft scald develops due to some active process in the fruit. Identifying these processes and associated genes would help clarify the aetiology of soft scald.

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Popular science summary

Storing apples might seem like an easy task, *e.g.* you could perhaps keep some from your garden in a cellar a few months or buy some from a supermarket and keep them in a bowl on a table. Whatever form of storage you choose, you will find that at some point they will deteriorate. They may show signs of rot, lose flavour or develop an unappealing texture. This is because apples are not inanimate objects, but in fact are alive and breathing, meaning that the fruit keeps using up sugar as it becomes older and its defences against moulds present in the fruit become weaker. The reason for the apple tree to produce apples is to disperse seeds so that new trees can grow. There is no advantage to the tree in apples that keep for a long time, as it benefits only when the apple is eaten and the seeds are dispersed or the fruit flesh rots away so that the seeds reach the soil. An apple that is ripening is actively ‘disassembling’ and becomes softer over time.

In commercial storage of apples, the aim is to prolong the period in which the fruit is healthy and fresh. To successfully prolong the storage period, damage to the apple should be avoided, as this could be a source of infection. If apples are picked at the right time before the ‘disassembly’ process starts, they will keep for longer if stored in cold storage rooms. If oxygen levels are kept low during storage, the fruit will respire more slowly, as both low oxygen and cold temperatures act to lower the respiration rate, and will remain healthy for longer. Factors during the growing period also affect how long apples can be stored. In particular, weather during the growing season affects fruit health, *e.g.* rainy weather helps some fungi to infect fruit and the fungus will then continue to grow in the storage room and spread to other fruit, causing rot.

The work in this thesis started with an investigation into soft scald, a physiological disorder in some apple cultivars, and fungal decay in apples during storage. Possible causes and ways to lower the level of soft scald and fungal decay were identified. Humidity was found to be the factor that probably contributed most to development of soft scald. The most consistent measure for lowering the incidence of soft scald and fungal decay was to store the fruit in a controlled atmosphere

A new tool for testing apple ripeness, the DA meter, was compared with other ripeness indices and its accuracy in predicting apple storability was tested, with the aim of developing ways to store Swedish apples for longer while maintaining high quality. The results indicated the accuracy of the DA meter varied from year to year, possibly due to seasonal weather conditions affecting apple maturation. Thus I_{AD} cannot be used as a sole maturity assessment tool, replacing the indices currently used, but it could be a valuable complement to existing approaches. A DA meter can make large numbers of measurements and requires minimal training, so it could be used to check for differences between parts of an orchard and identify where to start harvesting.

Populärvetenskaplig sammanfattning

Att lagra äpplen kan verka vara en enkel uppgift. Kanske sparar du själv några i en källare några månader eller köper några som ligger i en skål på köksbordet. Men ligger de tillräckligt länge så kommer de vid något tillfälle att försämras. Kanske ruttnar de, förlorar smak eller får en oangenäm textur. Du kanske inte vet om det men äpplen lever och andas vilket innebär att frukten använder upp socker när det åldras samtidigt som försvaret mot mögelsvampar försvagas. Ett äppelträd utvecklar frukter för att sprida frön så att nya träd kan växa. Så för trädet finns ingen anledning att utveckla frukt som håller länge, antingen ska frukten ätas eller så ska fruktköttet ruttna bort så att fröna kommer i jorden. I ett mognande äpple monteras cellväggen aktivt ner för att frukten ska bli mjukare. I kommersiell äppellagring är målet att förlänga perioden som frukten är frisk och färsk. För att förlänga lagringstiden bör frukten vara oskadad eftersom skadad frukt i större grad drabbas av lagringssjukdomar. Om frukten plockas innan nedmonteringen startar kommer den att kunna lagras längre. Lagring i låga temperaturer och med låga syrehalter kan ytterligare förlänga lagringstiden eftersom frukten då andas långsammare. Även faktorer under odlingen påverkar fruktens lagringsduglighet. Väder såsom regn kan gynna vissa mögelsvampar som kan smitta frukten för att sedan sprida sig till andra frukter i lagret.

Denna avhandling startade med en undersökning av den fysiologiska skadan mjuk skalbränna som vissa sorter av äpple kan utveckla. Möjliga orsaker och metoder för att minska förekomsten av skadan undersöktes. Dessutom undersöktes DA-mätaren, ett nytt sätt att mäta mognad i äpplen. DA-mätaren jämfördes med andra mognadsindex och dess förmåga att förutse lagringsförmåga hos äpplen undersöktes. Det övergripande målet var att förlänga lagringen av Svenska äpplen samt att höja kvaliteten på dem.

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Multiple factors affecting occurrence of soft scald and fungal decay in apple during storage

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Maturity

ABSTRACT

Some apple cultivars are highly susceptible to soft scald, a physiological disorder that can lead to large losses. The effect of harvest time, gradual cooling regimes and storage conditions on soft scald and fungal decay was investigated in two common apple cultivars, 'Aroma' and 'Frida' in a three year trial 2018–2020. Further, possible relationships between weather conditions during the growing season and 28 d before harvest and soft scald incidence along with fungal decay after storage were studied. The year with the highest rainfall had the highest incidence of soft scald and fungal decay. Our results suggest that the relative humidity during a period of 28 d before harvest was important for later development of soft scald in 'Frida', and together the results from 'Frida' and 'Aroma' showed a moderate correlation between relative humidity and soft scald. Gradual cooling showed conflicting results, and no treatment consistently lowered soft scald incidence. Gradual cooling led to inconclusive results, and storage in ambient air led to higher incidence of soft scald as compared to some investigated ULO storage conditions. Advanced maturity was associated with soft scald development and more fungal decay in one out of three years in 'Aroma', but did not affect incidence in 'Frida'. The etiology of soft scald seems to be dependent of multiple factors.

1. Introduction

Lately there has been an increased focus on reducing food loss and waste along the food chain. Losses occur all along the food chain and can be considerable also in the primary production (Gustavsson et al., 2011). In apple storage, as much as 10% of the fruit can be lost due to physiological disorders, and much more due to fungal decay. This is both an environmental and economic problem as many resources have been put into growing and storing fruit (Tahir, 2014).

Soft scald can cause substantial losses during storage of apples, and in severe cases up to 30% of the stored fruit can be lost (DeLong et al., 2004; Watkins et al., 2004). Affected fruit develops band-like browning of the upper part of the skin and flesh of the fruit. The disorder is considered to be a chilling injury where tissue affected by soft scald is clearly discernable from unaffected tissue and prone to fungal attack (Brooks and Harley, 1934; DeEll and Ehsani-Moghaddam, 2010). It is not clear exactly how and why the disorder develops, though it is most likely a form of metabolic disturbance, as ethylene blockers such as 1-MCP and controlled atmosphere storage may decrease incidence (Blankenship and Dole, 2003; DeLong et al., 2006; Fan and Mattheis, 1999; Watkins et al., 2004). Genes associated with stress reactions have been found to be upregulated in fruit affected by soft scald (Leisso et al., 2016). Further, changes in acetaldehyde and ethanol metabolism, as well as altered composition of fatty acids, have also been found in fruit affected by soft scald (Al Shoffe et al., 2018; Hopkirk and Wills, 1981). Despite the lack of knowledge of the mechanisms behind the occurrence of soft scald, some methods to decrease incidence have been suggested, although effectiveness seems to be varying with e.g. year and orchard location (Moran et al., 2009; Moran et al., 2010; Watkins et al., 2004).

Many factors both before and during storage seem to affect the incidence of soft scald. Some apple cultivars are more prone to develop soft scald than others (Leisso et al., 2016). Thus, there seems to be a genetic factor controlling soft scald susceptibility. Storage conditions can also trigger development of soft scald, since low storage temperatures have been suggested to lead to higher levels of soft scald, while a gradual cooling of the fruit may reduce the risk (Watkins et al., 2005;

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Watkins et al., 2004). Preharvest conditions like weather and mineral content of the fruit are other factors suggested to be involved in soft scald development (Al Shoffe et al., 2020; Lachapelle et al., 2013; Tong et al., 2003). Fruit affected by soft scald have been shown to contain higher levels of phosphorus, boron and magnesium, while manganese levels were lower than in unaffected fruit (Tong et al., 2003). Wet conditions after full bloom until the flowers were 0.01 m in diameter, cool conditions early in development of the fruit, and warm weather late in fruit development have all been suggested to increase soft scald incidence (Lachapelle et al., 2013). Late harvest was found to increase risk of soft scald (Watkins et al., 2005). Thus, multiple factors, or a combination of factors, seem to be able to induce the incidence of soft scald, though what physiological reactions in the fruit that are triggered still remain to be understood.

While attempting to minimize soft scald incidence, effects on other storage disorders and diseases have to be monitored. 'Frida' and 'Aroma' are two cultivars that are common and commercially important in the Nordic countries (Tahir et al., 2014). As for other common cultivars in this area, under Nordic conditions the most common storage diseases are caused by *Neofabraea spp*, *Colletotrichum spp.*, *Penicillium expansum, Botrytis cinerea* and *Monilinia spp.* (Maxin et al., 2012; Tahir, 2014).

A reduction of soft scald incidence as well as fungal decay is one of the main objectives of apple producers (Ishangulyyev et al., 2019). However, to reduce the losses due to soft scald, a better understanding of the factors inducing this disorder is needed. It has been shown that different atmospheric conditions affect fungal decay (Tahir, II, Nybom, 2013). Delayed CA (holding in cold ambient air before CA) has been reported previously (DeEll et al., 2016). Therefore, in this investigation the effects of storage conditions on both soft scald and fungal decay were studied simultaneously.

The aim of the present study was to evaluate how possible relationships between weather conditions during the season, from full bloom to harvest, affect soft scald incidence, fungal decay and fruit quality. Further, the investigation also aimed to assess how maturity level at harvest influence the incidence of soft scald as well as storage diseases and other disorders. In addition, the effects of gradual cooling and storage atmosphere on soft scald incidence, fungal decay and fruit quality were investigated.

2. Material and methods

The investigation was performed on fruit harvested in commercial apple orchards in Scania in the southern part of Sweden and were subjected to standard fertilization and IPM (Integrated Pest Management) practice with pesticide applications during the growing season. Before harvest, fruit was treated with fungicides (boscalid + pyraclostrobin, withdrawal period 7 days) to reduce storage diseases. According to commercial practice in Sweden, there were no postharvest treatments with fungicides. Fruit was harvested at different occasions, subjected to different cooling conditions as described in Table 1, and stored in either ULO (ultra-low oxygen), CA (controlled atmosphere) storage or in ambient air storage. Effects of weather conditions during the growing period on fruit storability were also examined. The cultivar 'Aroma' was harvested in 2018, 2019 and 2020 in western Scania at the same orchards and blocks (55°43'26.6"N 13°05'52.8"E), and 'Frida' in 2019 and 2020 in eastern Scania at the same orchard and blocks both years (55°37'35.6"N 14°16'21.9"E). Both cultivars were grown according to modern practices in commercial orchards. For each cultivar 20 trees were chosen that were between 8 and 20 years old at the start of the trial, 'Aroma' apples were on M9 rootstock while 'Frida' was on an unknown rootstock Table 2.

Table 1
Storage conditions for 'Aroma' and 'Frida'. 'Aroma' was exposed to all storage conditions while 'Frida' was stored either in ambient atmosphere or "ULO1".

	ULO1	ULO2	ULO3	CA	Ambient atmosphere
O_2 (kPa)	1	1	1	2	21
CO_2 (kPa)	1	2	3	2	0.04
Temperature, °C	2	2	2	2	2
Relative humidity	95 (%)	95 (%)	95 (%)	95 (%)	95 (%)

2.1. Harvest time, gradual cooling and storage conditions

Each year, fruit was harvested at three occasions, and the second harvest represented commercial maturity stage for harvest, determined by a combination of Streif index and days after full bloom (DAFB). Streif index was calculated as:

Firmness (kg cm $^{-2}$)* [SSC (%) * Starch degradation stage]$^{-1}$.

(Streif, 1996).

A lot of 450 'Aroma' or 'Frida' apples were picked at each occasion, and divided into three groups with 150 fruit in each (Fig. 1). The first group was kept in ambient atmosphere at 10 °C for 5 d, then at 4 °C for 5 d (gradual cooling). 'Aroma' was then divided into five subgroups and stored in experimental equipment for fruit storage (CO_2 incubator, model 3141, Thermo, Marietta, OH, USA), at 2 °C under five different conditions (ULO, CA or ambient air) as shown in Table 1. The second group was kept at 2 °C in ambient atmosphere for 10 d, divided into five subgroups and stored in five different storage chambers as described above. The third group was directly after harvest divided into five subgroups, which were stored in the five storage chambers (Table 1) without any initial cooling. 'Frida' was subjected to the same gradual cooling as 'Aroma', however, after storage the fruit was stored either at a commercial fruit producer in ULO conditions (1 kPa O_2, 1 kPA CO_2, 2 °C) or in ambient atmosphere.

After 2 months 'Aroma' apples from all storage conditions were assessed for soft scald and other physiological disorders, as well as fungal decay. Fungal decay, soft scald and other physiological disorders were recorded as either present or absent for each fruit (Leisso et al., 2019). Soft scald was identified according to the instructions in Hanrahan and McFerson (2014). As "Frida" apples were stored in a commercial storage facility we could not control when the storage room was opened. However, it was opened after five months storage each year with a variation within one week. Apples affected by pathogen rots or physiological disorders were removed. Of the healthy fruit, nine per treatment were subjected to quality tests. Firmness, measured by a penetrometer (Model FT 327; Effigy, Italy; plunger diameter of 11.1 *10^{-3} m, depth of 7.9 *10^{-3} m), was assessed on both the sunny and the shaded side of the fruit and an average was calculated. Soluble solid concentration (SSC) was measured by a digital refractometer (RFM80, Bellingham + Stanley, Tunbridge Wells, UK). The color of the apples were measured by a colorimeter (Minolta Ltd., Osaka, Japan) and a color index (CI) was calculated as (a*1000)(L*b)$^{-1}$ (López Camelo and Gómez, 2004). The measurements were repeated twice in 2018, i.e. after an additional two months, and then again after another month, and after that the experiment was terminated after a final recording of soft scald, fungal decay and quality parameters. In 2019 and 2020 the measurements were repeated once.

When the ULO storage room was opened after five months of storage, the 'Frida' apples, both in the ULO storage and in the ambient atmosphere, were assessed for physiological disorders and fungal decay, and nine healthy apples from each treatment were subjected to the same quality tests as described above for 'Aroma'.

2.2. Weather conditions

Solar radiation (MJ*m^{-2}), rainfall (L*m^{-2}), relative humidity, average daily temperature, daily highest temperature, and daily lowest temperature (°C) were recorded through the growing season, using weather stations (Vantage Pro, Davis, USA) located in the orchards. The time period 28 d before harvest was used for statistical analysis in

Table 2
Weather conditions during the whole growing season for 'Aroma' and 'Frida'. All values are average values calculated from daily measurements by weather stations located in the orchards.

	Year	Harvest	Average temperature °C	Maximum temperature °C	Minimum temperature °C	Relative humidity %	Season rainfall L*m^{-2}
Aroma	2018	H1	19.3	25.0	13.2	73.1	100
		H2	19.2	24.7	13.2	73.8	125
		H3	19.0	24.5	13.2	74.8	139
	2019	H1	16.5	21.2	11.9	80.1	207
		H2	16.6	21.3	11.9	80.3	219
		H3	16.5	21.1	12.0	80.8	287
	2020	H1	16.2	21.1	11.2	75.6	152
		H2	16.1	21.0	11.2	75.9	154
		H3	16.1	20.9	11.3	76.2	157
Frida	2019	H1	16.3	20.4	12.3	85.0	201
		H2	16.1	20.1	12.2	85.4	202
		H3	15.8	19.8	12.0	85.8	202
	2020	H1	15.3	20.0	11.0	79.5	151
		H2	15.3	19.9	11.0	79.5	169
		H3	15.3	20.0	11.0	79.4	171

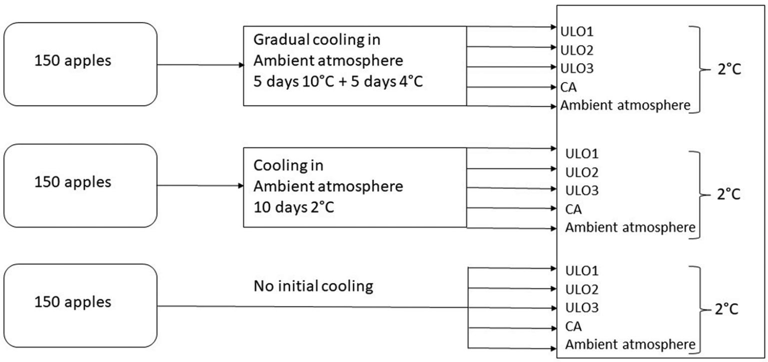

Fig. 1. Storage regime for 'Aroma' during the seasons 2018, 2019, and 2020 for one harvest occasion. This was repeated three times each year (i.e. three harvest occasions). The second occasion represented commercial harvest time.

accordance with previous investigations of weather conditions and their link to soft scald (Moran et al., 2009). Weather conditions were recorded every minute by the weather stations. In addition, weather parameters during the whole growing season (from full bloom to harvest) were summarized.

2.3. Statistics

Statistical analyses were performed using Minitab software v 18.1 (Minitab, Inc., USA). Effects of harvest date, gradual cooling and storage atmosphere, respectively, on soft scald and fungal decay were calculated using Friedman's test with significance level 0.05 followed by pairwise tests if Friedman's test showed a significant difference. Each variable was considered separately, and the blocks were formed by combining observations with the same treatment levels for the two variables that for the two variables that were not the response in the test. For each type of weather observation, the data was merged for all days during 28 d, 21 d, 14 d, and 7 d before harvest and then correlation with soft scald incidence was calculated. The data for 2018, 2019 and 2020 was combined for 'Aroma', and 2019 and 2020 was combined for 'Frida' for correlation calculations for each variety. Lastly, the data for the two varieties and all years was also pooled and correlations were calculated the same way as above for the two varieties combined.

3. Results

3.1. Maturity at harvest

In 'Aroma', the levels of soft scald and fungal decay were higher in 2019, than in 2018 and 2020 (Figs. 2 and 3). Harvest date had no significant effect on neither soft scald incidence nor fungal decay in 2018, and only minor effect in 2020. In 2019, at the latest harvest both soft scald and fungal decay showed the highest frequency as compared with the first harvest, and the first harvest showed the lowest incidence of fungal decay. Streif index values for the harvested fruit are available in the supplemental material (Table 12).

In 'Frida' harvest date had no effect on soft scald incidence in any of the investigated years 2019 and 2020, and the same was the case in 'Frida' concerning fungal decay.

3.2. Weather conditions affecting soft scald

The weather conditions were very variable between the years. For 'Aroma' in 2018 temperatures were high with average maximum temperatures between 24.5 and 25 °C compared to 2019 (21.1–21.3 °C) and 2020 (20.9–21.1 °C) (Table2). Daily average temperature and average daily minimum temperature followed the same trend with higher numbers in 2018 than the other two years. 2019 stands out as a rainy (207–287 L*m^{-2}) and humid year (80.1–80.8% relative humidity) while the other years had between 100 and 157 L*m^{-2} rainfall. Relative

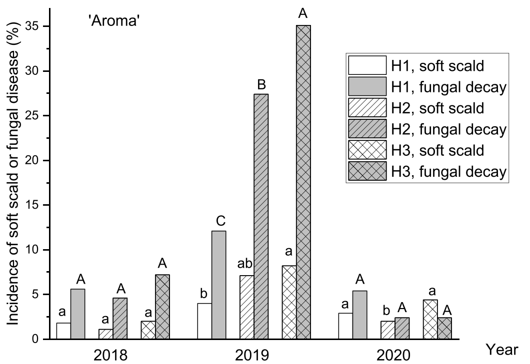

Fig. 2. Effect of harvest date on incidence of soft scald and fungal decay in 'Aroma' after storage. Maturity at harvest was determined based on Streif index and number of days after full bloom. H1: harvest one; H2: harvest two, H3: harvest 3, n = 150. Bars marked with the same letter (lowercase letters for soft scald and uppercase letters for fungal disease) within each year were not statistically significant different according to Friedman's test at $p \leq 0.05$.

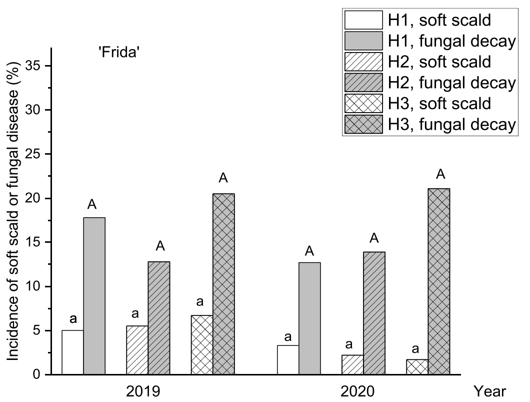

Fig. 3. Effect of harvest date on incidence of soft scald and fungal decay in 'Frida' after storage. Maturity at harvest was determined based on Streif index and number of days after full bloom. H1: harvest one; H2: harvest two, H3: harvest 3, n = 150. Bars marked with the same letter (lowercase letters for soft scald and uppercase letters for fungal disease) within each year were not statistically significant different according to Friedman's test at $p \leq 0.05$.

humidity was between 73.1 and 76.2 in 2018 and 2020. Frida also had higher relative humidity in 2019 (85–85.8) than in 2020 (79.4–79.5). Rainfall was also higher in 2019 (201–202 $L*m^{-2}$) than in 2020 (151–171 $L*m^{-2}$). Differences in temperature between 2019 and 2020 were small.

Relative humidity showed strong positive correlations with soft scald for all investigated time periods in 'Frida' (Table 3). For 'Aroma' rainfall was close to significant for 7 DBH (p = 0.089), while for the other investigated factors for this cultivar the correlations were not significant (data not shown).

Relative humidity during the time period 28 d before harvest showed a medium strong positive correlation with soft scald when data from both cultivars were pooled (Table 4). Relative humidity was also close to significant for 21 DBH (p = 0.055), while for the other factors the correlations were not significant.

3.3. Cooling conditions and storage atmosphere

Initial storage treatment after harvest before storage in ambient or controlled atmosphere led to varying results on soft scald incidence (Tables 5 and 6). In 2018, the incidence of soft scald was highest for 'Aroma' when fruit was initially stored at 2 °C in ambient atmosphere while in 2020 this treatment led to the lowest incidence. In 2019, independent of the initial storage conditions for the first 10 d, no difference in the incidence of soft scald could be found for neither 'Aroma', nor for 'Frida'. No significant differences regarding incidence of soft scald could be found between the different initial storage treatments for 'Frida' in 2020.

Also for fungal decay no difference between the different storage treatments could be found for any of the cultivars.

The storage in different atmosphere conditions showed varying results between different years for both soft scald incidence and fungal decay. In 2019 and 2020 the soft scald incidence in both 'Aroma' and 'Frida' was highest when the fruit was stored in ambient atmosphere. 2018 in 'Aroma' there were no significant differences between ULO/CA and ambient atmosphere for soft scald. For 'Aroma' the fungal decay frequency was much higher in 2019, than in 2018 and 2020, and was high irrespective of storage condition. In 'Frida', both years showed the highest frequency of fungal decay in fruit stored in ambient atmosphere.

Carbon dioxide injury was not detected in any fruit, and other physiological disorders were rare.

Neither harvest time, storage treatment, nor storage atmosphere had any large effects on the investigated quality parameters. Color parameters L (range 54.5–64.7), a (range 2.9–19.0) and b values (range 26.7–36.1), as well as firmness (range 42.2–62.9 N) and SSC (range 12.4–15.5%) after storage did not show any remarkable differences for 'Aroma' (Table 7, 8 and 9 in the supplemental material). Similar results was found for quality parameters in 'Frida': L (range 59.0–65.1), a (range 5.5–16.1) and b values (range 31.3–36.6), firmness (range 46.7–73.3 N) and SSC (range 11.8–14.0%). (Table 10, 11 and 12 in the supplement material).

4. Discussion

Although investigated in a number of studies, which factors that initiate the development of soft scald during storage still remain elusive. It has long been considered to be a cold storage disorder (Brooks and Harley, 1934; Watkins et al., 2005), but trials with gradual cooling of apples after harvest have given various results (Hanrahan and McFerson,

Table 3
Correlation between climate conditions during the growing season and soft scald prevalence in 'Frida'. Weather conditions were recorded by weather stations in the orchards during 2019–2020, n = 450. DBH stands for "days before harvest".

Factor	7 DBH		14 DBH		21 DBH		28 DBH	
	r	p	r	p	r	p	r	p
Daily minimum temperature	-0.723	0.104	-0.357	0.488	-0.266	0.610	-0.347	0.500
Daily average temperature	-0.500	0.313	-0.267	0.609	-0.249	0.634	-0.325	0.530
Relative humidity	0.849	0.033	0.846	0.034	0.919	0.010	0.860	0.028
Rainfall	-0.056	0.915	-0.199	0.822	-0.128	0.809	0.155	0.769
Solar radiation	-0.291	0.575	-0.799	0.115	-0.351	0.495	-0.238	0.649

Table 4
Correlation between climate conditions during the growing season and soft scald prevalence in 'Aroma' and 'Frida', n = 900. Weather conditions were recorded by weather stations in the orchards during 2018–2020 for 'Aroma' and 2019–2020 for 'Frida'. DBH stands for "days before harvest".

Factor	7 DBH		14 DBH		21 DBH		28 DBH	
	r	p	r	p	r	p	r	p
Daily minimum temperature	-0.161	0.566	-0.107	0.704	-0.169	0.547	-0.149	0.597
Daily average temperature	-0.158	0.574	-0.09	0.749	-0.144	0.608	-0.187	0.504
Relative humidity	0.393	0.147	0.403	0.137	0.505	0.055	0.528	0.043
Rainfall	0.463	0.082	0.23	0.41	0.08	0.777	-0.303	0.272
Solar radiation	-0.279	0.314	-0.282	0.308	-0.276	0.32	-0.081	0.775

Table 5
Effect of initial storage treatment n = 150, and storage atmosphere n = 30, on the incidence of soft scald and fungal decay in 'Aroma' 2018–2020. Fruit was subjected to initial storage treatment either 5 d at 10 °C followed by 5 d at 4 °C in ambient atmosphere, or 10 d at 2 °C in ambient atmosphere (gradual cooling), or was directly stored at 2 °C in the final CA/ULO condition or in an ambient atmosphere. After initial storage treatment, all fruit was transferred to 2 °C 95% RH storage. Storage conditions were as follows: ULO 1 was 1 kPa O_2 and 1 kPa CO_2, ULO 2 was 1 kPa O_2 and 2 kPa CO_2, ULO 3 was 1 kPa O_2 and 3 kPa CO_2, CA 4 was 2 kPa O_2 and 2 kPa CO_2 and storage atmosphere 5 was ambient atmosphere in ambient atmosphere storage. In 2018 fruit was stored for five months, while in 2019 and 2020 it was stored for four months. Means for a specific year followed by the same letter within a column are not significantly different according to Friedman's test at $p \leq 0.05$.

Year	Storage treatment	Soft scald (%)	Fungal decay (%)	Storage atmosphere	Soft scald (%)	Fungal decay (%)
	Gradual cooling	0.6 b	6.9 a	ULO1	1.5 a	11.8 a
2018	2 °C, ambient atmosphere	3.4 a	6.9 a	ULO2	1.5 a	3.2 a
	Direct final storage	0.9 b	3.6 a	ULO3	3.3 a	6.7 a
				CA	1.5 a	6.2 a
				Ambient atmosphere	0.4 a	1.1 b
	Gradual cooling	6.9 a	26.7 a	ULO1	1.1 b	26.3 b
2019	2 °C, ambient atmosphere	6.4 a	30.1 a	ULO2	2.3 b	26.7 a
	Direct final storage	6.0 a	17.9 a	ULO3	4.8 a	21.7 a
				CA	4.4 a	24.0 b
				Ambient atmosphere	19.6 a	25.9 b
	Gradual cooling	3.5 a	2.9 a	ULO1	1.1 a	3.3 a
2020	2 °C, ambient atmosphere	1.7 b	3.1 a	ULO2	1.1 a	2.2 a
	Direct final storage	4.0 a	4.2 a	ULO3	3.3 a	1.8 a
				CA	1.8 a	3.3 a
				Ambient atmosphere	8.1 b	6.4 a

Table 6
Effect of storage treatment, n = 150, and storage atmosphere n = 225 on the incidence of soft scald and fungal decay in 'Frida' 2019 and 2020. Fruit was subjected to initial storage treatment either 5 d at 10 °C followed by 5 d on 4 °C in ambient atmosphere, or 10 d at 2 °C in ambient atmosphere (gradual cooling), or was directly stored at 2 °C in the final ULO condition or in an ambient atmosphere. Storage condition 1 was CA-conditions at 1 kPa O_2 and 1 kPa CO_2 while storage condition 2 was ambient atmosphere storage in ambient atmosphere. Storage temperature in the final storage for five months was 2 °C, and 95% RH, both in CA and in ambient atmosphere. Means for a specific year followed by the same letter within a column are not significantly different according to Friedman's test at $p < 0.05$.

Year	Storage treatment	Soft scald (%)	Fungal decay (%)	Storage conditions	Soft scald (%)	Fungal decay (%)
	Gradual cooling	6.1 a	17.7 a	ULO1	3.3 b	10.3 b
2019	2 °C, ambient atmosphere	5.0 a	17.2 a	Ambient atmosphere	8.1 a	23.7 a
	Direct final storage	6.1 a	16.1 a			
	Gradual cooling	1.1 a	17.2 a	ULO1	0.0 b	13.3 b
2020	2 °C, ambient atmosphere	1.7 a	13.3 a	Ambient atmosphere	4.8 a	18.5 a
	Direct final storage	4.4 a	17.2 a			

2014; Moran et al., 2010) and several factors seem to influence the development of soft scald. In the present study the influence of different factors on soft scald incidence after storage has been investigated, namely maturity/harvest time, cooling and storage conditions, and pre-harvest weather conditions, following the time period from flowering to harvest of the fruit. Previous studies have usually focused on one or two of these parameters, which makes this study more comprehensive.

Several experiments have been performed based on the assumption that gradual cooling directly after harvest, before cold storage, may facilitate the adaptation to the cold temperature and decrease the incidence of the disorder (Al Shoffe et al., 2018; DeLong et al., 2006). However, gradual cooling seems to result in less soft scald in some cases, while in other cases no differences have been found (Al Shoffe and Watkins, 2018; Moran et al., 2010). Results found in this investigation seem to mirror the inconsistent previous results as we found no storage treatments that consistently lowered soft scald incidence for all years.

Variations in the weather conditions between the investigated years seemed to have a pronounced influence. Since storage conditions and cultivation practice were identical between the years, other factors must have affected the development of soft scald. The weather conditions were variable between the years, and especially in 2018, the temperature was higher than average during the growing season, with high summer temperature peaks, resulting in an average daily maximum temperature during the fruit growing season being more than 3 °C higher in 2018, than in 2019 and 2020 (values from local weather stations). On the other hand, the rainfall during the growing season in 2019 was about double amount than in 2018 and about 50% higher than in 2020 in the orchard where 'Aroma' was harvested, while it was about 30–50% higher in 2019 than in 2020 in the orchard where 'Frida' was harvested. In addition, the relative humidity (RH) differed between years. Year 2019 stands out as having higher relative humidity as compared with 2018 and 2020 for 'Aroma', and as compared with 2020 for 'Frida'.

The higher RH might have lowered the rate of evaporation from the fruit surface in the orchard, resulting in wetter surface conditions. In 2019, there were relatively high levels of soft scald regardless of harvest time, preconditioning or storage conditions. Corresponding to the different weather conditions in the investigated years, the average RH in the weeks preceding the harvest was found to correlate with incidence of soft scald, especially for 'Frida'. Other physiological disorders have been connected to wet conditions during the growing season, e.g. russeting of apples, visible as brown and corky areas at the surface of the fruit, has been suggested to appear under conditions of frequent rains, high humidity or dew, particularly during early fruit development (Faust and Shear, 1972; Chen et al., 2020). The occurrence of skin spot on some cultivars, especially 'Elstar' and occasionally 'Golden Delicious', was found to be associated with numerous exposures of surface wetness, caused by rain or dew during late stages of fruit development (Winkler et al., 2014). Supporting the findings related to humidity and soft scald frequency in this investigation, in a previous investigation the disorder was found to be strongly related to precipitation 90–120 d after bloom, as well as number of days when RH was higher than 85% (Moran et al., 2009). Wet conditions was found to be one of the major factors influencing soft scald while modeling the effects of preharvest conditions (Lachapelle et al., 2013).

Wet conditions before the harvest result in more turgid cells, and in analogy with what has been found for overly irrigated fruit and also for fruit harvested after heavy rainfall, this could result in micro-cracking, thinner cuticle, and subsequent higher water loss (Lufu et al., 2020). Cuticle formation has been found to be affected negatively by humid conditions, rendering the cuticle to be thin (Faust and Shear, 1972; Chen et al., 2020), and surface moisture may cause microcracks (Knoche and Grimm, 2008). While investigating microstructure of apples affected by soft scald, a previous investigation found that the cuticle of soft-scalded peel had tears, while the cuticle of unaffected peel was intact, which might indicate wax weakness, though tears in the cuticle was only discernable in stored fruit where the damage was visible and not directly at harvest (Xu et al., 2017). Recent findings indicate a more intimate interaction between the cuticle and epidermal cells, and it has been suggested that the cuticle should be understood as the outermost region of epidermal cell walls, and is important both for physical support and for regulating water status (Lara et al. 2019). While the soft scald disorder seems to develop in the outer cell layers, this interaction can be important to study further. Possibly changes in cuticle properties resulting in a higher water loss in soft scald affected tissue, could lead to a more rapid cooling due to increased heat transfer during evaporation, and contribute to tissue damage in affected fruit.

If the disorder of soft scald is linked to an inability of outer fruit tissue to acclimate to the cool temperatures during initial phase of storage, possibly due to increased heat transfer and more rapid cooling, the progress of the damage might be associated to cellular membrane function. In a previous investigation, fatty acid composition in fruit tissue affected by soft scald was found to be different than in sound fruit tissue, and the content of linoleic acid was lower in affected tissue (Hopkirk and Wills, 1981). Cold acclimation in plants have in general been found to be linked to an increasing proportion of unsaturated fatty acids, such as linoleic acid (C18:2) and linolenic acid (C18:3) (Badea and Basu, 2009; Wang et al., 2006). In addition, more cold-tolerant cultivars have been found to have the ability to change their fatty acid composition to a higher proportion of unsaturated fatty acids when subjected to lower temperatures than less cold tolerant cultivars (Tian et al., 2022). Membrane lipid functionality is considered important for maintaining cell homeostasis. The presence of one or more double bonds in the unsaturated fatty acids make it difficult for the molecules to pack tightly in the membrane, and will thereby increase the fluidity of the membrane. The increasing proportion of unsaturated fatty acids of the membrane lipids during the cold acclimation will thus maintain the membrane functionality at lower temperatures (Marangoni et al., 1996). In addition, recently an investigation found that genes involved in lipid peroxidation showed increased expression in fruit with soft scald, which also implicate that membrane functionality might be an important factor in connection with soft scald (Leisso et al., 2016). However, these physiological reactions can be considered as descriptive of the changes that take place, and not explaining the reasons for them to occur.

In the present study, the latest harvested fruit of 'Aroma' in one out of three years, 2019, developed more soft scald, confirming the findings in previous studies (Moran et al., 2010; Watkins et al., 2005), though in the year 2018 and 2020 when the incidence of soft scald was lower, no clear tendency was found. In 'Frida' maturity did not have a significant effect on soft scald development. Ripening of fruit has been shown to affect the mechanical properties of the cuticle, increasing stiffness and reducing its deformability, which would lower the force needed to break it (Lara et al., 2019). This might be of relevance for the increasing susceptibility of more mature fruit to the disorder.

In this investigation, storage of fruit in ambient atmosphere lead to higher incidence of soft scald in both 'Aroma' and 'Frida' as compared with storage in ULO conditions with the lowest oxygen content. To our knowledge, few investigations have been performed where soft scald incidence have been monitored at different concentrations of oxygen present during storage. A recent study found no conclusive results in apples stored in air or in 1.5–0.3 kPa oxygen, while in the first year there was more soft scald found among fruit stored at the lower oxygen levels, but the second year no difference was found (Mattheis and Rudell, 2021). Apple fruit stored in CA-storage tended to develop less soft scald than fruit stored in air (DeLong et al., 2006). Since long time it has been known that lowering oxygen levels during storage reduces respiration rate, ethylene biosynthesis, senescence, fruit maturation and affects expression of genes (Wright et al., 2015). These general effects on cell metabolism might also affect the development of soft scald.

Fungal decay varied between the investigated years and treatments, and showed similar yearly variation as soft scald. In 2019 there was more decay than the other years. Weather conditions can effect pathogens such as *Colletotrichum* ssp. which benefit from a hot, humid weather (Borve and Stensvand, 2007). 2019 was more humid than the other years (Table 2) which could possibly explain the increased decay that year. Optimal harvest time is another important factor in decreasing soft scald incidence (Valiuskaite et al., 2006). In 'Aroma' there was an increase in decay only in 2019 with maturity, possible due to softer fruit which is more sensitive to pathogens (Ahmadi-Afzadi et al., 2013). No conclusive results could be found in the effects on fungal decay regarding the different storage treatments or storage conditions. Multiple factors, alone or in combination, seem to be able to create the conditions in the fruit that initiate soft scald. The varying response the different years to the storage treatment after harvest indicate that environmental factors bring about the prerequisites needed in the fruit tissue for the disorder to occur, though previous findings (e.g. Lachapelle et al., 2013) point to that other factors than humidity before harvest can also be important. Other environmental factors might result in similar changes in the fruit tissue needed for the disorder to develop.

In conclusion, weather conditions during the season appeared to influence the development of soft scald, and especially wet conditions during the growing season and before harvest seemed to be important. The average relative humidity in the weeks preceding the harvest was found to correlate with incidence of soft scald, especially for 'Frida'. For 'Aroma', maturity affected fungal decay to a great extent in the year with high frequency, 2019, but had no effect the other years. Maturity had only effect on the incidence of soft scald in 2019 in 'Aroma'. In 'Frida' maturity did not show any significant effect on soft scald, nor in fungal decay. Gradual cooling did not lead to any conclusive results as compared with other storage treatments in any of the investigated cultivars. ULO storage conditions, especially ULO1 and ULO2 for 'Aroma', and ULO1 for 'Frida', resulted in lower incidence of soft scald as compared with storage in ambient atmosphere in 2019 and 2020, though no conclusive results were found for fungal decay.

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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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.postharvbio.2023.112344.

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II

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.

Keywords: *Malus domestica* Borkh.;Firmness; Ripening index by Streif; Ripening; Harvest; Starch

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 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 optimal harvest date. Correlations between I_{AD} and the other maturity indices were calculated to evaluate similarities or differences in the changes of these indices around the harvest date.

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 1-10), 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.

Table 1

Time of the first harvest each year for the nine apple cultivars. The first harvest was done approximately two weeks before the optimal 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

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 - 1.0 as very strong. Coefficient of variation was calculated by dividing the standard deviation with the mean value, and expressed as %.

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.

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

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).

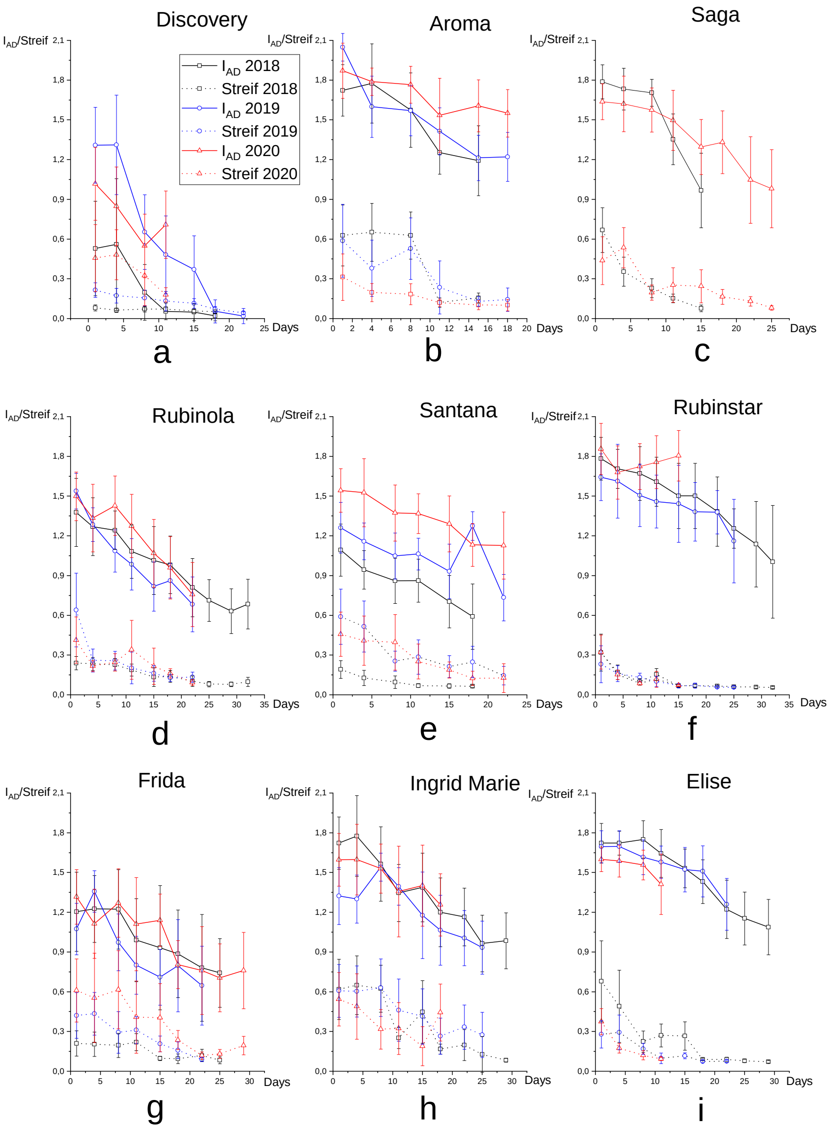

Fig. 1. Changes and standard deviations in I_{AD} and ripening index by Streif over time in ‘Discovery’, ‘Aroma’, ‘Saga’ 'Rubinola', ‘Santana’, ‘Rubinstar', Frida', ‘Ingrid Marie’ and ‘Elise’.

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

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 ‘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 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; DeLong *et al.*, 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 (Shoefs, 2002; 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.

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Only about 30% of the apples consumed in Sweden are produced within the country, even though many customers prefer locally produced fruit. This thesis is focused on reducing losses in Swedish apples with the Da-meter a, for Sweden, new way of measuring maturity. The DA-meter was found to be a possible complement to other maturity indices. Further, the disorder soft scald was also investigated. The most effective way to decrease soft scald was to store apples in controlled atmosphere.

Joakim Sjöstrand received his doctoral education at the Department of Plant Breeding, Swedish University of Agricultural Sciences, Alnarp. He received his MSc in Biology from the Swedish University of Agricultural Sciences, Alnarp.

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