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# Investigations into the pre-cooling rates of apples in controlled atmosphere storage chambers

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## Abstract

The objective of the present investigation was to model the rate of cooling of apples in a fruit storage unit using forced air pre-cooling. Apples of Royal, Red, Rich-a-red and Golden Delicious were procured from Shimla and Royal Delicious from the Kinnaur region of Himachal Pradesh, India. Apples were transported in refrigerated and non-refrigerated vehicles. After grading and sorting on a fully automatic machine, the apples were subjected to a cooling process. Apples were placed in perforated plastic crates and stacked in a controlled atmosphere chamber of 720 $m^3$ capacity. Temperature profiles of apples were recorded with a programmable logic controller connected to sensors. The effect of variety, initial apple temperature, and fruit quantity per chamber on the cooling rate were investigated. Initial fruit temperature significantly affected the cooling time. The apple variety did not significantly affect the cooling time, except that slow cooling was observed for golden delicious in the last cooling stage. Varied masses of apples resulted in a proportionate increase in cooling time. Cooling times are 132, 113, 78, and 65 hours for a mass of 165, 150, 140, and 130 Metric Tons (MT), respectively. Correlation coefficients ranged from 0.970 to 0.979 for different varieties. The rate of cooling with apple mass was modeled with linear, exponential and polynomial and found to best fit with the exponential model with $R^2$ values of 0.99, 0.96, 0.95, 0.966 for 165, 150, 140, and 130 MT, respectively. The times taken to cool 150 MT of apples were 97, 114, and 147 hours from an initial temperature of 35.2, 28.4, and 15.6°C, respectively. The drop rate was exponential, with $R^2$ values in the range of 0.936 to 0.973.

**Key words**: Apple (*Malus Domestica Borkh*), pre-cooling, cooling kinetics, unsteady state, controlled atmosphere storage (CAS)

## Introduction

Effective postharvest management of apples is crucial for maintaining quality and extending shelf life. As harvested fruits undergo physiological changes driven by respiration, managing these changes becomes essential to prevent losses (Kader, 2002). Cooling is a fundamental technique to regulate respiration and minimize deterioration, moisture loss, and shrinkage (Singh, 2010). This is particularly important for apples, a significant Indian crop grown predominantly in Himachal Pradesh, Jammu and Kashmir, and Uttarakhand. Pre-cooling, performed promptly after harvest, is a key practice in apple postharvest management. It reduces moisture loss, delays texture softening, and maintains desirable Total Soluble Solids (TSS) levels. Pre-cooling also sets the stage for sorting, grading, and packing, all contributing to improved overall quality. Controlled Atmosphere (CA) storage chambers offer an avenue for refining pre-cooling (Singh, 2010).

Ripening immediately after harvest can be reduced by immediate pre-cooling. Pre-cooling reduces the fruit temperature to 0-5°C, which controls the rate of biochemical reactions. The temperature can be brought down by using Forced-air cooling. The packaging design must be appropriate for heat transfer between the produce and the medium. Packaging design characteristics affect both rates of cooling and uniformity of cooling. Packing designs are well-documented for fruits like pomegranate (Ambaw *et al.*, 2017), citrus (Wu *et al.*, 2018). Several numerical models are reported in the literature. Hussain *et al.* (2021) compared the numerical and experimental values during forced air cooling of apples and oranges.

Heat and mass transfer occur simultaneously during the pre-cooling process. The temperature of the produce and medium, moisture evaporation from produce, and interaction of water and fruit moisture content in the case of hydro-cooling will affect the mass transfer characteristics. Dehghannya *et al.* (2010) reported the heat and mass transfer phenomenon and mathematical modeling procedures during forced air cooling of produce through a review article. Thermal properties significantly influence the cooling process. da Silva *et al.* (2018) reported changes in the thermal properties of bananas during cooling. The type of packaging significantly affects the rate of heat transfer. During the artificial ripening of fruits, partial cooling is done before setting the stage for ethylene-induced ripening. The latest reports on the rate of cooling are available for mangoes (Rao *et al.*, 2020b), bananas (Rao *et al.*, 2020a), and pineapples (Rao *et al.*, 2021). Ripening systems and cooling equipment for mangoes and bananas are designed to suit a higher temperature range of 10 to 25°C (Babu *et al.*, 2019).

Silva *et al.* (2006) studied the pre-cooling effect on apples using forced air and water cooling. Their efficacy has been compared. Half-cooling times (HCT) are predicted as a function of apple diameter. Water cooling was two times faster than air cooling in terms of cooling time. The varieties and positions of apples did not significantly affect the cooling rate during water cooling. However, HCTs of forced air cooling are significantly affected by the variety and position of apples. Their results can be useful in predicting HCTs for apples but cannot be generalized for other fruits. Serdyuk *et al.* (2016) reported the methods of pre-cooling pears and plum fruit. High air velocity resulted in more moisture loss in fruits in the order of 0.56 % for pear and 0.44 % for plum. Out of three methods, combined with initial cooling in antioxidant solutions and air cooling resulted in the least moisture loss in fruits.

The weight loss was 0.005 % for plums and 0.014% for apples and pears. Vigneault *et al.* (2004) studied the design of plastic containers for optimized pre-cooling using forced air for fruits and vegetables. They have developed different plastic containers for fruit handling and pre-cooling. Wall openings were designed to suit multi-purpose use. They found the opening surface area should be at least 25 % of the container wall for better results. The pressure loss was significant when the opening surface area was less than 25%. Teruel *et al.* (2004) reported size of fruits and vegetables affect cooling parameters during hydro cooling.

Mango, guava, orange, lemon, plum, orange melon, acerola, cucumber, carrot, and green bean were hydro-cooled to 1$^{o}$ C. Cooling time was proportional to produce volume. Volumes tested ranged from 8.18 $cm^3$ to 1150.35 $cm^3$ for fruits and 13.06 $cm^3$ to 438.4 $cm^3$ for vegetables. Cooling time ranged from 8.5 to 124 minutes for fruits and 1.5 to 55 minutes for vegetables. The cooling rate was affected by the medium used for cooling *i.e.*, air, water and ice. Evaporative cooling is another method used to preserve fruits and vegetables by cooling (Lal Basediya *et al.*, 2013). The rate of water evaporation and wetted thickness affects the cooling rate (Liberty *et al.*, 2013).

The data on the cooling rates of Indian varieties of apples is not found in the literature. The present investigation was conducted to study the effect of variety, mass, and initial fruit temperature of apples on cooling rates and to model the cooling curve with appropriate mathematical models.

## Materials and methods

**Apples:** Royal Delicious, Red Delicious, Rich-a-Red and Golden Delicious were procured from well-maintained orchards from the Khandaghai region of Shimla district and Recong Peo of the Kinnaur district of Himachal Pradesh. Upon receipt to the pre-cooling center, apples were checked for quality parameters like firmness, TSS and maturity index. Apple lots with a minimum of 20 Lbs firmness and a 2.5 Maturity Index (maximum on a five-point Maturity Index scale) were used for the study.

**Sorting-grading:** A fully automatic grading machine was used to grade apples. Fruits received in 20kg standard telescopic corrugated fiberboard were unloaded onto the soft rubber roller conveyors of the grading machine. Apples with surface defects were removed from the sorting table manually. The grading program was controlled by software (M/s Ellipse) integrated through Profibus and a computer. The Hunter scale L, a, b, hue, and saturation set the color grading parameters. The capacity of the grading line was 10MT per hr.

**Temperature measurement and Data logger:** The temperature was recorded with a sensor (M/s Carel, Italy) connected to a central monitoring system for logging the data with an alarm system (Plantvisor$^{TM}$). The central control system monitors and controls the temperature of the chambers.

**CA Chamber:** Chambers were made of stainless steel sheets with 100 mm thick Polyurethane insulation panels and were sealed with special elastic paint for gas tightness. The floor was insulated with 60mm thick polystyrene slabs. A moisture barrier sheet was present between the layers. The door was made of 100mm thick sandwich PUF panels. The chamber was sealed using elastic paint for all panel joints (M/s Ribbstyle). The door was semi-hermetically sealed using double neoprene gaskets. The floor joint of the door was fixed with a jack.

**Storage bins:** Each perforated plastic bin was 1200 x 1000 x 760 mm and carried 300 kg of apples. Bins were stacked up to nine in height. Sufficient ventilation holes were provided on the surface of bins for the free movement of cool air through apples.

## Results and discussion

**Effect of variety on cooling rate:** The cooling of all four apple varieties under the same conditions is shown in Table 1. The temperature decreased from 28$^{o}$C to 1$^{o}$C exponentially. The time taken for pull-down was 113 hrs for Royal, Red, and Rich-a-Red and 127 hrs for Golden. The rate of cooling was modeled with an exponential mathematical equation. The correlation coefficient values ranged between 0.924 and 0.977 for all varieties. Cooling time was almost the same for Royal, Red and Rich-a-Red. This may be due to these three varieties' similar sensible heat load. However, the Golden variety took longer than the other three varieties. This may be due to this variety's higher latent heat and or respiration heat. Golden Delicious variety was susceptible to quicker ripening (Ramesh Babu *et al.,* 2018). The rate constant of the exponential model was -0.02 for all four varieties. It is evident from the results that the effect of apple variety on pre-cooling time is not significant.

Table 1. Forced air cooling of four varieties of apple varieties Mass 150MT, Exponential equation: $T = 28\ e^{kt}$ . T = temperature in $^{o}$C, t = cooling time in hours, k = Exponential model constant.

| Variety | Cooling time (hr) | Exponential model parameter (k) | $R^2$ |
|---|---|---|---|
| Royal Delicious | 113 | -0.02 | 0.977 |
| Red Delicious | 113 | -0.02 | 0.979 |
| Rich-a-Red | 113 | -0.02 | 0.924 |
| Golden Delicious | 127 | -0.02 | 0.977 |

**Effect of apple mass on cooling rate:** The cooling rates of 165 MT of apples can be seen in Fig. 1. The temperature drop rate has been modeled with three mathematical models. The second-order polynomial model fitted the best with an $R^2$ value of 0.970 between experimental and predicted values. The time taken to achieve desired storage temperature was substantially higher than the 130MT quantity. This may be due to the high sensible heat load on the refrigeration unit. The coefficient of the exponential model was found to be -0.02.

Fig. 2 shows the model fitting between experimental and predicted values of three models, *i.e.*, linear, exponential, and second-order polynomial models for 150MT quantity of Royal variety. The best fit was found with an exponential model with an $R^2$ value of 0.970. The exponential model explains the cooling behavior with a kinetic coefficient of -0.02.

Fig. 3 reports the fitting curves for three models tested for the

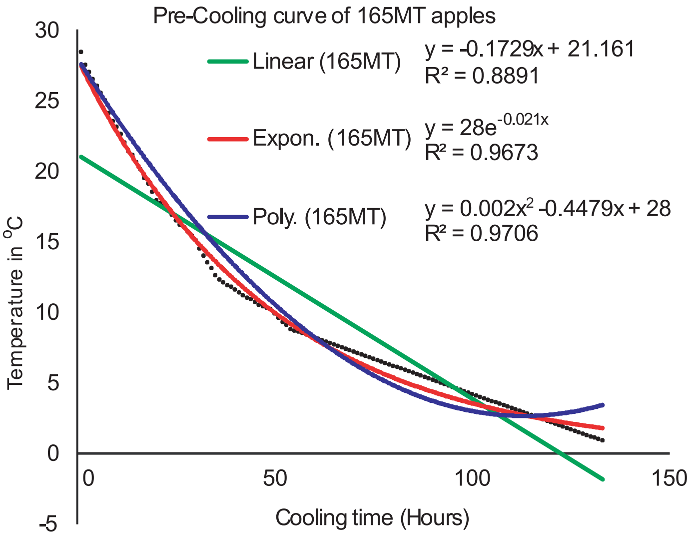


Fig. 1. Mathematical modeling of 165MT of Royal Delicious apples using linear, exponential and polynomial equations. Experimental values (••••••)

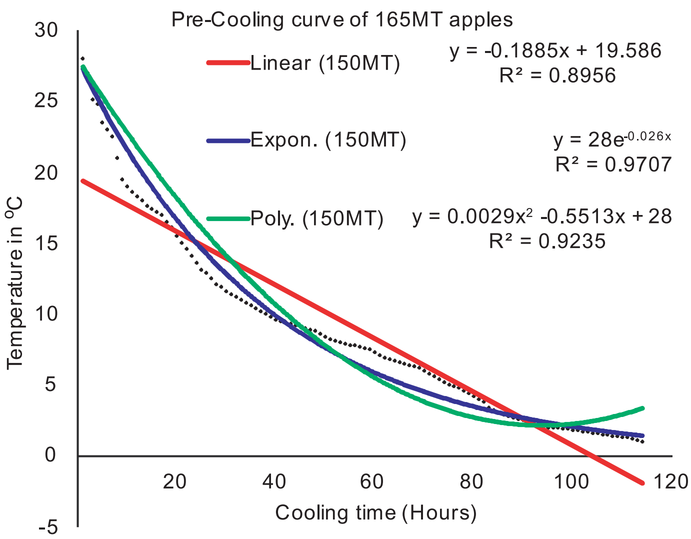


Fig. 2. Mathematical modeling of the cooling curve of 150MT Royal delicious apples. Experimental values (•••••••)

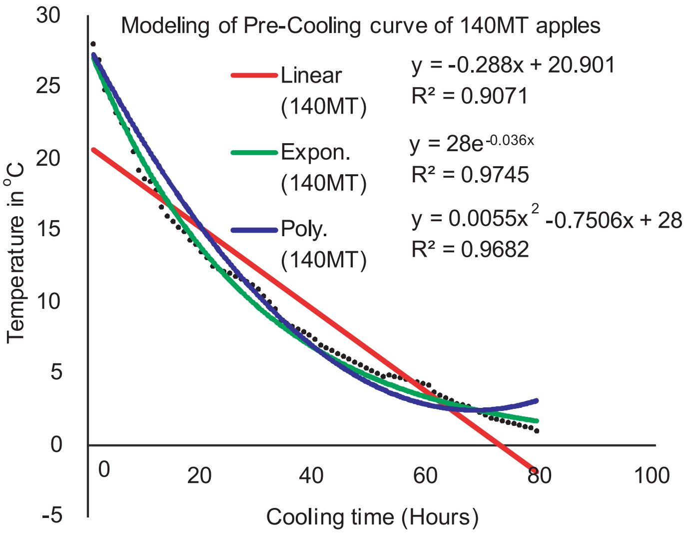


Fig. 3. Mathematical modeling of cooling data of 140MT apples. Experimental values (•••••••)

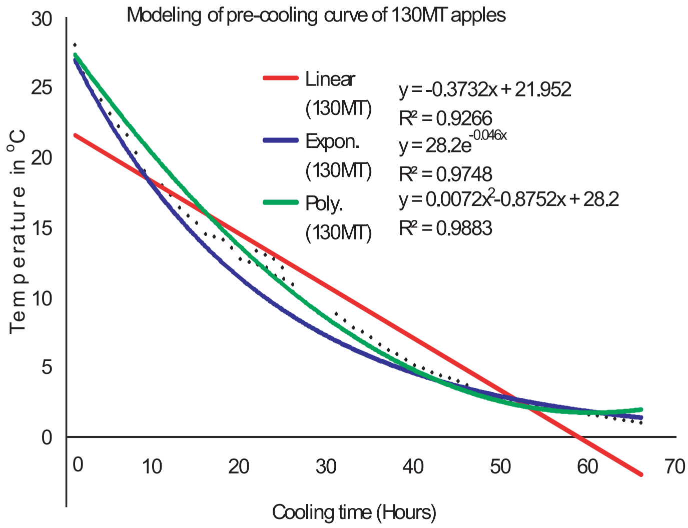


Fig.4. Mathematical modeling of the cooling curve of 130MT apples. Experimental values (•••••••)

cooling data of 140MT apples. The highest $R^2$ value of 0.974 was found with an exponential model with a kinetic constant of -0.03. The lowest fit was found with a linear model with $R^2$ value of 0.907. The behavior of the cooling curve has been best explained with the exponential mathematical model.

The rate of cooling of 130MT quantity with modeled data with linear, exponential, and polynomial models can be seen in Fig. 4. Out of the three models tested; the polynomial model fitted the best with an $R^2$ value of 0.988. The second-best model was exponential, with the $R^2$ value of 0.974. As expected, the time taken for cooling to the desired temperature was the lowest compared to 140, 150 and 165MT. This may be due to the low sensible heat load comparatively.

Different apple quantities were pre-cooled under similar refrigeration capacities and chamber dimensions differed in the cooling time (Fig. 5). The time taken for pull-down was 132, 113, 78, and 65 hours for an apple mass of 165, 150, 140, and 130 MT, respectively. The higher the mass of apples, the longer the cooling time to reach the set point of 1 °C. Quick cooling to the holding temperatures is always desirable for better shelf life and quality retention. However, the capacity of the CAS will be

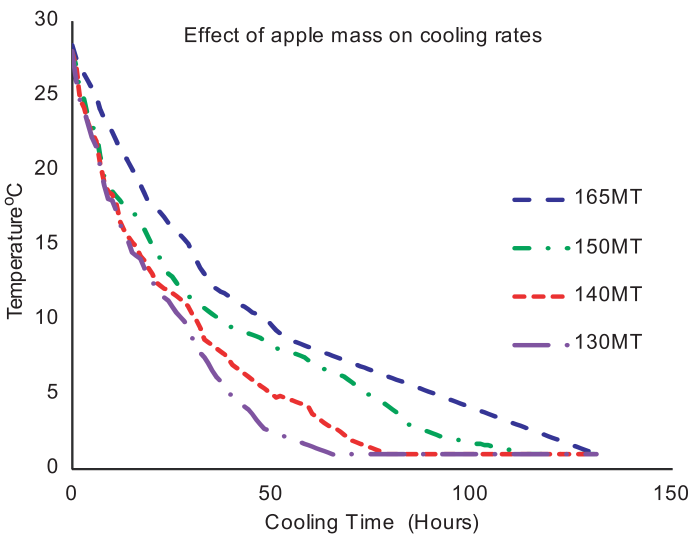


Fig. 5. Effect of apple mass on cooling rates of Royal delicious apples.

limited if 130MT quantity is stored to benefit from shorter cooling time. It is required to strike a balance between cooling time and storage capacity. Silva *et al.* (2006) reported similar trends on mass's effect on apples' half-cooling time and concluded that water cooling is twice faster than forced air cooling.

**Effect of fruit initial temperature on cooling rate:** The initial temperatures of apples are shown in Fig. 6. It took 97, 114, and 147 hr to cool from initial temperatures of 35.2, 28.4, and 15.6 ºC, respectively. Kinnaur apples transported in reefer containers at 15.6 ºC took the lowest time to reach the holding temperature. Shimla apples with an initial temperature of 35.2ºC, took the longest cooling time. This may be due to the sensible heat required to be removed from apples. The drop rate was exponential with $R^2$ values in the range of 0.936 to 0.973. The exponential model coefficient was comparable with the experiment conducted with different varieties with 150MT of apple quantity. Similar pre-cooling trends were reported by Wu *et al.* (2018) for lemon and oranges with different fruit size, package types and wrapping. Experiment duration ranged from 40.3 to 93 hours and average initial fruit temperatures ranged between 14.9 to 22.7ºC. Very few results were reported in the latest literature on full-scale forced air cooling of fruits.

Apple mass and initial temperature significantly affected the cooling time. The experimental results on cooling rates for different varieties, quantities, and initial temperatures will help design suitable systems for the commercial storage of apples and deciding on quick pre-cooling storage. Cooling time can be predicted with mathematical models. The modeled parameters are useful for all apple cold store operators for pre-cooling and storage planning.

Temperature plays an important role in controlling respiration rate, thereby associating mechanisms of pectin degradation, transpiration and firmness loss. Cooling of fruits immediately after harvest is a critical requirement for controlling temperature-regulated biochemical changes. Apples need to undergo pre-cooling before preserving in cool/ controlled atmosphere storage. Major apple-producing states in India are Himachal Pradesh (HP)

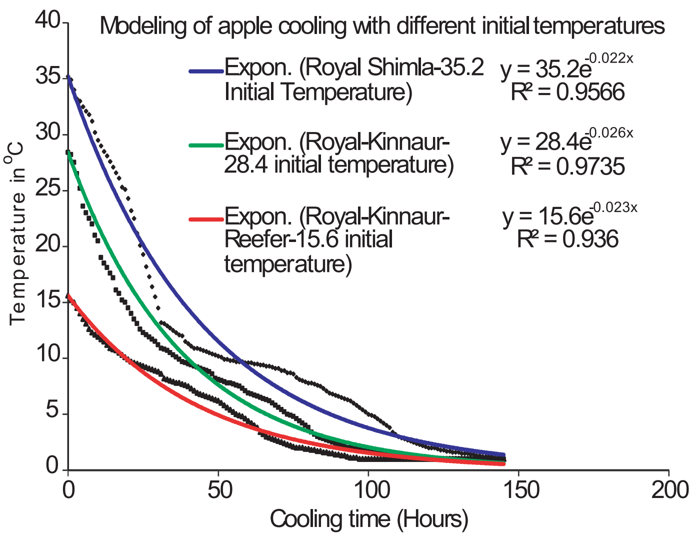


Fig. 6. Mathematical modeling of cooling of Royal Delicious apples at different initial temperatures. Experimental values are indicated with (•) for Royal-Shimla, (▪) for Royal-Kinnaur and (▲) for Royal-Kinnaur Reefer.

and Jammu & Kashmir (J&K), which have difficult terrain and almost negligible pre-cooling facilities are constructed in both these states. Some facilities are located in Delhi and Haryana, which are major storage locations for Indian apple varieties. Apples are shifted from orchards of HP and J&K to far distances of 300-600 km. The difficult terrain and road infrastructure make hurdles for the transportation of apples in temperature-controlled vehicles, *i.e.* sealed containers with refrigeration facilities. Typical temperatures for apple cooling range from 0 to 5 ºC.

The current experimental results reveal that the effect of variety is a negligible effect of apple mass is significant, the effect of initial temperature and quality is associated with storage. The cooling rate trend and data fitting to different models are comparable to the earlier report of Rao *et al.* (2020b). However, the temperature range was slightly different for the mangoes they reported. In apple case, the set point is lower than the temperatures needed for mangoes.

The ambient/apple temperatures of the Shimla district are higher than the Kinnaur region, which led to a slow pre-cooling process at the pre-storage point. Establishing pre-cooling facilities in the Shimla district is imperative to enhance the preservation of apples. This region should prioritize the development of infrastructure that enables farmers to pre-cool their produce and facilitate the transportation of fruits using refrigerated containers, trucks, or reefers. While Kinnaur benefits from naturally lower ambient temperatures compared to Shimla, the immediate necessity for pre-cooling facilities and refrigerated transport might not be as critical.

The effect of variety, initial apple temperature, and fruit quantity per chamber on the cooling rate was investigated and modeled. The initial fruit temperature affected the cooling time. The time taken to cool the apples from initial temperatures of 35, 28, 15.6 to 1ºC was 147 hr to 97 hr. Different varieties did not significantly affect the cooling time, except for the slow cooling of Golden Delicious during the last cooling stage. A varied mass of apples resulted in a proportionate increase in cooling time. Cooling times were 132, 113, 78, and 65 hrs for 165, 150, 140, and 130 Metric Tons (MT) quantities. Correlation coefficients of fitted models ranged from 0.970 to 0.979 for different varieties but were not significantly different among varieties. The time taken to cool 150MT apples was 97, 114, and 147 hrs from an initial temperature of 35.2, 28.4, and 15.6 ºC, respectively. The drop rate was exponential, with $R^2$ values in the range of 0.936 to 0.973. The cooling rate with different apple masses has been modeled with linear, exponential and polynomial equations. Exponential models fitted with $R^2$ values of 0.99, 0.96, 0.95, and 0.966 for 165, 150, 140, and 130 MT quantity, respectively. Further studies can be taken up to find the effect of cooling time on the quality parameters of apples after storage, especially firmness.

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