Modelling Postharvest Quality Behaviour as Affected by Preharvest Conditions

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INTRODUCTION

Some hundred years ago, wise men decided that preharvest research and applications had to be regarded separated from the postharvest handling and behaviour. Over the years, both areas developed completely separated. Control over both areas was obtained by different companies and advisory boards, with mostly not too good means of communication between them. This decision hampered seriously the consistent and integral development of knowledge on food production and usage. Bridging the gap between all the knowledge and expertise available in the preharvest area of growing food and the postharvest area of storing and processing food, has become and is still becoming more and more important over the last couple of years.

In this paper, based on theoretical considerations, on plausible (but unproven) mechanisms and applying the fundamental rules of chemical kinetics, a pathway to deduce general and generic models is developed towards a possible approach to integrate all available knowledge.

Still the validity of this approach is not proven. However, a number of examples from both the applied as well as the fundamental point of view are elaborated to indicate such an interaction exists, and to indicate how to tackle the modelling problem.

The examples range from physiological disorders like core brown, internal brown, chilling injury and the biological age of individual tomatoes in truss tomatoes as related to the maturity at harvest.

GENERAL AND GENERIC PRINCIPLES

The quality as perceived in the post harvest chain, has to be generated during the growth of the products. However, as already mentioned, quality attributes for growing are not the same as for storage and consumption. As a consequence, not too much is known how storage and consumption quality is actually produced. The fact that postharvest quality attributes are ill defined during the growth phase and that no sufficient accurate measuring methods are available does not improve the situation. Appropriate properties can therefore not be studied directly: all growing fruits are hard and most of them are green at any stage of growth. The riddle has therefore to be tackled in an indirect way.

Based on general available knowledge, a plausible mechanism of occurring processes has to be assumed, and tested against available data as good as possible. To ensure full generic applicability of the developed models, the conversion of mechanisms into differential equations can be and has to be conducted by applying the fundamental rules of chemical kinetics and physics. From the differential equations to practical models, useful for standard statistical analysis, is only a minor and easy step.

Of course, the selected mechanisms are most of the time massive simplifications of the real mechanisms at work. Selecting appropriate mechanisms for testing is therefore of utmost importance, but equally of utmost difficulty.

PRACTICAL AND THEORETICAL EXAMPLES

Dry Matter during Growing

For the production of dry matter as an example, three assumption are made:

- Dry matter (DM) is considered as the total of nutritional (sugars) and structural

(cellulose, pectin) compounds.

- The accumulation of e.g. dry matter (DM) is governed by formation catalysed by some enzyme (E) out of the daily made photosynthesis assimilates (reaction 1 in eq 1).
- the active enzyme is formed out of a limited amount of enzyme precursor (SE) by autocatalytic formation (reaction 2 in eq 1).
- dry matter (especially the nutritional compounds) is concurrently converted into structural biopolymers like pectins and cellulose and consumed in maintenance and respiration reactions (reaction 3 in eq 1).

The resulting mechanism could look like eq. 1.

$$E \xrightarrow{k_g} DM + E$$

$$SE + E \xrightarrow{k_e} 2 \cdot E \qquad \text{eq 1}$$

$$DM + E \xrightarrow{k_{dg}} E$$

This mechanism can be converted into a set of differential equations as shown in eq 2.

$$\frac{dE}{dt} = k_e \cdot E \cdot SE$$

$$\frac{dSE}{dt} = -k_e \cdot E \cdot SE \qquad \text{eq 2}$$

$$\frac{dDM}{dt} = k_g \cdot E - k_{dg} \cdot E \cdot DM$$

For values of parameters shown in Table 1 entirely imaginary values were used. The behaviour of DM accumulation during growth looks as an asymmetrical sigmoidal curve as shown in. This resembles pretty much the usually observed increase of total dry matter in growing plant parts and fruits (Marcelis and Heuvelink 1990, De Koning 1994). The interesting aspect of this mechanism is that the eventually reached maximum level of dry matter only depends on the ratio of the rate constants k_g/k_{dg}, and not on any of the initial conditions (parameters with index 0 in Table 1). Since these rate constants do depend on temperature according to Arrhenius law, this signifies that the maximal obtainable level of dry matter depends on the temperature history during growth. It has been reported (De Koning 1994) that the level of dry matter in fruits decreases with increasing temperature during growth. This implies that the temperature susceptibility (activation energy) for the maintenance reaction (k_{dg}) is larger than for the production reactions (k_e and $_{kg}$).

Firmness Behaviour with Harvest Maturity

Applying the same model to firmness development (substituting DM for F), a similar behaviour is obtained (Fig 1). It should be stressed here that dry matter is usually expressed as absolute mass. However, as the absolute amount of dry matter and the absolute amount of firmness generating compounds like cellulose and pectins, increases during growth, the amount of water also increases. Expressed on a fresh weight basis, the dry matter of fruits decreases somewhat over the growth period (Ehret and Ho 1986). No data are available to support this deduction for firmness. So, it is very likely that the firmness, expressed as concentration, does hardly change during the production period up to the moment ripening at the three starts. For the amount or concentration of enzymes important in postharvest quality decay, even less is known. But certainly, these levels will increase with increasing fruit maturity.

A possible mechanism could be the formation of an inactive enzyme precursor (Ep) during growth that is gradually converted into an active enzyme (E) during storage (eq 3) catalysing firmness (F) decay.

$$SEp \xrightarrow{k_{ep}} Ep$$
$$Ep \xrightarrow{k_e} E \qquad \text{eq 3}$$
$$F + E \xrightarrow{k_s} E$$

The effect of harvest time ranging from 12 (dark line) to 40 (light line) is shown in Fig. 3 (enzyme) and Fig. 4 (Firmness). The applied values for the parameters are shown in Table 2. As can be seen, the moment of harvest, or better the development stage of the product, has a marked effect on postharvest behaviour of firmness, but no effect on the initial firmness. The same general behaviour has been observed and described for accelerated firmness decrease in apples after prolonged CA storage (Tijskens et al. 1999).

Physiological Disorders

1. Chilling Injury. The occurrence and effects of chilling injury for bell peppers and cucumbers was modelled by Tijskens et al. (1994a, 1994b) as a kind of deferred action, where the seeds of chilling injury were induced by free radicals during cold storage, which subsequently show up during post-storage shelf-life exposure. Radicals are generated in all living individuals, plant and animal, as an inherent part of respiration and photosynthesis. To prevent damage by accumulating free radicals, scavenging systems are present in all species. The activity of this scavenging system, that is the specific rate constant of scavenging (k_r), multiplied by the molar concentration of the scavenging compounds (Sc) like e.g. antioxidants and specialised enzymes, almost certainly depends on the growing conditions and harvest maturity. In the case of bell peppers and cucumbers, it has been deduced that the threshold level of free radicals, that is the amount of free radical that just can be scavenged without doing damage, depends on this level of the scavenging system (eq 4).

$$R_{thr} = \frac{k_i}{k_r \cdot Sc - k_s \cdot M} \qquad \text{eq 4}$$

where k_i is the rate constant of influx of free radicals from photosynthesis and respiration, k_r is the rate constant of scavenging, k_s the rate constant of formation of chilling injury, Sc is the level of available scavengers and M is the (constant) amount of membranes present. The larger the scavenging efficiency ($k_r \cdot Sc$) is the less free radicals (R_{thr}) can exert damage to the product. In Figure 5 an example is shown of the accumulation of free radicals. To get some reliable prediction of possible occurrence of chilling injury, we need to know how these antioxidants are produced and stored during growth, and we need means to assess and measure the levels of these compounds.

2. Ca Related Disorders. Recently a research proposal has been submitted to EU that reflects the need to understand in a more generic fashion how calcium deficiency affects a number of physiological disorders like bitter pit, blossom-end rot and tipburn. In this proposal it is stated that: *"Within Europe the occurrence of calcium-related disorders (CaRD) causes heavy losses in a wide range of fresh produce and a consequent loss in revenue for all those involved in the production chain. The magnitude of the losses varies from year to year and between consignments and is largely unpredictable. There is a need for a model capable of predicting the occurrence and intensity of calcium-related disorders for all types of fruits and vegetables."*

The action of Ca is believed to be generic in all plant tissue, only different in apparent effect as a consequence of different levels of important compounds. One of the reasons for these different levels is expected to be the actual growing conditions of the produce.

1. Core and Internal Brown. Studying internal browning in pears (cvs Rocha and Conference), Veltman et al. (1999a, 1999b, 2000) found a relation between the occurrence and incidence of this physiological disease and the concentration of ascorbic acid in the tissue (see Fig. 5 and Fig. 7). Ascorbic acid is known to be a very effective

scavenger of oxygen free radicals. Different storage regimes like enhanced carbon dioxide and reduced oxygen partial pressures differently affect the decrease of ascorbic acid in the tissue after harvest. This is in accordance with the general observation that a decrease of the respiration rate (by the lower availability of oxygen), involves a decrease in the activity of several other physiological processes as well. Storage at enhanced carbon dioxide levels results in less a predictable picture; ascorbic acid levels are normally decreased by a factor 2-3 (at 5-10 kPa), while the respiration rate is not necessarily reduced. This suggests a possible negative effect of carbon dioxide on the anabolic route leading to ascorbic acid.

What is more relevant to the framework of this paper, is firstly that the appearance of the internal browning disorder among other factors depended on harvest (see several picking times in Fig. 5 and Fig. 7), and secondly on the amount of ascorbic acid present in affected pears. Maturity of the fruit depends on harvest time, but interestingly maturity stage after ripening on the shelf does not or nearly not seems to affect ascorbic acid concentrations. For understanding the behaviour of internal browning in pears of different growing seasons and of pears from different orchards in one season, the production of antioxidants like ascorbic acid in growing plants and fruits should be described.

Quality Variation in Truss Tomatoes

The colour of tomato changes during ripening according to a sigmoidal behaviour that frequently can be described by the logistic function (Tijskens & Evelo 1994c). Each tomato however, has its own stage of development, expressed as biological time tm.

In a large dataset on truss tomatoes, the colour of tomatoes of two cultivars (Durinta and Clothilde) harvested at three development stages (green, breaker and ripe) was followed individually during storage. All data could be analysed together, only allowing for separate values for the time at harvest tm. The mean value of tm was of course highly correlated with the maturity stage at harvest: the later the harvest time, the higher the obtained tm value (Fig. 8).

$$C = C_{min} + \frac{C_{max} - C_{min}}{1 + e^{k \cdot (t + tm)}} \qquad \text{eq 5}$$

However, the variation around the obtained mean (difference between actual and mean tm value) showed striking similarities irrespective of the maturity at harvest (Fig. 9). Analysing the difference to the mean value (see Table 3), all differences show the same behaviour (eq 6) as function of the location of the tomato in the truss with an explained part (R^2_{adj}) of well over 93%.

$$tm = tm_{fix} + tm_{var} \cdot e^{k_v \cdot Fruitnr} \qquad \text{eq 6}$$

Apparently, the variation in maturity in tomatoes does not depend on the cultivar or the actual ripeness of the individuals. For normal, non-truss tomatoes, it is quite likely that the same relations hold, what would indicate that in batches of tomatoes, always the same variation and distribution in properties is present, irrespective of the maturity and cultivar. So, this is actually an example of the contrary of what we hoped and expected to find. It would also indicate that for tomatoes, the actual growing conditions are not that important for the behaviour of colour. Most probably, the mechanism of growing colour and the associated enzymes is such, at least for tomatoes, that it affects only in a minor way the behaviour of colour in the post harvest storage.

CONCLUSIONS

In all these examples, the seeds of postharvest behaviour are generated during the growing period. The different conditions of growth (climate, radiation, rainfall, soil type, fertilisation, maturity at harvest etc.) have their effect on the available levels of substrates, precursors and enzymes. During subsequent storage, these different levels of available compounds will induce, each by their own mechanism, different behaviour of a vast range of product properties and related quality attributes.

A direct consequence of this line of reasoning and research is that during storage, even when applying the most sophisticated techniques and technologies, occurrence of physiological disorders and excessive quality decay can only be retarded and not be avoided. Avoiding disorders and excessive quality decay during storage can only be achieved by appropriate action taken during the growth period.

Another consequence of this approach is that the variation in growing conditions over the different seasons and growing areas is reflected in a sometimes-erratic behaviour and occurrence of this type of disorders and undesirable behaviour of quality attributes.

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Tables

Table 1. Parameter values for DM and firmness simulation based on eq. 2.

Parameter	DM	Firm
E_0	0.1	0.01
DM_0	0.01	0.01
SE_0	20.	2
k_g	0.15	1
k_{dg}	0.01	0.05
k_e	0.1	0.5

Table 2. Parameters used in eq 3.

Parameter	Value
SEp_0	2
Ep_0	0.1
E_0	0.01
F_0	5
k_s	0.5
k_{ep}	0.01
k_e	0.05

Table 3. Result of statistical analysis of individual tm deviations.

Name	Estimate	s.e.
k_v	0.676001	0.102
Δt_{var}	-0.327	0.188
Δt_{fix}	3.897	0.545
N_{obs}	29	
R^2_{adj}	93.8	

Figures

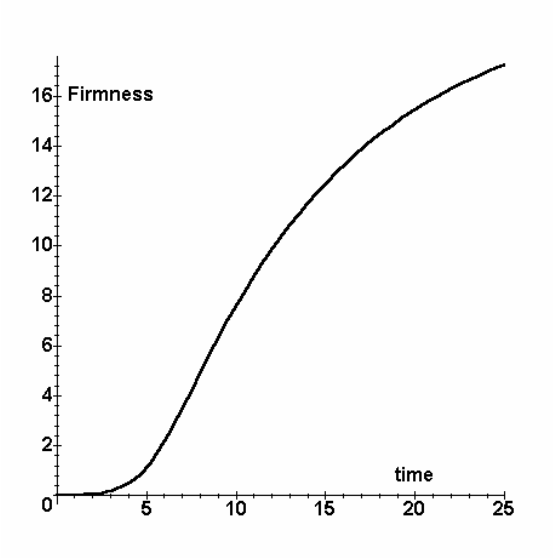

Fig. 1. Producing fruit firmness (not including ripening at the tree), based on the same assumed mechanism of eq. 1 and parameter values in Table 1.

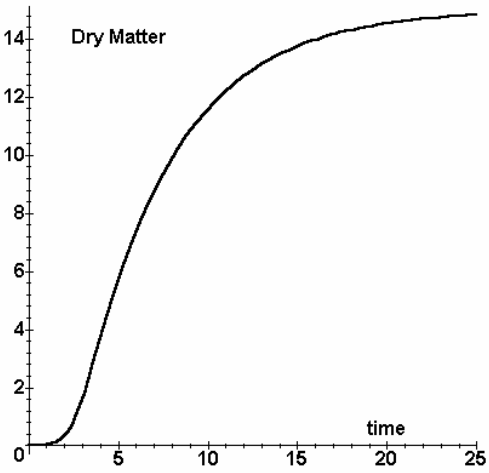

Fig. 2. Possible behaviour of dry matter accumulation in plant organs, based on the assumed mechanism of eq. 1 and parameter values in table 1.

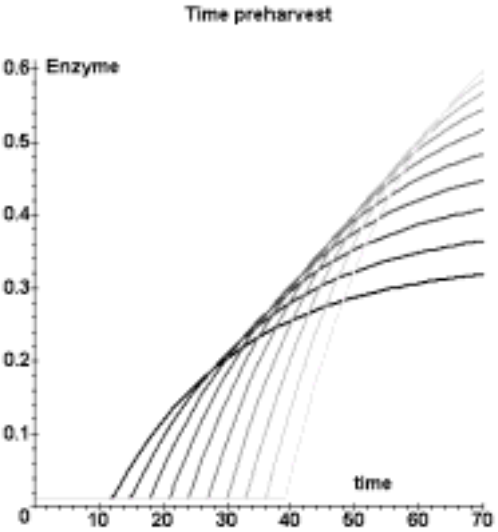

Fig. 3. Accumulation of active enzyme according to eq 3, with time expressed in growing time depending on the moment of harvest.

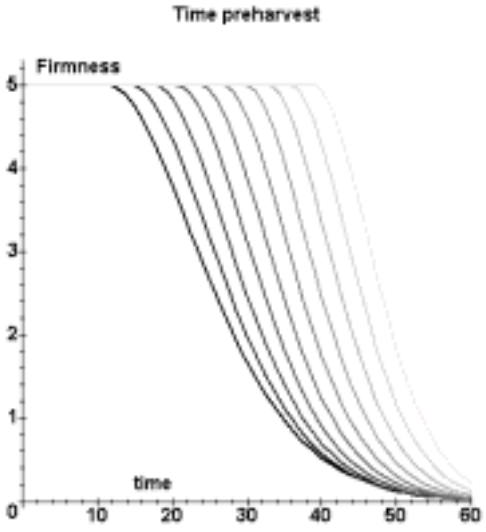

Fig. 4. Decay of firmness according to eq 3, with time expressed in growing time depending on the moment of harvest.

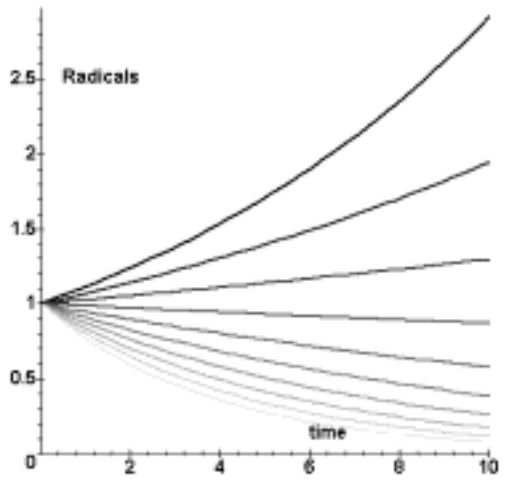

Fig. 6. Accumulation cq decrease of free radicals in cucumbers at 14 ºC, for relative scavenger levels ranging from 0 (black line) to 1 (light line), based on the model and data provided in Tijskens et al. 1994a.

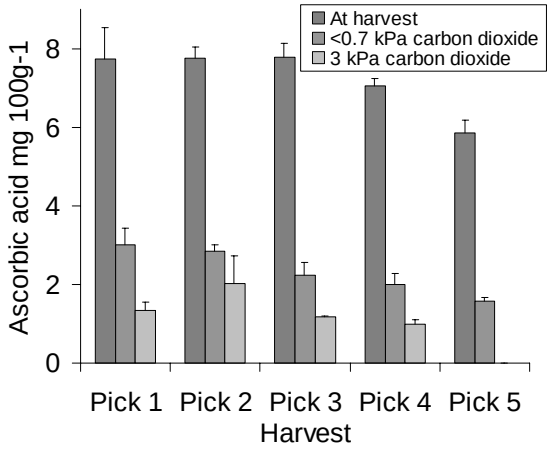

Fig. 5. Ascorbic acid concentration in pears at harvest and after 3 months storage on average at 2 kPa oxygen with <0.7 kPa or 3 kPa carbon dioxide. Pears were harvested in Ommeren (The Netherlands) at 3, 10, 16, 24 September and 1 October (Pick 1 to 5 respectively). Measurements were done at 22 December.

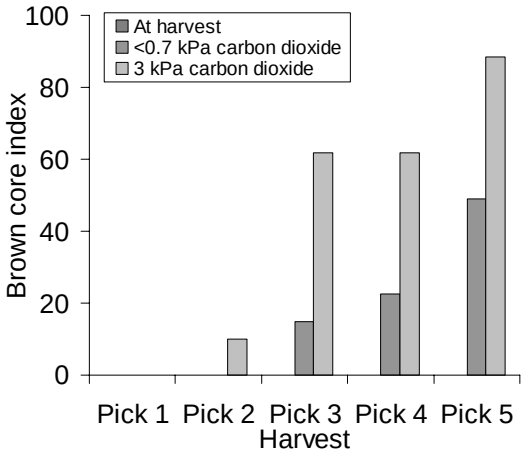

Fig. 7. Index of incidence of brown core in pears at harvest and after 3 months storage on average at 2 kPa oxygen with <0.7 kPa or 3 kPa carbon dioxide. Pears were harvested in Ommeren (The Netherlands) at 3, 10, 16, 24 September and 1 October (Pick 1 to 5 respectively). Measurements were done at 22 December.

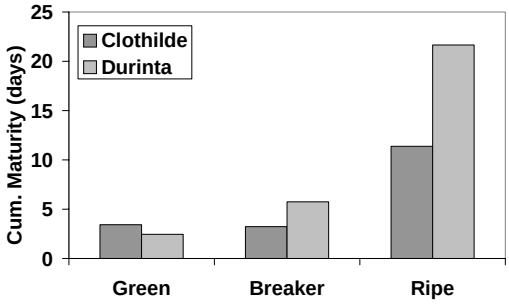

Fig. 8. Mean maturity tm at harvest expressed as days of development. A clear effect of the maturity at harvest is reflected in the higher values for maturity for different stages of development, as should be expected.

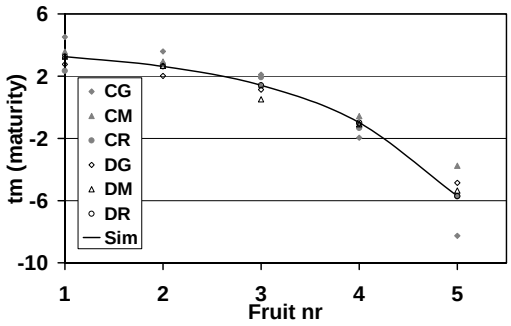

Fig. 9. Estimated values of individual differences between actual maturity and mean maturity (tm) as function of the location in the truss for both cultivars and all three stages of maturity at harvest (Symbols = measured, line = simulated).