QUALITY MODELS IN HORTICULTURE NEED PRODUCT QUALITY: A RARE BUT CHALLENGING FIELD OF EXPLORATION

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Abstract

Quality attributes of horticultural products include external aspects visible at the moment of purchasing the product, and internal non-visible aspects. Especially for ornamentals, some of these aspects will only be evident during use of the product by the consumer. Models predicting internal quality attributes as a result of growth conditions are rarely found in literature. Explanatory models for internal quality of cut flowers as result of growth conditions are totally lacking. Some bottle-necks and challenges to develop simulation models about internal quality attributes of horticultural products, based on cultivation conditions, are discussed with special emphasis on vase life of cut flowers.

A dynamic and deterministic conceptual model to simulate carbohydrate balance and development of lily inflorescence during vase life was developed. The inflorescence as a system was defined by the state variables: the carbohydrate pool in the stem and the carbohydrate pool, structural biomass and development stage of each floret in the inflorescence. An additional auxiliary state variable was used to describe whether a floret is alive or dead due to shortage of carbohydrate supply. An osmotic pool of the petal cells is included which is treated as an independent sink. Distribution of available carbohydrates among the osmotic and the non osmotic pool was assumed to be proportional to the sink strengths of both pools, defined as the capacity to accumulate carbohydrates under conditions of non-limiting carbohydrate supply.

The water balance of a cut flower is largely influenced by its rehydration ability after harvest. A great bottle-neck to achieve a model, that predicts the vase life behaviour as result of pre-harvest conditions, is the limited knowledge of the structural, chemical, or physiological basis for differences in this rehydration ability.

The value of modelling vase life behaviour, based on characteristics at harvest, is discussed in light of defining the 'quality of design' of a cut flower in terms of quantitative measurable parameters.

1. Introduction

The international market of many greenhouse commodities is intensely competitive. Many firms try to strengthen their position in the market not through price competition but through product competition, by creating differentiated products that appeal to different buyer segments. The quality of a product is an important basis for product differentiation. Quality changes will affect market demand as well as cost of production.

It is critically important that consumers are satisfied with their purchase of vegetables or flowers, since satisfaction is a primary prerequisite for the repeat sales on which any industry depends. To satisfy users expectations, a general prerequisite for any product is to be of good quality. This applies also to simulation models. In many cases, judgement of quality of models is mainly based on validation of the model, mostly demonstrated by the agreement between measured and simulated data. However, in many cases high

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accuracy will mean good quality, only, when the user of the model and the designer of the model is the same person.

In view of the market situation mentioned before, models intended to be used in control of greenhouse climate, mineral nutrition, watering or in farm management and decision support will only be of good quality (that means satisfy the users expectations) when they take into account the influence of measures and conditions during cultivation on the quality of the harvested product. It has to be mentioned that in horticulture, in many cases, predicting the production of dry matter has only a limited value to predict the possible use of a crop.

2. Quality

In general, product quality of a nondurable product is achieved by quality of design and quality of production (Juran, 1974). Basically, quality of design refers to the determination of the quality level the product must possess by: -identification of consumer's quality needs, -development of a product concept, and -translation into specifications. Quality of production is controlled in essentially two ways: -direct control of the production process itself, and -final inspection of the product.

In horticulture, in most cases, final inspection or 'grading' is the only quality control measure that is taken. In consequence of the desired product differentiation, quality management by means of controlling the production process in combination with the development of a product concept that meets the needs of the buyer of the product, will become more and more important. Therefore, however, it is a prerequisite to have the feasibility to predict quality attributes of vegetables and ornamentals as result of their growth conditions. Simulation models will be very helpful to obtain this complex goal .

A common characteristic of horticultural products is that they are the object of the aesthetic experience ('beauty, flavour and pleasantness') (Sakiyama, 1991). Therefore quality of horticultural products cannot be characterised by their energy content as is done for most agricultural crops which are used as energy source (food) for people or animals. Quality attributes of horticultural products include aspects visible at the moment of purchasing the product, like shape, size, colour, condition, residues, defects and damages mechanically or by insects, mites, disease as well as and non-visible aspects ('internal quality') like keeping quality, stress tolerance, taste, vase life, ornamental value at the consumer, safety and vitamin content.

Most of these quality attributes can be measured at the moment of buying the product. Attributes like keeping quality, stress tolerance during transport, vase life and aspects of ornamental value at the consumer, like flower opening, leaf yellowing, loss of turgor and abscission, however, will only be evident during use of the product by the consumer. Predicting future behaviour based on measurable characteristics at harvest, would be very helpful in defining the quality of design of horticultural products.

3. Published quality models

A survey within the CAB Abstract database from 1/90 - 1/97 showed only a very limited number of references dealing with models of quality aspects in relation to the cultivation of greenhouse crops. A more detailed analysis of the various quality attributes, shows that the situation is less desperate concerning external quality attributes. Knowledge of the effects of environmental conditions on development and shape of plants (height, branching, flower size) has expanded relatively rapidly the last years (Hendriks and Ueber, 1995; Larsen and Gertsson, 1992; Larsen and Hidén, 1995; Myster and Moe, 1995; Pearson, *et al.*, 1995; Schoellhorn, *et al.*, 1996; Tutty, *et al.*, 1994). Decision support systems based on models predicting plant height and branching have been developed by different authors (Adams, *et al.*, 1996; Fischer and Heins, 1996).

Models have been developed to describe and predict deterioration after harvest due to storage or transport conditions for cut flowers (Van Doorn and Tijskens, 1991), and recently also for potted plants (Tijskens and Polderdijk, 1996) and vegetables (Tijskens, *et al.*, 1996). Necessary information for these models, however, is the initial quality at the moment of harvest. In only very few cases methods are described to objectively determine product characteristics at harvest which predict keeping quality (Polderdijk, *et al.*, 1993). These characteristics as well as their relation to keeping quality were influenced by growth conditions.

Models predicting internal quality attributes as a result of growth conditions are rarely found in literature. Recently a model predicting the taste of peaches based on carbon partitioning into various forms of sugars was developed (Génard and Souty, 1996). At this symposium presentations on nitrate level in lettuce (Seginer, Buwalda and Van Straten) belong to the first in this field of greenhouse crops. Explanatory models for internal quality of cut flowers as result of growth conditions are totally lacking.

4. Bottle-necks and challenges

4.1. External quality attributes

Knowledge on factors and processes affecting flowering, leaf unfolding, internode elongation and branching will expand further. New approaches of simulating plant architectural development are reviewed in this Acta (De Reffye and Houllier, 1997). It may be expected that the number of crops for which predictive models of external quality attributes are developed will increase relatively fast.

4.2. Internal quality attributes

4.2.1. Fruits

Taste of fleshy fruits depends largely on their total sugar concentration and the individual carbohydrates that directly influence fruit flavour components. Most of the explanatory models for crop growth are photosynthesis-driven models simulating the production and partitioning of assimilates. Although assimilate partitioning is still partly understood, simulation of biomass allocation based on relative sink strengths is promising (Marcelis, 1994; Challa and Heuvelink, 1996). However, as the concentration of sugars is more important for taste than their amount, the import of water into the individual fruits is as important as the production and partitioning of assimilates.

In many fruits texture of the fruit is another important component of the taste as perceived by the consumer. Moreover, in tomato, firmness of the fruits predicts very well the keeping quality (Polderdijk, *et al.*, 1993).

Effects of growth conditions, especially the electrical conductivity of the nutrient solution, on firmness, taste and keeping quality of tomato are rather well known. Development of a model to simulate taste and keeping quality of tomato fruits, based on cultivation conditions seems to be a worthwhile challenge.

4.2.2. Cut flowers

Besides external quality aspects at the moment of buying cut flowers, changes in ornamental value at the consumers' home are the most important quality attributes of cut flowers. Knowledge about affecting this post-harvest behaviour by pre-harvest cultivation conditions is very limited notwithstanding many attempts to investigate this relation. Simulation models are powerful tools to understand complex systems. Therefore, in spite of the scarce available information, development of mechanistic simulation models to predict vase life seems to be of great value.

Vase life behaviour will be the result of changes in the carbohydrate balance, water balance and development stage of the cut flower during vase life. All cut flowers will use assimilates for maintenance and growth, without any significant assimilate supply by photosynthesis. The use of assimilate reserves of the cut flower will be a general aspect of vase life, which dynamic behaviour is especially important for inflorescences with many individual florets all in different development stages.

A prerequisite for a good and long vase life is a positive water balance of the cut flowers: at least the flowers have to replenish the transpired water to stay turgid and to open their buds into attractive flowers.

Important aspects of development are opening of flower buds, and ageing of flowers as well as leaves. Although both processes are aspects of the same phenomenon, opening of the flower buds has to proceed undisturbed as much as possible, while ageing has to be postponed as long as possible.

Carbohydrate balance, water balance and development are interrelated with each other and are affected to a large extent by the history of the flower. History comprises the cultivation of the flower and its handling from harvest until the vase period. If models can be developed which predict the changes in carbohydrate balance, water balance and development during vase life based on measurable characteristics at harvest, quality of the cut flower can be quantified using these characteristics. These models can also be used for sensitivity analyses to identify the most influential characteristics at harvest affecting length of vase life and ornamental value. The next step should be to extend crop growth models with simulation of these characteristics.

4.3. Case studies

To demonstrate bottle necks and challenges for the development of the above mentioned models for cut flowers, two case studies are presented: a. a conceptual model about the carbohydrate balance and development of lily inflorescence during vase live; b. a case about the water relations of cut chrysanthemum flowers.

4.3.1. Carbohydrate balance and development of lily inflorescence during vase life

4.3.1.1. General description of the conceptual model

The model is dynamic and deterministic, driven by temperature (Fig. 2). The inflorescence as a system is defined by the following state variables: the carbohydrate pool in the stem and the carbohydrate pool, structural biomass and development stage of each floret in the inflorescence. Besides the development stage as result of the genetic program of the floret, an additional auxiliary state variable is introduced to describe whether a floret is alive or dead due to shortage of carbohydrate supply. It is assumed that there is no shortage of water, nitrogen or other nutrients except carbohydrates.

Flowers accumulate sugars in their petals in accordance to their development stage, as shown for freesia florets (Van Meeteren, *et al.*, 1995). This accumulation is not the result of an surplus in the supply of carbohydrates as there is also an accumulation in accordance to their development stage under limited supply of carbohydrates in florets of cut freesia inflorescences. Therefore, in the conceptual model an osmotic pool of the petal cells is included which is treated as an independent sink. The maximum value of the osmotic pool is reached around anthesis of the floret.

It is assumed that all carbohydrates imported by a floret can be used to provide for the need of maintenance respiration. The remaining carbohydrates are partitioned among a hypothetical short term substrate pool used for the formation of new structural biomass and the osmotic pool. Distribution of available carbohydrates among the osmotic and the non osmotic pool is proportional to the sink strengths of both pools. Sink strength is defined as the capacity to accumulate carbohydrates and is quantified by the rate of increase (growth) under conditions of non-limiting carbohydrate supply.

The carbohydrates of the osmotic pool are not available for the formation of structural biomass. When imported carbohydrates cannot fulfil the need for maintenance respiration, carbohydrates stored in the osmotic pool will be used for maintenance. The growth rate is assumed to be proportional to the amount of the short term non osmotic substrate pool, with a maximum rate related to the development stage of the floret (potential growth rate); growth is irreversible.

Florets are assumed to die when the available carbohydrates for maintenance (so the sum of available carbohydrates imported from the stem and the osmotic pool) cannot fulfil the need for maintenance. By definition, florets will also die when they have reached their maximal development stage.

The conceptual model was implemented by using FORTRAN Simulation Translator (FST) of Rappoldt and Van Kraalingen (1996). Using an assimilate requirement of 1.43 g CH_2O for the formation of 1 g of structural dry weight (Goudriaan and Van Laar, 1994), a CO_2 production factor for growth of 0.30 g CO_2 g^{-1} d.m., and a maintenance respiration coefficient of 0.035 g CH_2O g^{-1} (d.m.) d^{-1} as parameters, the results of a simulation with the proposed conceptual model were consistent with the principles on which the model was based (Fig. 2).

Development rate, potential growth rate and potential osmotic need were implemented as a table with data of an experiment with one lily flower bud attached to the plant (all other buds were removed). As shown (Fig. 2), the osmotic carbohydrate pool can be a very pronounced part of the total dry weight. The total sink strength of a floret is assumed to become zero at anthesis. As a result of maintenance respiration floret dry weight decreases after anthesis by using the osmotic pool. This is in accordance with experimental data.

4.3.1.2. Available carbohydrates

In most crop growth models, the amount of available carbohydrates is simulated based on the calculated interception of light by the leaf canopy. Due to the low light intensities at the consumers' home, photosynthesis of cut flowers can be neglected. Carbohydrates are available only from reserves stored in stem, leaves and florets. An uncertainty to be aware of in determining the amount of stored carbohydrates is their chemical composition. With all flowers, one has to pay attention on specific storage forms of carbohydrates.

4.3.1.3. Respiration

In general, there is reasonable consensus concerning the simulation of growth respiration, but the simulation of maintenance respiration is still an area of great uncertainty. The contribution of maintenance respiration to the carbohydrate balance is very pronounced during vase live of cut flowers (Fig. 3). Progress in understanding the underlying principles and validation of maintenance respiration will be of great importance for a satisfactory accuracy of models of the carbohydrate balance of cut flowers.

4.3.1.4. Carbohydrate distribution among florets

To simulate the ornamental value of the whole inflorescence, distribution of the carbohydrates among the individual florets plays an important role. In principal 3 different strategies of distribution control can be considered: i) First all the needs of one floret(bud) will be fulfilled, probably the most basal oldest bud; the remaining carbohydrates are available for the next floret(bud) and so on, ii) The available carbohydrates are distributed among the florets(buds) proportional to their sink strengths, iii) All florets(buds) are supplied with carbohydrates to fulfil their maintenance needs; thereafter, remaining carbohydrates can be used for growth and storage of the various florets(buds). In most crop growth models, the last strategy is applied.

In case of the first control mechanism, a constant limiting carbohydrate supply will result in a clear difference between the weights and sizes of the individual florets within an inflorescence. The weight of the floret will be largely depended on its position within the inflorescence. However, there was no difference in dry weight between florets(buds) at different positions when the amount of available carbohydrates was varied during the growth of lily flower buds attached to the plant, either by varying the number of sinks by removing floret buds (Fig. 4A), or by varying assimilation rate by different light intensities (Fig. 4B).

At this moment there is no experimental proof for either of the two other partitioning mechanisms. In the preliminary model, it is assumed that carbohydrates are distributed proportional to the total sink strengths of the florets.

4.3.1.5. Preliminary results

The presented model is used to investigate the possible effects of various amounts of carbohydrates in the stem at harvest, of different numbers of buds within the inflorescence in various development stages at harvest, and of a constant addition of a low amount of sugar to the vase water.

The carbohydrate amount in the stem at harvest affects largely the number of buds that develop into full bloom (Fig. 5). At low amounts an increase enhances mostly the lives of the oldest buds; when a critical level has been passed, a small increase in carbohydrate amount can have a tremendous effect on the young buds. According to the simulation outcome, the minimum amount of carbohydrates needed for full development of six florets (when the flower is harvested at the normal commercial harvesting stage) is about 4 gram. As the total dry weight of a lily flower stem is about 5-6 gram, this seems to be rather high. Especially when it is realised that respiration of the stem itself was not taken into account.

Vase life varies from 7 to 10 days depending on the number of buds present at the moment of harvest and their relative development stages (Fig. 6). Vase life is assumed to be finished when there are no florets present anymore which at least has reached the orange coloured development stage. Vase life and ornamental value are especially enhanced when less young buds are present at harvest.

A constant supply of a low amount of sugar to the vase water of the cut flower, especially enhances the development of the young buds (Fig. 7). In the simulation a daily uptake of 100 mg of sugar by the inflorescence was assumed. The effect is mainly the result of preventing premature death of the young buds, by which they can grow as soon as the oldest florets are senesced and lose their sink strength. The result may interact strongly with the initial amount of carbohydrates in the stem.

4.3.1.6. Shortcomings

The presented model does not simulate the size of the florets (length and width), which is an important quality aspect. Also effects of carbohydrate availability and mutual effects of florets on senescence are not included, nor is the model yet validated. Methods for an accurate description and determination of development stage of the florets of a harvested inflorescence has to be developed, as the concept of temperature sum, measured as degree-days from a well characterised development stage, cannot be used.

4.3.2. Water relations of cut chrysanthemum flowers

Water-uptake is one of the most important processes for keeping-quality of a cut flower. Post harvest water relations of different cut flower species or different cultivars can vary substantially (Evans, *et al.*, 1996). Within a cultivar there is a strong seasonal influence on transpiration and water uptake (Urban, *et al.*, 1995). Also conditions during cultivation like supplementary lighting (Slootweg and Van Meeteren, 1991), relative humidity (Mortensen and Fjeld, 1995) and electrical conductivity of nutrient solution (De Kreij and Van den Berg, 1990) influence water balance of cut flowers during vase life.

The changing water balance of a cut flower, whether measured by its hydric status (*H*) as % of its initial fresh weight, or as its xylem water potential (Ψ) is a function of the difference between the uptake of water from the vase solution and transpiration by the leaves, flower, and stem. The uptake rate (*dU/dt*) will be a function of the water potential and the resistance for water transport of the flower stem (R_{stem}):

$$\frac{dU}{dt} = \frac{-\Psi}{R_{stem}}$$

Water potential is directly related to the hydric status in a function that is relatively linear. According to Dixon, *et al.* (1988) for roses this function has a slope of approximately -1/10:

$$\Psi = \frac{-H}{10}$$

As consequence of the above mentioned relations, at a constant transpiration rate, there will be reached an equilibrium state with a constant fresh weight, whatever the initial hydric status at the start of the vase life. The value of the weight at equilibrium will depend on the transpiration rate and the stem resistance for water transport. The rate of water loss in the post-harvest environment is relatively low compared with that in the greenhouse, where temperature and light intensity stimulate transpiration of the leaves.

However, in practice fresh weight of cut flowers often decreases during vase life, indicating restrictions on water uptake. For instance, with some cultivars of chrysanthemum, the cut flowers can have wilted leaves within 2 days of vase life resulting from a negative water balance, under normal standard conditions (Van Meeteren, 1989, 1992). The occurrence of the problem, however, is very variable and many factors seem to be involved. At least it seems to be sure that air emboli in the xylem vessels play an important role (Van Meeteren, 1992). The air enters the vessels via the cut surface of the stem at harvesting of the flowers or during dry storage and transport.

When it is supposed that the number of air blocked vessels increases as result of a decrease of the hydric status of the cut flower, this will result in an increase in the water transport resistance (Fig. 8). As consequence, the initial hydric status will largely influence the system behaviour: there will be a critical level of hydric status at the start of vase life.

In reality, water uptake is only slightly hampered, when air is introduced into the stem vessels by exposing the cut flowers, soon after harvest, for one hour to circumstances resulting in a fast water loss (Fig. 9). It seems that the flowers have some mechanism to remove the entrapped air or to circumvent the air blocks. A necessary condition for the rehydration ability is, that the stems are cut at some minimum distance above the roots.

Pre-harvest growth conditions seem to be rather important for the rehydration ability after aspiration of air into the stems of cut flowers. In an experiment with chrysanthemum, following a short dry period after harvest, the flowers grown in a greenhouse behaved totally different from cut flowers grown under artificial light in a climate room (Fig. 10). The responsible environmental factor causing this difference in water balance between the two lots of cut flowers is not yet known. Interesting is that high relative humidity during the early period of rose shoot development seems to increase stem water transport resistance (Mortensen and Fjeld, 1995).

To achieve a model that predicts the vase life behaviour of a cut flower as result of its pre-harvest conditions, it seems critically important to understand the structural, chemical, or physiological basis for the differences in rehydration abilities of cut flowers.

5. Concluding remarks

As shown by the two case studies, modelling the vase life behaviour of cut flowers, based on characteristics at harvest, can be a very useful tool in defining the quality of design of a cut flower in terms of quantitative measurable parameters. A great bottle neck, however, to develop mechanistic models is the limited knowledge of the fundamental processes involved. This applies also to internal quality attributes of other horticultural commodities. At the same time, modelling attempts will pinpoint areas where knowledge is lacking and will be very helpful to understand which are the most influential processes and factors.

Incorporating produce quality attributes into crop growth models intended to be used in horticulture is a real challenge, not only to control quality of the horticultural products but also to enhance the quality (satisfaction of users) of the models itself.

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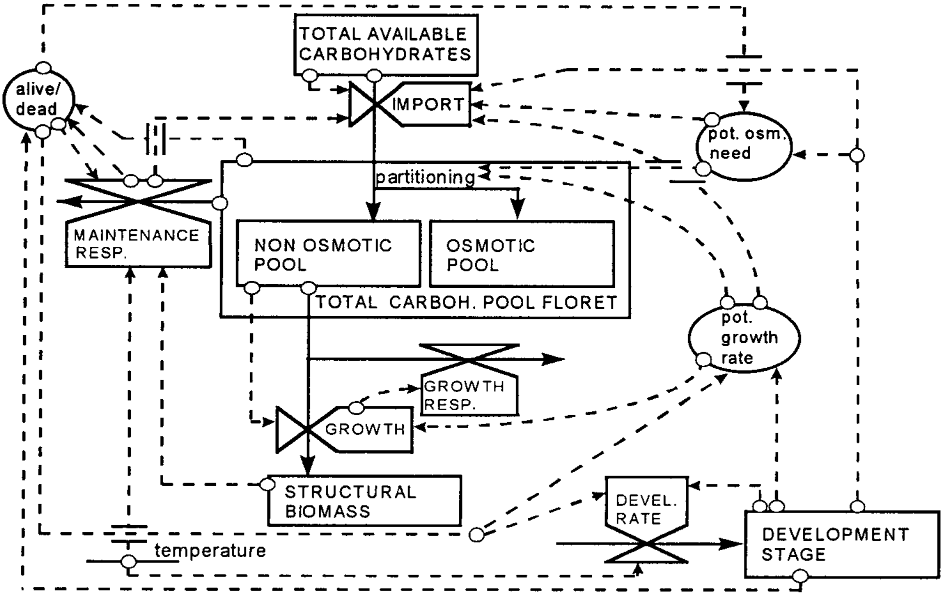


Fig. 1. Diagram illustrating a conceptual model about the carbohydrate balance and development of a floret during vase life of a cut lily inflorescence.

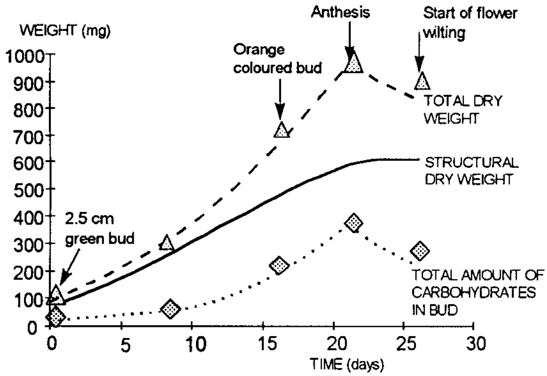


Fig. 2. Time curves of dry weight and carbohydrate amount of petals of a lily floret. Lines are simulated values of a cut inflorescence with only one floret and a high initial carbohydrate content (12000 mg) in the stem; markers are measured data of an experiment with one bud attached to the plants. The first four measured values of dry weight and carbohydrate amount are used to calculate potential growth rate and potential osmotic need in the preliminary model.

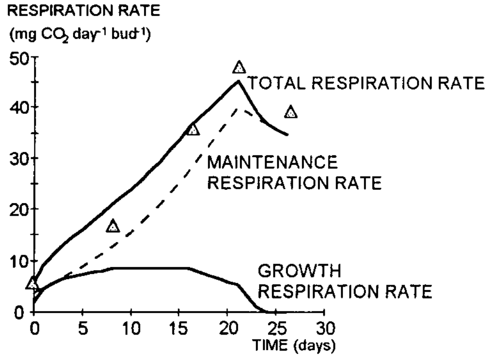
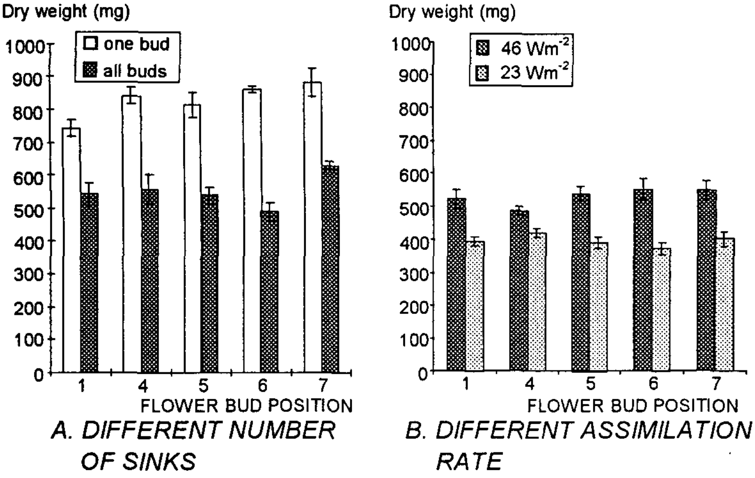


Fig. 3. Simulated maintenance and growth respiration rate (lines; with high initial amount of carbohydrates in the stem) and measured total respiration rate (triangles; one floret attached to a plant) of a lily floret.



A. DIFFERENT NUMBER OF SINKS

B. DIFFERENT ASSIMILATION RATE

Fig. 4. Dry weight at anthesis of intact lily florets at different positions within the inflorescence (position 1 is the most basal position). Available amount of assimilates during growth of the inflorescence was influenced by: A. either removing buds at the moment they reached a length of 1 cm except the bud at the investigated bud position or no bud removal; B. growing plants at two different light intensities. Plants grown in a climate room at 20 °C.

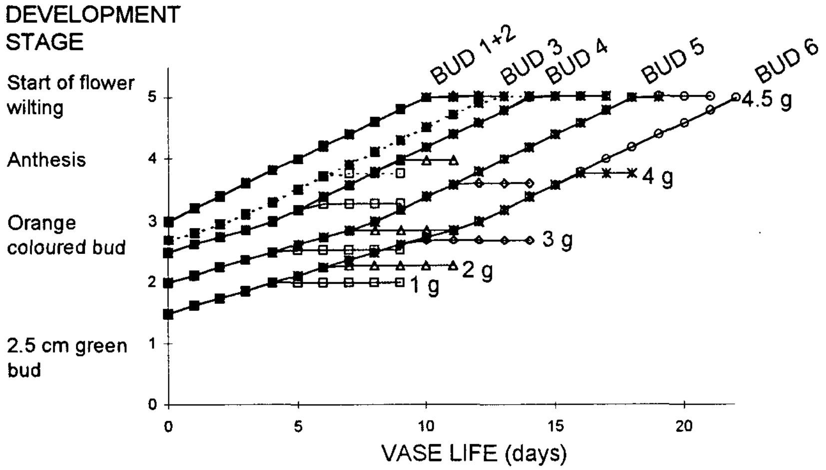


Fig. 5. Simulated effect of initial amount of carbohydrates in stem on development stage lily florets reach during vase life of an inflorescence cut at the commercial harvest stage. Inflorescence is composed of 6 florets. Bud 1 is the most basal bud. Initial amount of carbohydrate used in the simulation run was 1g (□), 2g (Δ), 3 g (◊), 4 g (x) or 4.5 g (O).

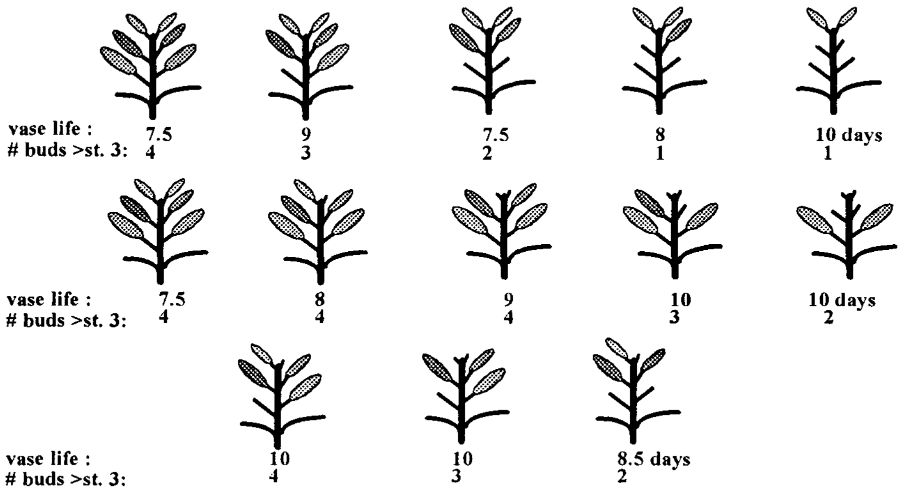


Fig. 6. Simulated effect of the number of buds present at harvest of the inflorescence and their development stages on length of vase life and ornamental value (number of buds that reach at least development stage 3 (= orange coloured bud)) of lily.

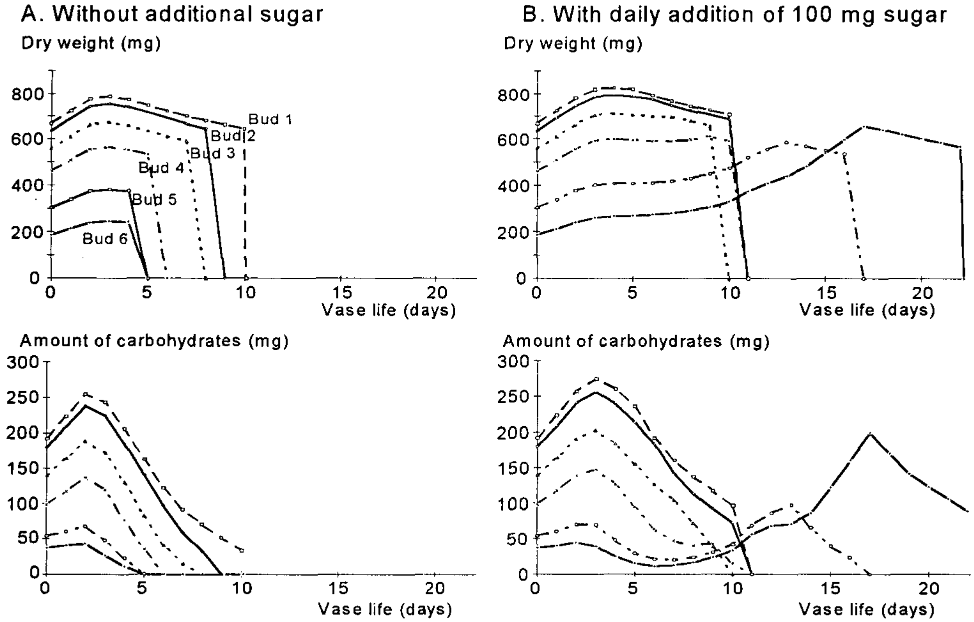


Fig. 7. Simulated effect of a constant sugar addition to the vase water on dry weight and carbohydrate amount of lily cut flowers. It is assumed that the inflorescence is composed of 6 florets, is harvested in the commercial harvest stage (developmental stages at harvest: bud 1 + 2: 3; bud 3: 2.7; bud 4: 2.5; bud 5: 2 and bud 6: 1.5), had an initial carbohydrate amount of 1200 mg in the stem and took up 100 mg of sugar each day.

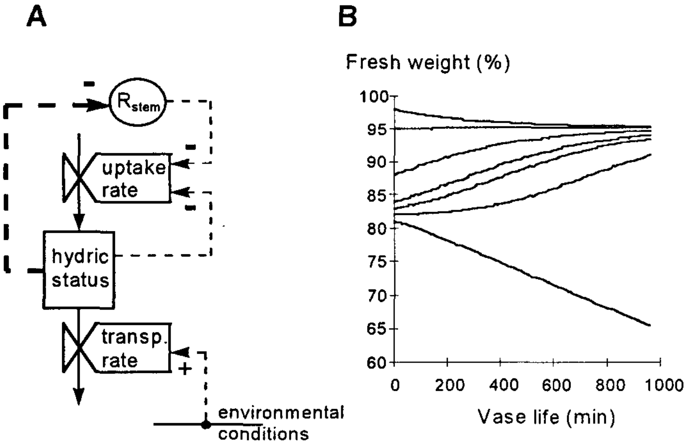


Fig. 8A. Relational diagram of water balance of a cut flower when it is assumed that the stem resistance for water transport is negatively influenced by the hydric status of the cut flower. B. Time curves of fresh weight as result of the relational diagram in Fig. 8A for various hydric status at start of the vase life.

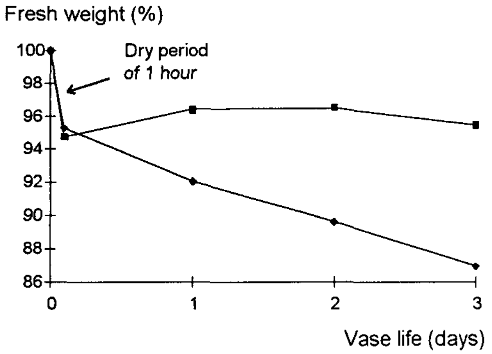


Fig. 9. Time curve of fresh weight of chrysanthemum cut flowers after harvest. After harvest, flowers have been fully saturated with water, followed by a desiccation period of one hour, before vase life at 20°C. Flowers were cut at the soil level (◆) or 10 cm above soil level (■).

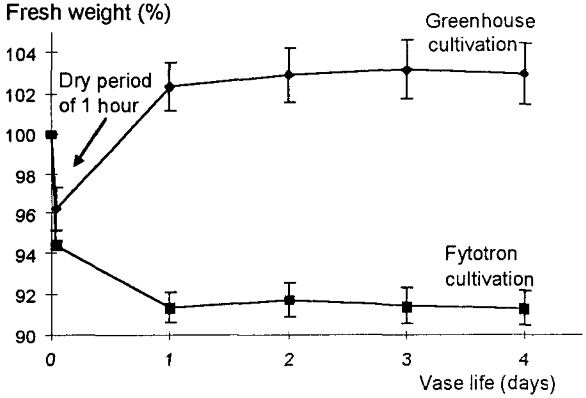


Fig. 10. Time curve of fresh weight during vase life of two lots of cut chrysanthemum flowers, either grown in a greenhouse (◆) or in a climate room (■). After harvest, flowers have been fully saturated with water, followed by a desiccation period of one hour, before vase life at 20°C. After Van Meeteren and Jordi (1997).