Why Do We Treat Flowers the Way We Do? A System Analysis Approach of the Cut Flower Postharvest Chain

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Abstract

Although temperature is one of the most important factors in the post-harvest chain to control quality losses of cut flowers, decisions related to temperature management are often poorly underpinned. The effects of temperature on some physiological, physical and phytopathological processes involved in quality loss are described, with special attention to rate of senescence, infection by *Botrytis cinerea* and placing flower stems in water. Senescence-temperature relations were fitted using data from a literature survey. It was obvious that sensitivity of senescence rate to temperature is rather different between flower species. Gerbera, jonquil and rose showed a maximum rate of senescence that was reached at about 20°C. Germination of *Botrytis* conidia showed an exponential relation with temperature. At 5°C it took more than 10 hrs before 50% of conidia were germinated in a nutritient solution. On rose petals it took much longer. A 2-hrs dry period during incubation of conidia inhibited germination during the subsequent period in water, indicating that previous conditions in a post-harvest chain will affect the consequence of condensation on *B.* infection. The reasoning of putting cut flower stems in water during storage and transport was questioned. When flowers are placed in water, the temperature of this water should be low. In some simulation experiments, using a preliminary model, the effect of specific temperatures in some hypothetical chains were analysed. It was shown that in short local chains the short duration of the chain is of more importance than its temperature. Because of relatively high temperatures (≥15°C) often found in these local chains, the risk of *Botrytis* at the consumer (germination of conidia at the end of the transport phase) is rather high. Therefore, a constant temperature seems to be of more importance than a low temperature. After an international distribution chain of 86 hours the expected vase life at the final consumer will be acceptable when the temperature during most of the transport links (with a long duration) is below 10°C. Especially conditions during sorting were very critical for *B.* infection. It was discussed that the outcomes of the simulations had only a limited meaning, because of simplifications in the model and the lack of sound data. Experiments about temperature effects on quality, however, could be more generally useful when they are designed with the objective to generate parameters for quality simulation models.

INTRODUCTION

The cut flower market has become a real globalized market. For example, at Dutch flower auctions some 30% of the current cut flower volume traded originates from outside the country, and more than 80% of the flowers and plants are exported. As a result, cut flowers are transported for several days or even weeks over various distances. In these supply chains several links (partners) will be involved, often with different environmental conditions. Transport and handling in the chain will affect the quality of the flowers at the final consumer. Until now, there have been rarely critical analyses of these chains to identify the principal sites of quality loss and their relative importance. To ensure a certain quality of the flowers at the final consumer, and to prevent investments without a

clear positive return, we should investigate where the critical control points for quality are in the production and distribution chain. Temperature is one of the most important factors in the post-harvest phase to control quality losses (Goszczyńska and Rudnicki, 1988; Nell and Reid, 2000; Kader, 2002), yet temperature management in commercial flower chains is still poorly underpinned. Temperature affects as well physiological (development and senescence of flowers, wound responses) as physical (water loss, condensation/drying) processes involved in quality loss. Moreover, also pathogens like *Botrytis* (germination rate of conidia, flower-petal resistance against *B.* growth) are affected by temperature. Sometimes physiological, physical and pathogen related quality effects of temperature (changes) are opposite. Moreover, although we may expect that physiological processes, such as senescence rate, will be lowered by lowering the temperature, the lowest temperature to obtain the lowest rate of a physiological process doesn't have to be the most economical profitable treatment. The final result of temperature (fluctuations) in the post-harvest chain on quality of the flowers will depend on the duration of the (links of the) chain. Due to the complexity, simulation models may be good tools to identify the critical points for quality management by temperature control. In this paper, some thoughts and possibilities to simulate the effects of temperature management on quality in the cut flower post-harvest chain are described and some outcomes of applying a preliminary model to hypothetical chains (scenarios) are discussed in relation to the critical control points in these chains.

KEY PROCESSES AND ASSUMPTIONS

The effect of temperature on the rate of flower senescence will be one of the most important parts of a model to simulate the effects of temperature during the post-harvest phase on flower quality for the final consumer. The model used for the studies in this paper was based on the assumption that flower senescence is a developmental process from stage zero (commercial harvesting stage) to unity (senescent stage ≈ end of vase life) with a rate that is affected by temperature but not by the developmental stage of the flower.

For most cut flowers, infection of flower petals by the fungus *Botrytis cinerea* is one of the main causes of quality loss in the post-harvest chain. Spread of a large number of necrotic spots on the flower petals or total collapse of the flower will be the end of vase life, whatever the development stage of the flower is. Different steps are critical in the infection process: germination of conidia, penetration of the petal tissue, killing of petal tissue followed by lesion expansion and tissue maceration (van Kan, 2006). It can be expected that the rates of these processes are temperature dependent. Conidia of *Botrytis* need a very high relative humidity (>93%) or a thin layer of water to germinate (Salinas et al., 1989). Temperature changes, which will occur in the post-harvest chain, affect air humidity (vapour pressure) and can cause condensation on plant tissue or packaging materials as well as drying of the petal and packaging surfaces. As a result there can occur periods of different lengths with high air humidity or free water on the petals. The temperature of condensed water will affect the germination rate of the conidia. It may also be expected that a period without the presence of water on the petals, following a short period of water-presence, will affect the germination during a subsequent period of high humidity or condensation.

Many flowers do not reach the fully senesced stage at the consumer because of loss of sufficient ornamental value due to a negative water balance of the flowers, that is, their rate of water uptake becomes lower than the transpiration rate. The negative water balance is due to an occlusion in the xylem vessels in the stems (van Meeteren, 1989, 1992; van Meeteren et al., 2006). The occlusion can be caused by (i) growth of bacteria on the cut stem surface or in the xylem vessels, (ii) wounding induced enzymatic reactions in the stem tissue as part of a plant defence mechanism, or (iii) presence of air in the xylem vessels that is aspired directly after cutting or during dry storage of the cut flower stems (van Doorn, 1997). For all three causes the effect will be diminished by a low water temperature when cut stems are placed in water. However, already present

bacteria or formed plant wounding-defence-metabolites will not disappear because of a low water temperature.

A transient water deficit in flower tissues could hasten the senescence process of flowers (Mayak et al., 1985; Mayak and Faragher, 1986). When flowers are dry stored or transported, the occurrence and extent of a water deficit will be related directly to the transpiration rate times time. Transpiration is a physical process driven by vapour pressure deficit between the flower tissue and its environment. The vapour pressure deficit is a result of humidity in the air surrounding the flower, the temperature of this air and the temperature of the flower. The resistance for water to leave the flower is a result of flower properties and the velocity of possible air movement around the flower. In most commercial flower chains, air velocity around the flowers will be low due to packaging, and humidity within the packages will be high. Because of this, transpiration rate will be low. Exceptions can be in coolers, during pre-cooling, sorting and (un)loading of trucks and airplanes.

Condensation of water on flower petals or on the surface of packaging material like sleeves will happen when near the petal or sleeve surface the maximal vapour pressure at the surface temperature is reached, mostly due to a temperature difference between the surfaces (petal or sleeve) and the air surrounding the flowers. Often this will happen when the environmental temperature is changed. Evaporation of water present on petal or sleeve surfaces will start as soon as the vapour pressure near the surfaces is below the maximal vapour pressure.

METHODS

Flower Senescence

To obtain data about the effect of temperature on senescence rate a literature survey was performed. However, published data on senescence-temperature relationships of cut flowers are rather limited. The data used in the present simulations are from experiments describing the effect of a storage period of a fixed length at various temperatures on the subsequent vase life for gerbera and sunflower (Çelikel and Reid, 2002), 'Jonquil' and 'Paper White' narcissus (Cevallos and Reid, 2000), rose 'First Red' and Gypsophila (Çelikel and Reid, 2005), and daffodil, iris and carnation (Cevallos and Reid, 2001). Senescence rate, k_s [day^{-1}], at a specific temperature T_s [K] was defined as

$$k_s = \frac{Q_{ref} - Q_s}{Q_{ref}} * \frac{1}{t_s} \quad (1)$$

where Q_{ref} [days] is the length of the vase life at 20°C without storage, Q_s [days] is the vase life after a storage period at T_s and t_s [days] is the length of the storage period. To obtain the effect of temperature on senescence rate, relationships between k_s and T_s were fitted with linear and non-linear regression using GraphPad Prism version 5.00 for Windows, GraphPad Software, San Diego, California, USA. For non-linear regression equations (2) and (3) were used. In equation (2) it is assumed that the rate of senescence is determined by a single rate-controlling enzyme reaction and is based on the Arrhenius equation for the rate of a chemical reaction as function of temperature:

$$k_s = k_{ref} . e^{\frac{E_a}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T_s} \right)} \quad (2)$$

k_{ref} [day^{-1}] is the rate of senescence at the reference temperature (20°C ≈ 293.15 K), E_a [J mol^{-1}] is the 'activation energy' of the senescence process, R is the universal gas constant (8.314 J mol^{-1} K^{-1}) and T_{ref} is the reference temperature (293.15 K). Equation (3) is a general sigmoidal dose-response equation with variable slope; it assumes that at a certain temperature a maximum senescence rate is reached.

$$k_s = \frac{k_{\max}}{1 + 10^{(T_{half} - T_s).slope}} \quad (3)$$

k_{max} [day^{-1}] is the maximum rate of senescence, T_{half} [K] is the temperature at which the senescence rate is half of k_{max} and slope [K^{-1}] describes the steepness of the curve.

Botrytis

Experiments about the rate of germination of conidia at different temperatures were performed. By exposing the conidia to a dry period, at various moments after the imbibition of conidia was started, followed by re-applying water, the effect of intermittent condensation on conidia germination was investigated.

1. Conidia Germination. Conidia of a *Botrytis* isolate were provided by the Laboratory of Phytopathology of Wageningen University. Temperature effects on germination rate were investigated in vitro: 5 µL droplets of PDB solution (12 g L^{-1} Potato Dextrose Broth) with 10^5 conidia mL^{-1} on a microscope glass slide were put into Petri-dishes with moistened filter paper and placed at 2, 5, 10, 12.5, 15 and 20°C. There were 3 replicates for each temperature. Germinated conidia were counted under a microscope at regular time intervals (adapted to the temperature used).

2. Germination after Interrupted Presence of Water. The consequence of an interruption of the germination process by a dry period was investigated at 20°C in vitro and in vivo. In vitro: 10 µL droplets of PDB solution with 10^5 conidia mL^{-1} on a microscope glass slide were placed in Petri-dishes with moistened filter paper. After 1h, 2h or 3h after the start of the experiment, the glass slides were exposed to a flow of dry air (air velocity 1 m^3 s^{-1}) to evaporate the water. The 10 µL water was evaporated in about 30 minutes. After a dry period of 2 hours 10 µL of PDB solution was re-supplied to the conidia on the glass slides. Germinated conidia were counted under a microscope with a one hour interval from the beginning of the experiment except during the 2-hours dry period. In vivo: One-cm petal discs of 'Passion' roses were inoculated with 10 µL of conidia suspension in water (10^4 conidia mL^{-1}). The discs were placed in Petri-dishes with moistened filter paper. After 5, 8 or 10 hrs after the start of the inoculation the conidia were exposed to a dry period of 2 hours (in the way described above for in vitro); thereafter 10 µL sterilized water was applied at the same spot where conidia were inoculated. Numbers of lesion spots were counted 16 hrs after the re-incubation.

Stem Hydraulic Conductivity

Experiments with cut chrysanthemum stems were conducted to investigate the role of water temperature on the rate of wounding induced xylem blockage. Stems were cut under water to prevent air uptake, and placed for 24hrs in water of 20°C or 5°C (air temperature in both cases 20°C). After this period stem hydraulic conductivity was measured as described by van Ieperen et al. (2000).

Model

To have the possibility for some scenario studies about effects of various temperature-time combinations in hypothetical chains on vase life, a preliminary model was developed. Only part of the above mentioned possible key processes were implemented. Driving forces in the model were the air temperature and humidity. Flower temperature was simulated using the air temperature and taking into account a heating and cooling delay because of heat transport processes and heat capacity of the flower. Heat production by the flower as result of respiration was not taken into account. Flower temperature was assumed to control the rate of flower senescence. Using flower temperature, air temperature and air humidity the occurrence of condensation and evaporation of condensed water was simulated. The temperature of condensed water was assumed to be the dew point temperature at which condensation took place. Germination processes of *Botrytis* conidia were assumed to start as soon as condensation started, and to take place at the calculated water temperature. The effect of temperature on germination

rate of conidia was implemented in the model. When water is evaporated before germination is finished it was assumed that the conidia were not germinated; successive periods with the occurrence of condensation were treated separately. Vase life was assumed to be finished when germination of conidia occurred. In the model it was assumed that no water stress occurred in the flowers, nor that there was any problem with water uptake by the flower stems at the consumer. To simulate a chain with several links, a link of the chain was treated as a module. At the start of a link flower temperature, flower senescent (development) stage and the presence or absence of condensed water at the end of the previous link were used as starting values. It was assumed that within a link air temperature and air humidity stayed constant. At the end of the transport chain the remaining vase life at the consumer was calculated using the simulated senescent stage and the potential vase life of the specific flower at harvest. The model was implemented using Powersim Studio Academic 2003, Powersim Software AS, Norway.

RESULTS AND DISCUSSION

Flower Senescence – Temperature Relations

There was a large difference in senescence rate between the various flowers (Fig. 1). The *Narcissus* (Jonquil, Paper White, Daffodil), iris and Gypsophila were flowers with a high rate of senescence at 20°C, while gerbera and 'First Red' rose had the lowest rate of senescence. The senescence rate of gerbera was not very sensitive to temperature. The effect of temperature on senescence rate in sunflower and roses was moderate as compared to the other reported flowers. A linear regression fitted rather well to describe the effect of temperature on senescence rate for most of the tested flowers, except for gerbera and Gypsophila (Table 1, Fig. 1). For sunflower the residuals of a linear regression, however, were not normally distributed (according to the D'Agostino and Pearson omnibus normality test). For gerbera, jonquil, iris and carnation the number of data was too small to test the normality of the residuals. The low r^2 for a linear regression for Gypsohila relative to the values for the other flowers was due to the wider temperature range for which data were available (for Gypsophila more data points at low temperatures). Using equation (2) (the Arrhenius type) for the fitting procedure did not improve the low r^2 for gerbera but improved the r^2 for Gypsophila largely; for the other flowers there was no consistent change in r^2 as compared with the linear regression. Using equation (3) (a sigmoidal relation) improved the r^2 for gerbera and Gypsophila and resulted in higher r^2 for most of the other flowers (except sunflower and carnation) as compared with the linear regression. The number of data and most of the temperature regimes were too small to base a decision about the regression relation for specific flowers. Because of the general applicability of the sigmoid function (equation (3)) we used this in the model. The sigmoid implies that there is a maximum rate of senescence; the fitted curves indicate that for gerbera, jonquil and rose 'First Red' this maximum rate is already reached at 20°C (293K).

Botrytis

Temperature largely affected the time until the first germinated conidia were observed (lag-time) and the rate of germination after this lag period (Fig. 2). The data could well be fitted using a sigmoidal time-response relationship. The time it took until 50% of the conidia were germinated (t_{50}) in PDB solution, which is a result of lag-time and germination rate, showed an exponential relation with temperature (Fig. 3). We were not able to quantify germination rate on rose petals (in vivo), but preliminary results indicated that the rate in vivo is much lower compared to germination in PDB solution. At 20°C germination rate was at its maximum about 8 hrs after incubation on rose petals. The results indicate that the presence of free water (condensation) is mostly dangerous for the quality of cut flowers when the temperature of this water is relatively high. The data obtained in vitro indicate that at water temperatures below 5°C condensed water needs to be present longer than about 10 hrs before germination will occur. For germination of

conidia on flower petals, it may be expected that it even takes much longer. The relation between temperature and t_{50} of Figure 3 is used in the model to calculate if germination of *Botrytis* conidia will occur. As discussed above, this will result in an overestimation of the occurrence of *Botrytis* infection in flowers.

The results obtained in vitro demonstrated that an interruption by 2 hrs of the water-presence during germination had a negative effect on the subsequent germination rate (Fig. 4). The germination percentage after the first hour of re-incubation remained about the same as it was at the starting of the dry period in all four treatments. It might be that the germination process needed to start all over again. After the germination was restarted, the rate was much lower compared to the control without interruption by a dry period, especially when the dry period was applied 2 hrs after start of the incubation period. Also in vivo, when rose petals were incubated with conidia of *B. cinerea*, the petals showed less lesion spots when a dry period of 2 hrs was applied compared to the non-interrupted control (data not shown). Exposing the petals to the dry interruption 8 hours after the start of the incubation period resulted in the lowest number of lesion spots among all the treatments after a 16 hrs re-incubation period. The results suggest that the most critical phase during the germination process to be affected by a dry interruption is when the rate of germination is at about its maximum, as well in vitro as in vivo. It is clear that the effect of the presence of condensed water or high air humidity on the germination of *B. cinerea* conidia will be affected by previous conditions in the post-harvest chain. Short periods of high humidity or condensation could even be positive to diminish the problem of *Botrytis* infection. This phenomenon was not implemented in the used model.

It is considered that enzymatic activity is required for penetrating intact host tissue (van Kan, 2005); therefore penetration will be temperature dependent. After penetration of the host tissue by *Botrytis* necrotic spots are formed from which a small proportion eventually develops into aggressive, spreading lesions. The first attempts of pathogens to infect plant cells will trigger a cascade of defence processes in the plant tissue to prevent spreading of the fungus (van Kan, 2005). Stopping the penetration of pathogens during plant infection is dependent on the accurate time-course of the pathogen perception by the plant host cells and the activation of defence mechanisms resulting in the induction of secondary metabolites, reactive oxygen species and pathogenesis related proteins. It is suggested that this defence response is less at low temperatures of the plant tissue. Salinas and Verhoeff (1995) showed that all initial lesions on gerbera flowers inoculated with *B. cinerea* and stored at 4°C resulted in spreading lesions, while during storage of the flowers at 20°C only restricted lesions were observed. Therefore, exposing cut flowers to low temperatures could probably hasten the spread of lesions afterwards (especially at the consumer), when conidia have been able to germinate. However, spread of lesions is hastened by ageing of petals, probably because the plant defence mechanisms are less in more aged tissues. Ageing is positively affected by temperature. Because of the two opposite effects of temperature on the plant defence mechanism, it is an optimization problem to predict the final result.

Water Temperature

Often cut flowers are placed for a short period in water in one or more links of the post-harvest chain. The temperature of this water can be the same or can differ from the air temperature of the environment, depending of the source of the water and the time the water was present at the specific location. Low temperature of the water will slow down the growth rate of bacteria as shown by de Stigter and Broekuysen (1983). Besides plugging by bacteria, wounding induced processes can be a reason for xylem vessel plugging. When cut chrysanthemum stems were placed in water of 20°C for 24 hrs hydraulic capacity of the stems was decreased to 20% of the initial capacity; when the stems were placed in water of 5°C the hydraulic capacity after 24 hrs was still 100% of the initial capacity (data not shown). Neither bacteria nor air emboli were involved in this decrease of water transport capacity. Placing cut flowers in water will have a positive

effect on the appearance of the flowers when they had loosed their turgor due to excessive water loss. Without this excessive water loss, data in literature showing a positive effect on vase life of placing flowers in water somewhere in the transport phase of the post-harvest chain are scarce. Water is the medium for transport of bacteria from the outer stem surface into the xylem vessel. The longer the introduction of bacteria into the xylem vessels is postponed in the chain, the better. Therefore it could be wondered whether flowers should be placed in water before the end of the transport chain at the flower shop. In the case flowers are placed in water, the temperature of this water should be as low as possible.

Scenario Studies

In a first study we supposed a chain existing of one link with a constant temperature. The combined effects of various temperatures and lengths of the chain on vase life were simulated for two flowers that differed in their senescence rate-temperature relationship, viz. rose and Gypsophila (Fig. 5). For rose flowers the effect of temperature during transport on vase life at the consumer was rather limited when the length of the transport phase was less than about 4 days; most temperatures below 10°C will result in an acceptable vase life. With transport periods longer than 4 days, it becomes more and more important to lower the temperature as much as possible (when only rate of senescence is taken into account). Due to the higher sensitivity of senescence rate of Gypsophila to temperature, also for transport phases as short as 48 hrs, it is important to have the temperature below 7-8°C. Opposite to rose, for Gypsophila it is worthwhile to decrease a temperature of 20°C to 15°C when there are no options for cooling to lower temperatures. Interesting is the short vase life after storage at 20°C. Because vase life is determined at 20°C, it was expected that loss of vase life during storage at 20°C should be identical to the length of the storage period. According to the data used for fitting the senesce rate-temperature relationship (Çelikel and Reid, 2005) the loss is much more. Probably heating of the Gypsophila flowers due to their high respiration rate was involved in the experiments. When this is the reason for this observation, the outcomes of the vase life experiments will be different when different numbers of flowers are packed, more boxes with flowers are placed together, and so on. The authors did not mention the actual flower temperature.

More interesting are simulations of post-harvest chains in which several links with different temperatures and humidities are involved. Two different chains for roses were simulated: (i) production in the Netherlands, transported to and sold at a Dutch flower auction and transported to a flower shop in Germany, and (ii) an international chain with production in Colombia, transport by air plane to the Netherlands followed by truck transport to Italy. Time, temperature and humidity conditions used in the simulations are given in Table 2. The conditions in the 'short chain' (Table 2A) resulted in a decrease of vase life to 9.57 days compared to the maximum vase life directly after harvest of 10 days. Increasing the temperature in the last transport phase to the flower shop from 15 to 20°C resulted in a vase life of 9.56 days and increasing the temperature of the cooler at the auction to 20°C (combined with the high temperature in the last transport phase) in a further decrease to 9.55 days. From these results it is clear that investments in cooling in such a local chain are very questionable. To keep the duration of the chain as short as possible seems to be more profitable. However, due to the high temperatures, the danger of germination of *Botrytis* conidia is rather high. When RH in the last 4 hrs-transport to the flower shop is 82% (at 15°C; vapour pressure of 14 hPa) conidia will germinate at the end of the transport. When the water vapour during the short sorting phase is 15 hPa (RH is 77.5%) conidia will start to germinate the first hour of the final transport. According to the simulation, this could be overcome by lowering the temperature during the last 4 hours of transport to 10°C when RH during this phase is below 80%. These results show that temperature (and humidity) management in this chain is important to prevent loss of quality due to *Botrytis* and not because of senescence of the flowers. A constant temperature (the same temperature in all links) is even more important than a low

temperature (on the condition that RH<92%). The simulation of the international chain (Table 2B) resulted in a vase life of 7.91 days. Although the international chain is 73.5 hrs longer than the local chain, the difference in potential vase life for the consumer is only 1.5 days. At 3 moments during this 'international chain' there occurred condensation on the flowers: during sorting, at the start of the transport to the airport after the post-cooler, and at the start of the transport to the auction after the air plane transport. In all cases, because of the low temperature, this did not result in germination of conidia. The most critical was the condensation during sorting, because the flowers dried only very slowly during the post-cooler period. Increasing the temperature in the airplane to 15°C resulted in a vase life of 7.76 days, or increasing the temperature to 10°C during the last 40 hrs (stay at the auction and transport to Italy) resulted in a vase life of 7.33 days. So, even for this long chain, decisions about investments in cooling have to be carefully considered. Besides development and senescence of the flowers, the other processes affected by temperature should be taken into account, as well as the costs of the investments.

We have to keep in mind, that the simulation model was developed for flowers without being sleeved or packed. As result of this, condensation mostly takes place when a cold flower is transferred to a warmer environment. The consequence of this is that the temperature of the condensed water is low, resulting in a long lag-phase and slow rate of germination of *Botrytis* conidia. When flowers are sleeved, it may be expected that transferring the sleeved flowers from a warm environment to a cooler one will cause condensation on the inside of the sleeves. When this water drops on the (still warm) flowers germination rate will be high.

Due to the simplifications in the model, the meaning of the outcomes is very limited; also there has been no validation of the model. The purpose was to demonstrate the complexity of temperature management in the post-harvest flower chain and the possible use of a simulation model as tool for critical analyses. Experiments designed to parameterise and validate a model about temperature effects on key processes for the maintenance of quality could be more efficient for good temperature management than a large number of trials with all kinds of possible time, temperature and humidity combinations. The approach of Tijskens and Polderdijk (1996) for a generic model for keeping quality of vegetables will be very worthwhile to apply to vase life of cut flowers.

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Tables

Table 1. The r^2's of linear, Arrhenius and sigmoid regression of senescence rate as function of temperature (for details see Methods) for various flowers.

	r^2-linear	r^2-Arrhenius	r^2-sigmoid	N
Sunflower	0.9879	0.9113	0.966	8
Gerbera	0.8767	0.7861	0.9518	7
'Jonquil' narcissus	0.9329	0.8395	0.9996	5
Narcissus 'Paper White'	0.9106	0.9766	0.9842	8
Rose 'First Red'	0.9042	0.8005	0.9813	8
Gypsohila	0.7623	0.9718	0.9861	10
Daffodil	0.9535	0.9586	0.9641	8
Iris	0.9345	0.9915	0.9926	5
Carnation	0.9853	0.9541	0.9676	5

Table 2. Conditions used in simulations of two different post-harvest chains of cut rose flowers.

A. Short local chain.

Link	Length (hr)	Temperature (°C)	RH (%)
Greenhouse	1	20	77
Cooler	4	4	86
Sorting	1.5	17	62
Transport to auction	1	15	82
Cooler at auction	1	5	80
Transport to flower shop	4	15	77
Total length	12.5		

B. International chain.

Link	Length (hr)	Temperature (°C)	RH (%)
Greenhouse	1	25	77
Pre-cooler	3	10	65
Sorting	2	20	81
Post-cooler	15	5	92
Transport to airport and by airplane	20	10	73
Transport to auction	5	15	82
Cooler at auction	10	5	92
Transport to Italy and retailer	30	5	92
Total length	86		

Figures

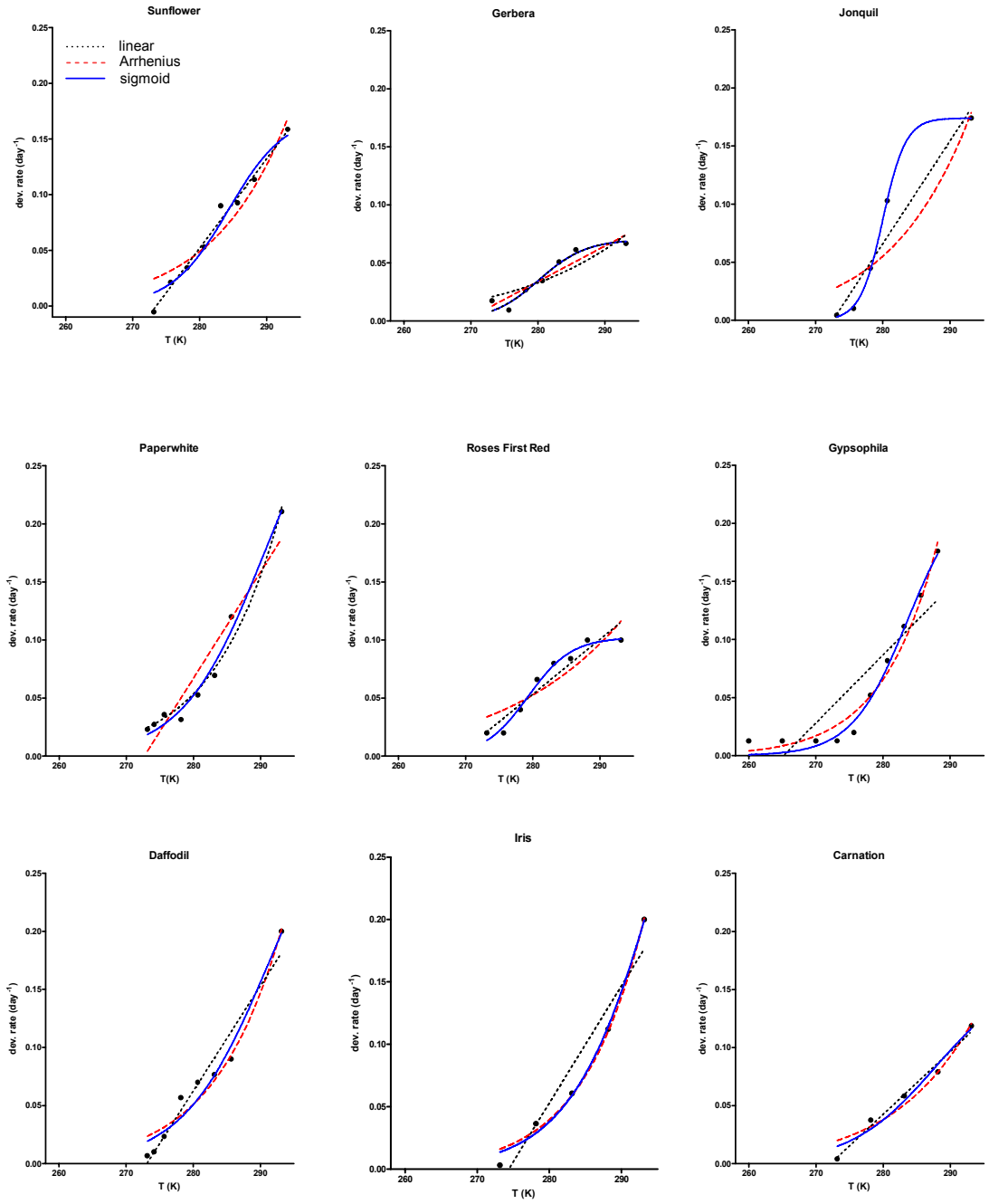

Fig. 1. Fitted curves of rate of senescence (development rate) of several cut flowers as function of temperature. For the equations of the non-linear curves see Methods.

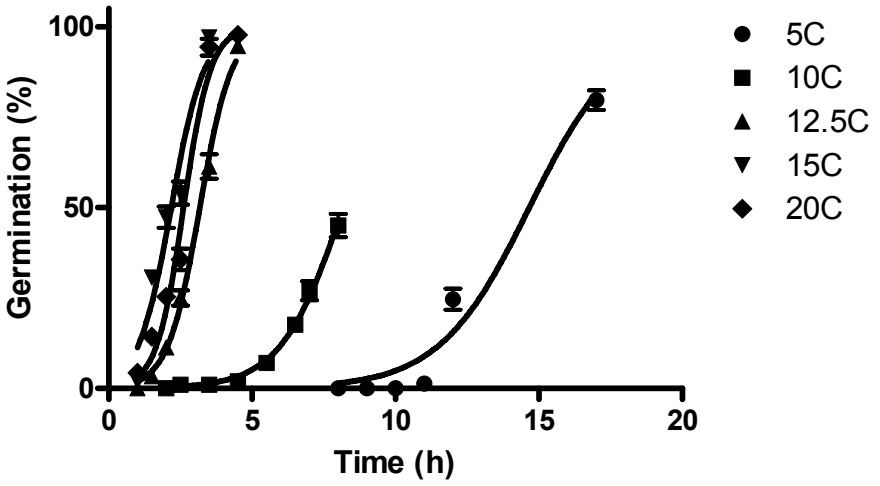

Fig. 2. Time curves of germination of *B. cinerea* conidia in PDB solution at different temperatures.

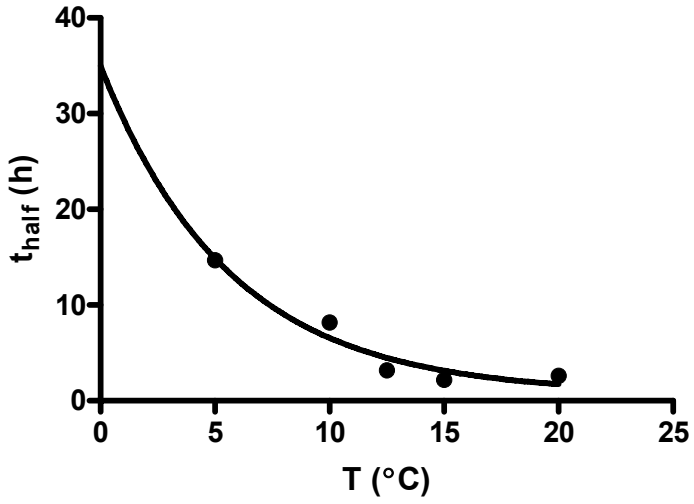

Fig. 3. Relation between the time it takes to 50% germination of *B. cinerea* conidia in PDB solution (t_{50}) (calculated using the regression lines of Fig. 2) and temperature during incubation. Regression used: $t_{50} = (t_{T0}-t_{min})*\exp^{(-K*T)} + t_{min}$ where t_{50} = time to 50% germination [h], $t_{T0} = t_{50}$ at 0°C [h], t_{min} = minimum t_{50} [h], and K is a rate constant [h $°C^{-1}$].

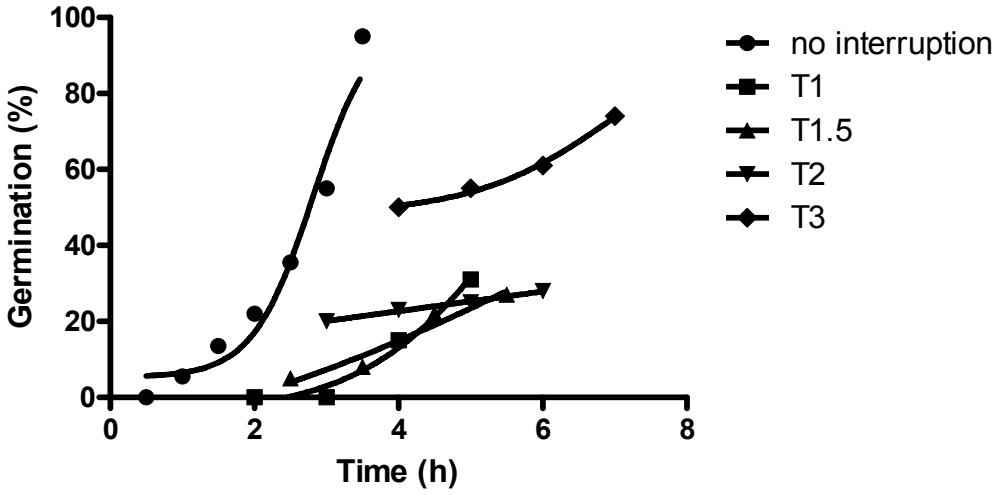

Fig. 4. The effect of a dry period (2 hrs) at different times after start of the incubation on germination of *B. cinerea* conidia in PDB solution at 20°C. The dry period was started 1h (T1), 1.5h (T1.5), 2h (T2) or 3h (T3) after start of the incubation or there was no dry period (no interruption) applied. To facilitate comparison, as 'Time' for the interrupted treatments the time after reapplication of PDB solution + the time before the dry period was started, was used in the graph.

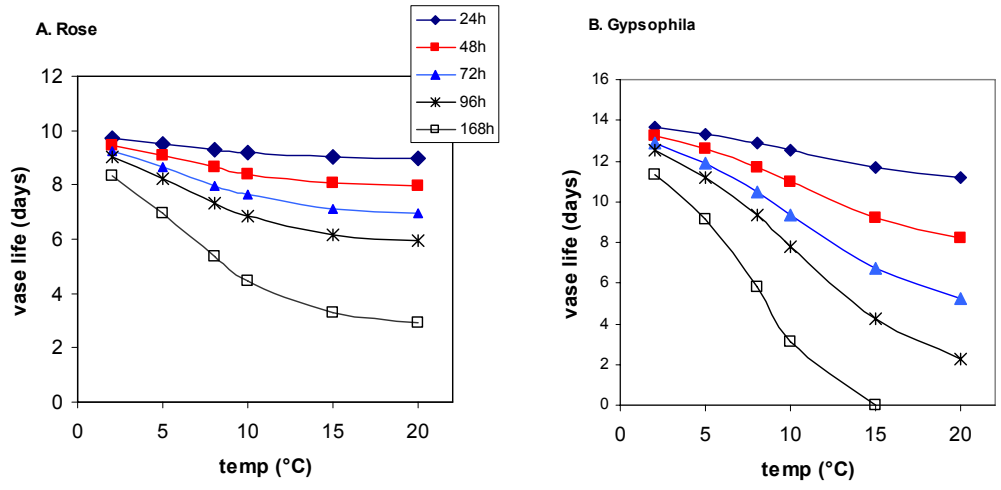

Fig. 5. The simulated effect of constant temperatures during a transport phase of different durations for rose (A) and Gypsophila (B). The markers are outcomes of a simulation run.