Review

Not peer-reviewed version

Novel Energy-Saving Strategies in Apple Fruit Storage

Felix Büchele , Kiran Hivare , Kartik Khera , Fabio Rodrigo Thewes , Luis Carlos Argenta , Tuany Gabriela Hoffmann , Pramod V. Mahajan , Robert K. Prange , Sunil Pareek , Daniel Alexandre Neuwald *

Posted Date: 1 December 2023

doi: 10.20944/preprints202312.0040.v1

Keywords: fruit storage; energy savings; carbon footprint;1-MCP; DCA; digital twin; SDG 12

Review

Novel Energy-Saving Strategies in Apple Fruit Storage

Felix Büchele [1], Kiran Hivare [1], Kartik Khera [1], Fabio Rodrigo Thewes [2], Luis Carlos Argenta [3], Tuany Gabriela Hoffmann [4], Pramod V. Mahajan [4], Robert K. Prange [5], Sunil Pareek [6] and Daniel Alexandre Neuwald [1,*]

[1] Lake of Constance Research Center for Fruit Cultivation (KOB), Schuhmacherhof 6, 88213 Ravensburg, Germany; felix.buechele@kob-bavendorf.de; Kiran.Hivare@kob-bavendorf.de; kartik.khera@kob-bavendorf.de; neuwald@kob-bavendorf.de

[2] Department of Plant Science, Federal University of Santa Maria, Roraima Avenue 100, Camobi, 97105-900, Santa Maria, RS, Brazil; fthewes@yahoo.com.br

[3] EPAGRI, Experimental Station of Caçador, C.P. 501, 89501,032, Caçador, SC, Brazil; argenta@epagri.sc.gov.br

[4] Department Systems Process Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany; thoffmann2@atb-potsdam.de; pmahajan@atb-potsdam.de

[5] Special Graduate Faculty, School of Environmental Sciences, University of Guelph, Guelph, ON N1G 2W1, Canada; rkprange@gmail.com

[6] Department of Agriculture and Environmental Sciences, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonipat, Haryana 131028 India; sunil.pareek@niftem.ac.in

* Correspondence: neuwald@kob-bavendorf.de

Abstract: Storing apples for up to a year is a well-established practice aimed at providing a continuous, locally-produced fruit supply to consumers and adapting to market trends for optimized profits. Temperature control is the cornerstone of postharvest conservation and apples are typically kept at temperatures from 0 to 3 °C. However, the energy-intensive process of the initial cool down and subsequent temperature maintenance poses significant financial challenges and contributes to the carbon footprint. Higher storage temperatures could reduce cooling-related energy usage but also pose the risk of enhanced ripening and quality loss. This work explores different storage technologies aiming to reduce energy consumption such as 1-methylcyclopropene, ultra-low oxygen and dynamic controlled atmosphere together with raised temperatures. The integration of advanced monitoring and control systems, coupled with data analytics and energy management in apple storage is also discussed. These sustainable strategies can be implemented without cost-intensive construction measures in standard storage facilities. Furthermore, beneficial side effects of higher storage temperatures in terms of a reduced occurrence of storage disorder symptoms and higher maintenance of quality attributes are also discussed for this special issue on sustainable horticultural production systems and supply chains.

Keywords: fruit storage; energy savings; carbon footprint; 1-MCP; DCA; digital twin; SDG 12

1. Introduction

The principal step for the postharvest handling of apples is the management of storage temperatures. Apples are usually kept at their lowest tolerated temperatures, which suppress the fruit metabolism, thereby slowing down the ripening and associated quality deterioration, without the risk of chilling injuries (CI) developing [1,2]. Cultivar-specific optimum temperature ranges exist, typically determined empirically. Most apple cultivars are recommended to be kept in a range from 0 to 3 °C [3]. It is widely assumed that these proposed optimum temperatures should be maintained throughout the full storage period, which can be extended to several months, on average 6 to 12 months [4]. This practice ensures the optimum conservation of quality attributes and avoids losses due to the possible occurrence of physiological disorder symptoms [1,5].

However, the initial cool-down process of the harvested fruit and the subsequent maintenance of these low-temperature ranges necessitate a significant energy input [6–9]. Estimating the total energy usage associated with the long-term storage of apples can prove difficult, as factors such as the design of storage facilities, installed technology and equipment, management practices, storage conditions, and the type of the stored commodity influence the total energy balance of a storage facility [7,10]. Geyer and Praeger approximated the electricity usage of fruit storage rooms for capacities from 50 to 450 t in a range from 3.0 to 5.5 kWh m^{-3} $month^{-1}$ [11], similar results were reported by Evans et al. [12]. Interestingly, the most significant share of the total energy usage accrues in the initial cool-down phase when filling the rooms. During this phase, the cooling system operates at full capacity mainly to remove the field heat of the harvested fruit. Additionally, fruit exhibit a higher respiratory intensity leading to increased heat production. The continuous operation of cooling and ventilation technologies constitutes a major source of heat load, and there is a greater heat input in the room during the filling process [11,13]. For the subsequent storage duration, there is a significantly smaller heat load originating from the respiratory heat by the commodity, running fan motors or heat infiltration.

Long-term apple storage is therefore, associated with substantial energy consumption, but nonetheless crucial to provide a year-round supply of locally produced fruit. The required energy input however confronts fruit storage facilities with immense challenges: Energy prices have risen rapidly over the recent years, while the market prices for the apples remained more or less constant and primarily responsive to the seasonal fruit supply (Figure 1) [14]. This presents an enormous financial constraint, especially as locally-grown products face the competition of imported produce, often produced under cost-effective conditions [15]. Furthermore, if still reliant on conventional energy sources, long-term storage also contributes to a considerable carbon footprint [6,9,10]. These aspects highlight the critical need to improve the energy efficiency of the postharvest sector, ensuring long-term sustainable, environmentally friendly, and economically viable domestic fruit production.

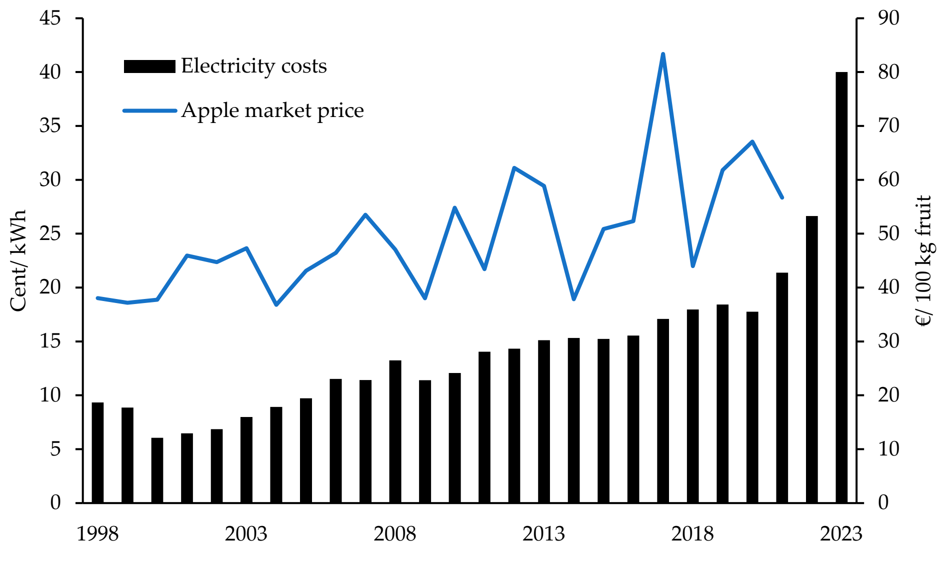

Figure 1. Average apple market prices and electricity costs in the Lake Constance Region in Southern Germany (with permission [16]).

As aforementioned, the cold room design, primarily the insulation, as well as the installed cooling and ventilation equipment, predominantly influence energy efficiency, and therefore, also provide the highest energy saving potential [10,17]. However, improvements in this aspect require cost-intensive construction and renovation measures, which also cannot always be realized in existing storage facilities. It is subsequently essential to devise alternative approaches, which can be implemented short-term and with little investment costs.

Previous studies have already suggested that adjusted programming of the cooling and ventilation system has the potential to reduce energy consumption without compromising fruit quality conservation [8]. Optimized bin stacking and vent areas design of the bin are furthermore easy to implement and have been shown to improve the airflow distribution in the cold room, thus

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2023 doi:10.20944/preprints202312.0040.v1

allowing a reduced ventilation program [18,19]. Other aspects such as watering the room floor, pre-cooling the fruit, and optimizing the filling schedule can also contributing to a higher energy efficiency [11,20].

This review focuses exclusively on three novel storage strategies to lower energy usage during the long-term storage of apples. These include elevated storage temperature together with the application of 1-methylcyclopropene (1-MCP), ultra low oxygen / dynamically controlled atmosphere (ULO/DCA) and data-driven decision-making. It is hypothesized that elevating storage temperatures under the usage of these mentioned postharvest technologies can contribute to lower energy usage during storage.

2. Raised temperatures with 1-MCP application

The application of 1-MCP has become a commercial standard in the postharvest management of several horticultural products including apples [21]. By blocking the ethylene receptors in the fruit, the ripening-inducing action of the hormone is inhibited, thereby slowing down ripening-associated quality deterioration in apples such as softening, peel yellowing, reduction in acidity and sugar levels or the occurrence of senescence disorder symptoms [21–23]. As 1-MCP-treated apples ripen more slowly, a variety of studies have proposed that they may be stored at higher storage temperatures, without enhancing fruit metabolism intensity and compromising quality preservation. This should primarily contribute to reduced energy usage of the cooling system (Table 1), while potentially limiting the occurrence of certain physiological disorders or improving the preservation of quality attributes (Table 2). Furthermore, although respiratory heat accounts only for a minor share of the total heat load that needs to be removed from the room throughout the full season [11], 1-MCP's effect in lowering the respiration rate of apples might also reduce heat energy produced by the stored products.

McCormick et al. tested this concept in a commercial setting by tracking the energy usage in two identical rooms with a capacity of 210 t [24]. Apples of the cultivar 'Gala' were kept for 5.5 months under a) 1.5 °C and b) 4.0 °C + 1-MCP application. The total energy balance shows a 35% reduction in energy usage with higher storage temperatures [24]. Specifically, energy consumption associated with running the cooling system, room ventilation, and defrosting was lowered. Interestingly, the energy usage of CO_2 adsorbers was also lowered with elevated temperatures + 1-MCP, presumably due to a reduced fruit respiration rate. In terms of quality conservation, 1-MCP treated fruit had a higher firmness, titratable acidity and ascorbic acid levels and experienced a lower mass loss, despite the storage at higher temperatures. Sensory evaluations furthermore showed a consumer preference for 1-MCP-treated fruit [24].

In a similar study published in 2012, apples of different cultivars were treated with 1-MCP and held at a temperature ~ 2.5 °C above the untreated control group [25]. For the 'Gala' cultivar, the findings of the previous work could be confirmed, as higher storage temperatures resulted in 35% lower total energy usage [25]. Furthermore, no adverse effects on firmness and acidity values were observed. For 'Jonagold' apples, energy savings of 26% could be achieved by this approach. The differential in energy savings was attributed to differences in the efficacy of the installed technology and different room ventilation settings [25]. A cultivar effect could also be suggested, as 'Jonagold' is known to have a higher respiration and ethylene production rate [26]. Sensory studies affirmed the conclusion that consumers rate 1-MCP-treated apples higher in terms of fruit texture quality and purchase preference [25].

Subsequent work by Kittemann et al. created an energy comparison in identical rooms (11 t apples capacity) between ULO at 1 °C and ULO at 5 °C + 1-MCP [27]. Apples of the cultivars 'Golden Delicious', 'Jonagold' and 'Pinova' were kept together in each room for 7 months. The results highlight an even greater energy savings potential than the previously described studies. A 70% lower energy usage due to the 4 °C temperature differential could be demonstrated [27]. Refrigeration compressors and ventilation fans accounted for the main proportion of the energy savings. The study also emphasized that at higher storage temperatures, no electrical defrosting of the evaporators was necessary after the initial cool-down period [27]. 1-MCP was confirmed to compensate for the elevated temperatures, as no adverse effects on firmness conservation were described. It was furthermore shown that the combination of higher storage temperatures + 1-MCP can reduce the mass loss of the fruit. Both 'Jonagold' and 'Pinova' apples furthermore had higher scores for texture in sensory studies [27].

A recent 4-year study conducted in a commercial storage facility (room capacity 640 t apples) in Brazil showed that temperatures can be increased from 0.7 to 2.0 °C for 'Gala' apples, if treated with 1-MCP [28]. Energy consumption for operating the evaporator fans and compressors was reduced by 21±1% and 20±4%, respectively. Furthermore, it could also be demonstrated that an increase in storage temperature limits the development of fungal decay, particularly for apple fruit produced in warmer regions [28].

A substantial advantage of 1-MCP is that the ethylene-inhibiting effect persists for a certain time period after the fruit removal from storage [21,23]. Studies have accordingly shown that applications before storage prolong the shelf life of apples and also provide benefits in long-distance transportation and subsequent marketing [22,29,30]. 1-MCP applications have been demonstrated to improve the quality conservation post storage during a 7-day simulated shelf life period, for multiple apple cultivars including Braeburn', 'Red Prince', 'Jonagold', 'Pinova', 'Santana', 'Fuji, 'Galaxy' and 'Pink Lady®' [22,30–34]. Furthermore, Toivonen et al. showed in a multi-year study that 1-MCP permits the short-term storage (4 weeks) of 'Sunrise' summer apples at temperatures of up to 22 °C [35]. 1-MCP application may subsequently also render the fruit less sensitive to possible temperature variations in the post-storage sector, and maintaining the cool-chain may be consequently of lower importance. So far, no studies on apples have tested under practical conditions whether 1-MCP applications pre-storage can directly translate to energy savings in the post-storage and marketing sector. However, the idea of delaying the 1-MCP application until after storage to improve quality conservation and potentially reduce the energy usage during the marketing period can be ruled out as a viable strategy, as the timing of application majorly affect the efficacy of the ethylene-inhibitor [21,36].

While these findings indicate a great potential of 1-MCP to cut energy usage during storage without requiring extensive renovations or installation measures, it is nonetheless important to acknowledge that the usage of this compound is not suitable or recommended for all apple cultivars. There are some great differences between the cultivars in their responsiveness to the ripening-enhancing action of ethylene as well as their sensitivity to 1-MCP [21]. It is, therefore, crucial to confirm the effectiveness of 1-MCP for any cultivar, especially as in some instances the application of this product may also play a role in increasing the occurrence of disorders [37]. As 1-MCP inhibits ripening it also maintains apples in an unripe state in which they are more susceptible to physiological injuries caused by elevated CO_2 values [21], as could be shown for 'Braeburn' or 'Empire' in which 1-MCP increased the risk of internal browning or skin necrosis symptoms [31,38].

Furthermore, it must be ensured that the energy savings and the additional value in fruit conservation cover the cost of the application. Another great limitation is that as a synthetic product, the usage of 1-MCP is not permitted in organic fruit production. It is consequently essential to implement other ripening-suppressing measures that allow higher temperatures in apple storage.

3. Raised temperatures in ULO and DCA storage

Controlled atmosphere (CA) settings, meaning the adjustment of oxygen (pO_2) and carbon dioxide partial pressures (pCO_2) in the room atmosphere, slow down fruit respiration and suppress ethylene production in apples, and thus greatly extending their storability [5]. ULO refers to storage conditions with a lower pO_2 than in traditional CA, in ranges around 1.0 kPa [39]. A further development of CA storage is the principle of DCA technologies, which was introduced more than two decades ago and finds application in many apple-producing countries for a great variety of apple cultivars [40]. DCA systems, regardless of the mode of action, aim to monitor in real-time the respiration dynamics of stored apples in order to identify stress signals by the fruit caused by low-oxygen stress and accordingly define the lowest possible pO_2 in the storage atmosphere which is hypothesized to slow down fruit ripening to a minimum and therefore provide optimum quality conservation [41]. Thus far, DCA systems based on chlorophyll fluorescence (DCA-CF), ethanol (DCS or DCA-Eth), respiratory quotient (DCA-RQ) and carbon dioxide release rate (DCA-CD) have been introduced [41]. Further DCA systems improvement can be done by integrating its control with real-time respiration data [42]. These improvements enable the system to dynamically adjust temperature, pO_2 and pCO_2 based on the unique requirements of the stored apples, thereby reducing unnecessary energy consumption.

It must be acknowledged at this point that DCA technologies necessitate a higher standard for the gas-tightness of the room [41]. Leakages potentially distort the identification of low oxygen stress signals and prevent a precise pO_2 control, with potentially adverse consequences such as fermentation damages in the fruit material [43]. Gas-tightness must consequently be tested and ensured before the usage of a DCA system.

The idea behind energy savings with ULO or DCA technologies mirrors the principle discussed for 1-MCP applications. It is assumed that these storage conditions suppress the metabolism intensity of the fruit and thus allow higher storage temperatures. In addition, as mentioned before for 1-MCP, the combination of low pO_2 and elevated pCO_2 in ULO/DCA storage works as a ripening brake, reducing the fruit respiration intensity and thereby limiting respiratory heat production [44].

Neuwald et al. tested the potential of elevating storage temperatures from 1 to 5 °C in ULO and DCA storage for multiple apple cultivars and determined total energy savings of ~15 to 50% during a 5 to 7 months storage time [45]. The highest savings potential was shown for the cooling compressors and the evaporator fans. Interestingly, higher temperatures provided an unsuspected beneficial side effect as they were associated with lower rot incidences in 'Pinova' apples. However, higher temperatures were also found in this cultivar to increase peel yellowing [45].

Table 1. Energy savings potential through the combination of ULO/DCA, 1-MCP and elevated temperatures.

Room Size [t]	Cultivars	Control	High Temperature	Energy savings [%]	Ref.
210	Gala	1.4 ° ULO	4.0 °C ULO + 1-MCP	35	[24]
210	Gala	1.3 ° ULO	3.7 °C ULO + 1-MCP	35	[25]
640	Gala	0.7 ° CA	2.0 °C CA + 1-MCP	20	[28]
100	Elstar	1.5 °C ULO	4.0 °C ULO + 1-MCP	25	[25]
250	Jonagold	1.5 °C ULO	4.0 °C ULO + 1-MCP	26	[45]
11	Jonagold, Pinova, Golden Delicious	1.0 °C CA/DCA	5.0 °C ULO + 1-MCP	63	[27]
11	Jonagold, Pinova, Topaz, Golden Delicious	1.0 °C CA/DCA	4.0 °C ULO + 1-MCP	26	[45]
11	Jonagold, Pinova	1.0 °C ULO/DCA	4.0 °C ULO + 1-MCP	51	[45]
11	Jonagold, Pinova, Golden Delicious	1 °C ULO	3 °C ULO/DCA	12	[45]
11	Pinova	1 °C ULO	3 °C ULO	15-50	[45]
-	Royal Gala, Pink Lady	3 °C	DCA 5 °C	35% cool-down 15% storage	[40]
11	Red Prince	1 °C DCA	DCA + variable Temp.	35%	[46]
11	Red Prince, Jonagold, Pinova	1 ° C DCA	DCA + variable Temp.	20%	[32]

For 'Nicoter' apples, both DCA-CF and DC-RQ were demonstrated to allow raising storage temperatures by 2 °C [47]. While this study did not attempt to create an energy balance, it could nonetheless be shown that higher storage temperatures may provide secondary beneficial effects as lower flesh breakdown, core breakdown, and cavity incidences were found. This effect could also be demonstrated for the 'Braeburn' variety, as the storage at 3 °C in DCA-RQ storage resulted in reduced cell damage and a slowed-down fruit softening [48].

Both et al. made similar conclusions, arguing that it is possible in DCA-RQ to store 'Galaxy' apples at higher temperatures of 2 °C while maintaining high flesh firmness and limiting the occurrence of physiological disorders [22]. This could be confirmed in a later study, which showed that 'Galaxy' apples can be stored at 2.5 °C in DCA-RQ, and compared to 1.5 °C showed higher firmness and reduced mealiness incidences [49]. Ludwig et al. proposed a similar potential for 'Royal Gala' apples, proposing that by lowering the pO_2 in the storage atmosphere from 1.2 to 0.8 kPa, temperatures can be increased by 0.5 °C [50]. The combination of higher temperatures and extremely low oxygen levels resulted in higher flesh firmness and total soluble solids, and reduced flesh breakdown and mealiness incidences. This potential could also be confirmed in the same study for 'Galaxy' apples, as lower pO_2 of 0.4 kPa allowed to raise storage temperatures by 0.5 °C without adverse consequences for fruit conservation. Furthermore, this was also associated with lower mealiness symptoms and ethylene production [50].

While it can be concluded based on these previously listed studies that elevated and static-kept storage temperatures in DCA systems have the potential to save on energy usage, this approach doesn't necessarily consider the stored product's physiology, meaning its sensitivity to the storage temperature. It could be suggested that in the early stages of DCA storage, fruit have a higher metabolism intensity than later on in the storage season, and respectively, may be more responsive to the atmosphere and temperature settings. Based on this hypothesis, a recent work investigated a novel temperature variation program: In DCA-RQ storage, temperatures were kept for the initial 30 days at 0.5 °C until the fruit adapted to the low pO_2 levels, and were then raised to 2 ° to 3 °C for the subsequent 8 months storage [51]. Although this study was conducted on a smaller scale and therefore did not attempt to create a comparison in terms of energy efficiency, it could be demonstrated that this temperature management in DCA-RQ 1.3 results in higher quality maintenance than storage at 0.5 °C or under CA/ULO + 1-MCP conditions [51]. Based on the above-described studies a significant potential for energy savings could subsequently be assumed as well.

Recently, a new approach for temperature management in DCA storage has been introduced, which aims to monitor the fruit respiration dynamics in storage as a function of the established temperature. This storage system is referred to as DCA-CD Plus [52]. Its principle hypothesizes that similarly to an optimum pO_2, an optimum storage temperature can also be defined which fluctuates during the storage period and can be estimated by monitoring the CO_2 release rate of the stored apples [31,32,52]. Thus far, limited research has been published on the efficacy of this new concept in reducing the energy consumption of the cooling system while maintaining high fruit quality. Nonetheless, a preliminary study on 'Red Prince' apples stored for 9 months showed the DCA-CD Plus system to dynamically adjust the storage temperature setpoints from the baseline 1 °C to temperature ranges up to 4.5 °C, without adverse consequences to the conservation of quality parameters such as firmness, titratable acidity or peel color [46]. Subsequent studies on rooms filled with 'Red Prince', 'Pinova', 'Jonagold' or 'Braeburn' confirm the efficacy of DCA-CD Plus in dynamically adjusting and elevating storage temperatures without accelerating fruit ripening and the associated quality deterioration [31,32].

In terms of energy efficiency, DCA-CD Plus was shown to reduce the energy usage by the evaporators, the compressors, and electrical defrosting, cumulating in total to energy savings of more than 35% [46]. Subsequent work found 40% less energy usage of the evaporators due to dynamic temperatures in DCA-CD Plus. Energy usage for evaporator defrosting was cut by 30% as well [32]. Although defrosting of ventilators accounts for a relatively small proportion of the total energy consumption of the cooling system, these findings nonetheless suggest that dynamic temperature adjustments limit the risk of ice buildup on the evaporator. Ice accumulation on the evaporators reduces the heat transfer and increases the pressure drop, and accordingly negatively affects the cooling capacity of the refrigeration system. In addition, this might also dehumidify the air cycling inside the rooms and thereby promote fruit transpiration and mass loss [53]. According to these initial findings, dynamic temperatures may allow running the refrigeration air coolers throughout the storage duration in a defrost-free modus, with possible benefits in terms of energy efficiency and fruit quality conservation [46].

 doi:10.20944/preprints202312.0040.v1

When considering the discussed findings on 1-MCP and DCA technologies, it could be argued that the combination of both approaches may ultimately provide the highest energy savings potential, during storage as well as in the subsequent marketing period. Köpcke et al. tested this idea by storing 'Elstar', 'Jonagold', and 'Gloster' apples for 5 months under DCA-CF + 1-MCP under higher temperature ranges of 3.5 to 10 °C [54]. Results highlighted that elevated storage temperatures reduced chilling injuries, watercore and internal browning. The combination of 1-MCP and DCA was found to maintain higher fruit quality than either treatment alone. Furthermore, it was argued in this work that using DCA technologies could limit risks, if the 1-MCP application should have an insufficient effect due to an incorrect application timing or advanced ripeness of the treated fruit material [54,55]. Findings by Büchele et al. support these arguments, as they showed that storage temperatures can be increased by 3 °C for 'Santana' apples if kept under DCA-CD + 1-MCP [30]. No adverse effects of higher storage temperature on firmness, titratable acidity, and peel color were observed, even after an additional 7 d shelf life period at 20 °C. This simultaneously underlines the earlier proposed energy savings potential in the post-storage sector. As these two listed studies did not include a comparison of energy usage, the energy savings potential can naturally only be hypothesized based on similar studies that showcased increased temperatures to reduce the energy consumption of the cooling system.

Table 2. Interactive effects of raised temperature + ULO/DCA and/or 1-MCP on stored fruit.

Beneficial effect	References
Higher firmness, higher TSS, higher TA	[22,24,25,27,32,34,46,51,54]
Lower mass loss	[24,25,27,46]
Higher scores in sensory consumer panels (texture, taste, buying preference)	[24,25,27]
Reduced chilling injuries, flesh breakdown, core breakdown, water core, cavities, and mealiness	[22,33,40,46,48–51,54]
Reduced rot incidences	[27,28,45,56]
Increased abundance of volatile organic compounds	[30]

3. Advanced monitoring and data analytics

In the evolving landscape of apple storage practices, the incorporation of advanced monitoring and control systems, coupled with data analytics, represents a revolutionary approach to precision energy management. Such systems, equipped with air-flow [57] and heat-flux sensors [58], enable real-time data collection, providing a comprehensive understanding of the storage environment. Such advanced monitoring technology ensures meticulous tracking of temperature dynamics and airflow patterns within storage facilities. Paired with real-time control systems, this technology allows for dynamic adjustments tailored to the specific needs of stored apples, reducing unnecessary energy consumption. For instance, by adapting temperature settings and regulating air-flow with precision, these systems contribute not only to the preservation of fruit quality but also to significant energy efficiency gains.

Furthermore, the integration of data analytics enhances decision-making processes. Analyzing the wealth of data collected by monitoring systems provides insights into trends and patterns, empowering stakeholders to make informed decisions about storage conditions. This proactive approach, rooted in data-driven insights, minimizes energy wastage by identifying areas where energy may be expended unnecessarily. The continuous improvement cycle facilitated by data analytics ensures that apple storage facilities evolve over time, aligning with the most efficient and sustainable energy usage practices. By strategically combining technology and data-driven insights, the industry not only ensures optimal fruit preservation but also lays the groundwork for a future where energy-intensive processes are managed with unparalleled efficiency and sustainability.

One promising avenue for future exploration is the application of digital twin technology in the realm of apple storage. Digital twins, which replicate physical systems in a virtual environment, offer the potential for real-time simulations and data-driven decision-making [59]. In the context of energy conservation, a digital twin of an apple storage facility could enable precise monitoring and adjustment of conditions, optimizing energy usage.

5. Conclusions

There is an evident need to enhance the energy efficiency of the postharvest sector in pome fruit storage striving for SDG 12 'Sustainable consumption and production'. The high energy usage associated with cooling the product jeopardizes the sustainable and economic viability of the storage of locally produced fruit and stands as a major contributor to the carbon footprint across the entire fruit production chain. This review explored three strategies aimed at reducing energy consumption in refrigeration systems. Research shows that, depending on the apple cultivar, storage temperatures can be increased by 2 to 4 °C with the application of the ethylene inhibitor 1-MCP or the establishment of extremely low pO_2 (< 1.0 kPa) in ULO/DCA storage. Furthermore, positive benefits of increased temperatures on fruit preservation can be concluded as well, as research shows lower incidences of internal browning, watercore, mealiness, or storage rot, while 1-MCP and/or ULO/DCA improved firmness and maintained titratable acidity. The incorporation of advanced monitoring and control systems, coupled with insightful data analytics and digital twin, can also serve as a crucial strategy for effective energy management in apple storage. In this context, it can be asserted that these technologies contribute to more sustainable fruit preservation and economic efficiency by limiting food loss and waste in the postharvest sector. Importantly, the broad commercial applicability of these technologies is suggested, as they may be implemented in standard CA storage facilities without the need for cost-intensive construction measures.

Author Contributions: "Conceptualization, F.B., K.H. and D.A.N.; writing—original draft preparation, F.B., T.H., P.V.M.; writing—review and editing, F.B., K.H., K.K., F.R.T., L.A., T.H., P.V.M., R. K. P., D.A.N., S.P.; visualization, F.B.; supervision, D.N.; All authors have read and agreed to the published version of the manuscript.".

Acknowledgments: We are grateful to the Landwirtschaftliche Rentenbank, Germany for supporting the research project 'DyNatCool' and financing the position of the first author (F. Büchele).

References

1. Streif: J.; Kittemann, D.; Neuwald, D.A.; McCormick, R.; Xuan, H. Pre- and Post-Harvest Management of Fruit Quality, Ripening and Senescence. *Acta Horticulturae* **2010**, *877*, 55–68, doi:10.17660/ActaHortic.2010.877.2.
2. Leisso, R.S.; Buchanan, D.A.; Lee, J.; Mattheis, J.P.; Sater, C.; Hanrahan, I.; Watkins, C.B.; Gapper, N.; Johnston, J.W.; Schaffer, R.J.; et al. Chilling-Related Cell Damage of Apple (*Malus* × *Domestica* Borkh.) Fruit Cortical Tissue Impacts Antioxidant, Lipid and Phenolic Metabolism. *Physiol Plantarum* **2015**, *153*, 204–220, doi:10.1111/ppl.12244.
3. Prange, R.K.; Wright, A.H. A Review of Storage Temperature Recommendations for Apples and Pears. *Foods* **2023**, *12*, 466, doi:10.3390/foods12030466.
4. Gross, K.C.; Wang, C.Y.; Saltveit, M.E. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66; *U.S. Department of Agriculture, Agricultural Research Service* **2016**. Washington, DC.
5. DeEll, J.R. Chapter 14.1 - Pome Fruits: Apple Quality and Storage. In *Controlled and Modified Atmospheres for Fresh and Fresh-Cut Produce*; Gil, M.I., Beaudry, R., Eds.; Academic Press, 2020; pp. 293–298 ISBN 978-0-12-804599-2.
6. Blanke, M.M. Life Cycle Assessment (LCA) and Food Miles - An Energy Balance for Fruit Imports versus Home-Grown Apples. *Acta Hortic.* **2008**, 59–64, doi:10.17660/ActaHortic.2008.767.4.
7. Lewczuk, K.; Kłodawski, M.; Gepner, P. Energy Consumption in a Distributional Warehouse: A Practical Case Study for Different Warehouse Technologies. *Energies* **2021**, *14*, 2709, doi:10.3390/en14092709.
8. East, A.R.; Smale, N.J.; Trujillo, F.J. Potential for Energy Cost Savings by Utilising Alternative Temperature Control Strategies for Controlled Atmosphere Stored Apples. *International Journal of Refrigeration* **2013**, *36*, 1109–1117, doi:10.1016/j.ijrefrig.2012.10.028.
9. Boschiero, M.; Zanotelli, D.; Ciarapica, F.E.; Fadanelli, L.; Tagliavini, M. Greenhouse Gas Emissions and Energy Consumption during the Post-Harvest Life of Apples as Affected by Storage Type, Packaging and Transport. *Journal of Cleaner Production* **2019**, *220*, 45–56, doi:10.1016/j.jclepro.2019.01.300.

10. du Plessis, M.J.; van Eeden, J.; Goedhals-Gerber, L.L. The Carbon Footprint of Fruit Storage: A Case Study of the Energy and Emission Intensity of Cold Stores. *Sustainability* **2022**, *14*, 7530, doi:10.3390/su14137530.
11. Geyer, M.; Praeger, U. *Lagerung Gartenbaulicher Produkte*; *KTBL-Schrift* **2012**, 493, ISBN 978-3-941583-62-7.
12. Evans, J.; J-M, H.; Reinholdt, L.; Fikiin, K.; Zilio, C.; Houška, M.; Bond, C.; Schreurs, M.; van Sambeek, T.W.M. Cold Store Energy Usage and Optimization. 23rd International Congress of Refrigeration (ICR) **2011**; Prague, Czech Republic.
13. Ambaw, A.; Bessemans, N.; Gruyters, W.; Gwanpua, S.G.; Schenk, A.; De Roeck, A.; Delele, M.A.; Verboven, P.; Nicolai, B.M. Analysis of the Spatiotemporal Temperature Fluctuations inside an Apple Cool Store in Response to Energy Use Concerns. *International Journal of Refrigeration* **2016**, *66*, 156–168, doi:10.1016/j.ijrefrig.2016.02.004.
14. Radulescu, C.V., Gole, I., Troaca, V.A. and Gombos, C.C.,2022. Rising Energy Prices: The Impact on Inflation, Economic Activity and the Results of the Fight Against Global Warming. In: R. Pamfilie, V. Dinu, C. Vasiliu, D. Pleșea, L. Tăchiciu eds. 2022. 8th BASIQ International Conference on New Trends in Sustainable Business and Consumption. Graz, Austria, 25-27 May 2022. Bucharest: ASE, pp.58-65. doi: 10.24818/BASIQ/2022/08/006
15. Blanke, M.; Burdick, B. Food (Miles) for Thought - Energy Balance for Locally-Grown versus Imported Apple Fruit (3 Pp). *Env Sci Poll Res Int* **2005**, *12*, 125–127, doi:10.1065/espr2005.05.252.
16. Sellwig, M.; Neuwald, D.A.; Büchele, F. Äpfel Mit Weniger Energie Lagern: Einsparpotentiale Ausloten Und Kosten Senken. *POMA* **2022**, *8*, 13–16.
17. Küçüktopcu, E.; Cemek, B.; Simsek, H. Application of Spatial Analysis to Determine the Effect of Insulation Thickness on Energy Efficiency and Cost Savings for Cold Storage. *Processes* **2022**, *10*, 2393, doi:10.3390/pr10112393.
18. Praeger, U.; Jedermann, R.; Sellwig, M.; Neuwald, D.A.; Truppel, I.; Scaar, H.; Hartgenbusch, N.; Geyer, M. Influence of Room Layout on Airflow Distribution in an Industrial Fruit Store. *International Journal of Refrigeration* **2021**, doi:10.1016/J.IJREFRIG.2021.06.016.
19. Berry, T.M.; Fadiji, T.S.; Defraeye, T.; Opara, U.L. The Role of Horticultural Carton Vent Hole Design on Cooling Efficiency and Compression Strength: A Multi-Parameter Approach. *Postharvest Biology and Technology* **2017**, *124*, 62–74, doi:10.1016/j.postharvbio.2016.10.005.
20. Duan, Y.; Wang, G.-B.; Fawole, O.A.; Verboven, P.; Zhang, X.-R.; Wu, D.; Opara, U.L.; Nicolai, B.; Chen, K. Postharvest Precooling of Fruit and Vegetables: A Review. *Trends in Food Science & Technology* **2020**, *100*, 278–291, doi:10.1016/j.tifs.2020.04.027.
21. Watkins, C.B. The Use of 1-Methylcyclopropene (1-MCP) on Fruits and Vegetables. *Biotechnology Advances* **2006**, *24*, 389–409, doi:10.1016/J.BIOTECHADV.2006.01.005.
22. Both, V.; Brackmann, A.; Thewes, F.R.; Weber, A.; Schultz, E.E.; Ludwig, V. The Influence of Temperature and 1-MCP on Quality Attributes of 'Galaxy' Apples Stored in Controlled Atmosphere and Dynamic Controlled Atmosphere. *Food Packaging and Shelf Life* **2018**, *16*, 168–177, doi:10.1016/j.fpsl.2018.03.010.
23. Blankenship, S. Ethylene Effects and the Benefits of 1-MCP. *Perishables Handling Quarterly* **2001**, 2–4.
24. McCormick, R.; Neuwald, D.A.; Streif, J. A Case Study: Potential Energy Savings Using 1-MCP with "Gala" Apples in Commercial CA Storage. *Acta Horticulturae* **2010**, *877*, 323–326, doi:10.17660/ActaHortic.2010.877.39.
25. McCormick, R.; Neuwald, D.A.; Streif, J. Commercial Apple CA Storage Temperature Regimes with 1-MCP (SmartFreshTM): Benefits and Risks. *Acta Horticulturae* **2012**, 263–270, doi:10.17660/ActaHortic.2012.934.32.
26. Saquet, A.A.; Streif, J. Respiration Rate and Ethylene Metabolism of 'Jonagold' Apple and 'Conference' Pear under Regular Air and Controlled Atmosphere. *Bragantia* **2017**, *76*, 335–344, doi:10.1590/1678-4499.189.
27. Kittemann, D.; McCormick, R.; Neuwald, D.A. Effect of High Temperature and 1-MCP Application or Dynamic Controlled Atmosphere on Energy Savings during Apple Storage. *European Journal of Horticultural Science* **2015**, *80*, 33–38, doi:10.17660/eJHS.2015/80.1.5.
28. Wood, R.M.; Argenta, L.C.; Büchele, F.; De Lima, E.W.; Nesi, C.N.; Neuwald, D.A. Effect of 1-MCP and Storage Temperature on 'Gala' Apple Grown in Southern Brazil and Stored under Commercial Conditions. *Acta Hortic.* **2023**, 79–86, doi:10.17660/ActaHortic.2023.1364.10.
29. Tomala, K.; Małachowska, M.; Guzek, D.; Głąbska, D.; Gutkowska, K. The Effects of 1-Methylcyclopropene Treatment on the Fruit Quality of 'Idared' Apples during Storage and Transportation. *Agriculture* **2020**, *10*, 490, doi:10.3390/agriculture10110490.
30. Büchele, F.; Khera, K.; Wagner, R.; Thewes, F.R.; Neuwald, D.A. Interaction between Dynamic Controlled Atmosphere (DCA-CD), 1-Methylcyclopropene and Elevated Temperatures in the Long-Term Storage of Organic 'Santana' Apples. *Postharvest Biology and Technology* **2023**, *204*, 112471, doi:10.1016/j.postharvbio.2023.112471.
31. Büchele, F.; Thewes, F.R.; Khera, K.; Voegele, R.T.; Neuwald, D.A. Impacts of Dynamic Controlled Atmosphere and Temperature on Physiological Disorder Incidences, Fruit Quality and the Volatile Profile of "Braeburn" Apples. *Scientia Horticulturae* **2023**, *317*, 112072, doi:10.1016/j.scienta.2023.112072.

32. Büchele, F.; Khera, K.; Thewes, F.R.; Kittemann, D.; Neuwald, D.A. Dynamic Control of Atmosphere and Temperature Based on Fruit CO2 Production: Practical Application in Apple Storage and Effects on Metabolism, Quality, and Volatile Profiles. *Food Bioprocess Technol* **2023**, doi:10.1007/s11947-023-03079-0.
33. Thewes, F.R.; Anese, R.O.; Thewes, F.R.; Ludwig, V.; Klein, B.; Wagner, R.; Nora, F.R.; Rombaldi, C.V.; Brackmann, A. Dynamic Controlled Atmosphere (DCA) and 1-MCP: Impact on Volatile Esters Synthesis and Overall Quality of 'Galaxy' Apples. *Food Packaging and Shelf Life* **2020**, *26*, 100563, doi:10.1016/j.fpsl.2020.100563.
34. Schmidt, S.F.P.; Schultz, E.E.; Ludwig, V.; Berghetti, M.R.P.; Thewes, F.R.; Anese, R. de O.; Both, V.; Brackmann, A. Volatile Compounds and Overall Quality of 'Braeburn' Apples after Long-Term Storage: Interaction of Innovative Storage Technologies and 1-MCP Treatment. *Scientia Horticulturae* **2020**, *262*, 109039, doi:10.1016/j.scienta.2019.109039.
35. Toivonen, P.; Lu, L. Studies on Elevated Temperature, Short-Term Storage of 'Sunrise' Summer Apples Using 1-MCP to Maintain Quality. *The Journal of Horticultural Science and Biotechnology* **2005**, *80*, 439–466, doi:10.1080/14620316.2005.11511957.
36. Argenta, L.C.; Fan, X.F.; Mattheis, J.P. Factors Affecting Efficacy of 1-MCP to Maintain Quality of Apples Fruit after Storage. *Acta Hortic.* **2005**, 1249–1256, doi:10.17660/ActaHortic.2005.682.166.
37. Larrigaudière, C.; Ubach, D.; Chiriboga, M.A.; Cascia, G.; Soria, Y.; Recasens, I. Biochemical Changes in 1-MCP Treated Skin Tissue during Cold Storage and Their Relationship with Physiological Disorders. *Acta Hortic.* **2008**, 119–123, doi:10.17660/ActaHortic.2008.796.12.
38. Koushesh Saba, M.; Watkins, C.B. Flesh Browning Development of 'Empire' Apple during a Shelf Life Period after 1-Methylcyclopropene (1-MCP) Treatment and Controlled Atmosphere Storage. *Scientia Horticulturae* **2020**, *261*, 108938, doi:10.1016/j.scienta.2019.108938.
39. Wright, A.H.; Delong, J.M.; Arul, J.; Prange, R.K. The Trend toward Lower Oxygen Levels during Apple (Malus × Domestica Borkh) Storage - A Review. *Journal of Horticultural Science and Biotechnology* **2015**, *90*, 1–13, doi:10.1080/14620316.2015.11513146.
40. Prange, R.K.; Wright, A.H.; DeLong, J.M.; Zanella, A. History, Current Situation and Future Prospects for Dynamic Controlled Atmosphere (DCA) Storage of Fruits and Vegetables, Using Chlorophyll Fluorescence. *Acta Horticulturae* **2013**, *1012*, 905–916, doi:10.17660/ACTAHORTIC.2013.1012.122.
41. Thewes, F.R.; Wood, R.M.; Both, V.; Keshri, N.; Geyer, M.; Pansera-Espíndola, B.; Hagemann, M.H.; Brackmann, A.; Wünsche, J.N.; Neuwald, D.A. Dynamic Controlled Atmosphere: A Review of Methods for Monitoring Fruit Responses to Low Oxygen. *Comunicata Scientiae* **2021**, *12*, e3782, doi:10.14295/cs.v12.3782.
42. Keshri, N.; Truppel, I.; Herppich, W.B.; Geyer, M.; Weltzien, C.; Mahajan, P.V. Development of Sensor System for Real-Time Measurement of Respiration Rate of Fresh Produce. *Computers and Electronics in Agriculture* **2019**, *157*, 322–328, doi:10.1016/j.compag.2019.01.006.
43. Boeckx, J.; Hertog, M.; Geeraerd, A.; Nicolaï, B. Regulation of the Fermentative Metabolism in Apple Fruit Exposed to Low-Oxygen Stress Reveals a High Flexibility. *Postharvest Biology and Technology* **2019**, *149*, 118–128, doi:10.1016/j.postharvbio.2018.11.017.
44. Boeckx, J.; Pols, S.; Hertog, M.L.A.T.M.; Nicolaï, B.M. Regulation of the Central Carbon Metabolism in Apple Fruit Exposed to Postharvest Low-Oxygen Stress. *Frontiers in Plant Science* **2019**, *10*, 1–17, doi:10.3389/fpls.2019.01384.
45. Neuwald, D.; Sellwig, M.; Wünsche, J.; Kittemann, D. New Apple Storage Technologies Can Reduce Energy Usage and Improve Storage Life. *ecofruit* **2016**, Stuttgart, Germany, 184–187.
46. Neuwald, D.A.; Thewes, F.R.; Wirth, R.; Büchele, F.; Klein, N.; Brackmann, A. Dynamic Controlled Atmosphere (DCA) - A Chance for Sustainable Organic Fruit Storage. *ecofruit* **2020**, Stuttgart, Germany, 241–245.
47. Weber, A.; Thewes, F.R.; Sellwig, M.; Brackmann, A.; Wünsche, J.N.; Kittemann, D.; Neuwald, D.A. Dynamic Controlled Atmosphere: Impact of Elevated Storage Temperature on Anaerobic Metabolism and Quality of 'Nicoter' Apples. *Food Chemistry* **2019**, *298*, 125017, doi:10.1016/j.foodchem.2019.125017.
48. Weber, A.; Neuwald, D.A.; Kittemann, D.; Thewes, F.R.; Both, V.; Brackmann, A. Influence of Respiratory Quotient Dynamic Controlled Atmosphere (DCA – RQ) and Ethanol Application on Softening of Braeburn Apples. *Food Chemistry* **2020**, *303*, 125346, doi:10.1016/j.foodchem.2019.125346.
49. de Oliveira Anese, R.; Brackmann, A.; Wendt, L.M.; Thewes, F.R.; Schultz, E.E.; Ludwig, V.; Berghetti, M.R.P. Interaction of 1-Methylcyclopropene, Temperature and Dynamic Controlled Atmosphere by Respiratory Quotient on 'Galaxy' Apples Storage. *Food Packaging and Shelf Life* **2019**, *20*, 100246, doi:10.1016/j.fpsl.2018.07.004.
50. Ludwig, V.; Thewes, F.R.; Wendt, L.M.; Berghetti, M.R.P.; Schultz, E.E.; Schmidt, S.F.P.; Brackmann, A. Extremely Low-Oxygen Storage: Aerobic, Anaerobic Metabolism and Overall Quality of Apples at Two Temperatures. *Bragantia* **2020**, *79*, 458–471, doi:10.1590/1678-4499.20190496.
51. Wendt, L.M.; Ludwig, V.; Rossato, F.P.; Berghetti, M.R.P.; Schultz, E.E.; Thewes, F.R.; Soldateli, F.J.; Brackmann, A.; Both, V. Combined Effects of Storage Temperature Variation and Dynamic Controlled

Atmosphere after Long-Term Storage of 'Maxi Gala' Apples. *Food Packaging and Shelf Life* **2022**, *31*, 100770, doi:10.1016/j.fpsl.2021.100770.
52. Thewes, F.R.; Brackmann, A.; Neuwald, D.A. Dynamic Controlled Atmosphere Method and Apparatus 2022. Pending US Patent Application. Pub. No.: US 2022/0282883 A1
53. Anese, R. de O.; Brackmann, A.; Thewes, F.R.; Schultz, E.E.; De Gasperin, A.R. Mass Loss by Low Relative Humidity Increases Gas Diffusion Rates in Apple Flesh and Allows the Use of High CO2 Partial Pressures during Ultralow O2 Storage. *Scientia Horticulturae* **2016**, *198*, 414–423, doi:10.1016/j.scienta.2015.12.015.
54. Köpcke, D. 1-Methylcyclopropene (1-MCP) and Dynamic Controlled Atmosphere (DCA) Applications under Elevated Storage Temperatures: Effects on Fruit Quality of 'Elstar', 'Jonagold' and 'Gloster' Apple (Malus Domestica Borkh.). *European Journal of Horticultural Science* **2015**, *80*, 25–32, doi:10.17660/eJHS.2015/80.1.4.
55. Satekge, T.K.; Magwaza, L.S. Postharvest Application of 1-Methylcyclopropene (1-MCP) on Climacteric Fruits: Factors Affecting Efficacy. *International Journal of Fruit Science* **2022**, *22*, 595–607, doi:10.1080/15538362.2022.2085231.
56. Neuwald, D.A.; Kittemann, D. The Incidence of Neofabraea Spp. in 'Pinova' Apples Can Be Reduced at Elevated Storage Temperatures. *Acta Horticulturae* **2016**, *1144*, 231–236, doi:10.17660/ActaHortic.2016.1144.34.
57. Geyer, M.; Praeger, U.; Truppel, I.; Scaar, H.; Neuwald, D.A.; Jedermann, R.; Gottschalk, K. Measuring Device for Air Speed in Macroporous Media and Its Application Inside Apple Storage Bins. *Sensors* **2018**, *18*, 576, doi:10.3390/s18020576.
58. Hoffmann, T.; Mahajan, P.; Praeger, U.; Geyer, M.; Sturm, B.; Linke, M. Small Peltier Element to Detect Real-Time Heat Flux between Apple and Environment during Postharvest Storage. *Computers and Electronics in Agriculture* **2023**, *213*, doi:10.1016/j.compag.2023.108247.
59. Jedermann, R.; Singh, K.; Lang, W.; Mahajan, P. Digital Twin Concepts for Linking Live Sensor Data with Real-Time Models. *Journal of Sensors and Sensor Systems* **2023**, *12*, 111–121, doi:10.5194/jsss-12-111-2023.