The intelligent container for banana transport supervision and ripening

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Abstract

Bananas differ from other fruits by the fact that a special ethylene treatment is applied in the destination country to turn 'green' into ripe bananas. Moderate differences in bunch age at harvest, transport duration and temperature have no measurable effect on the fruit quality after ripening as long as the bananas are maintained in a mature green state with no signs of unwanted self-induced ripening (turners) before ethylene treatment. Therefore, systems for automated transport supervision should focus on the detection of turners by higher respiration activity and gas production as well as by the detection of potential hot spots caused by high respiration heat in combination with insufficient air flow through the affected pallet. Under optimal cooling conditions, the subsequent ripening process can be carried out directly in the container. This paper will focus on three topics related to meeting this challenge. Firstly, the technical system of the intelligent container for remote on-line supervision of transports, which has been tested during three transports of bananas from Costa Rica to Europe, but can also be used for different types of perishable products. Second, a simple heat transfer model is introduced which allows estimating index values for local cooling effects and respiration activity per pallet from the measured temperature curves. The model can thereby predict the risk of hot spots. Finally, we present the first test results for container ripening of bananas. The major obstacle therein is the large amount of heat generated during the process, which is about 5 times higher than during the transportation of green bananas. We applied different modifications in the packing scheme to improve the air flow, which showed clear benefits with regard to the amount of heat removed by cooling.

INTRODUCTION

Product losses in the food chain sum up to 35% on average (Scheer, 2006). Although only 5% of losses are assigned to transport and processing, there is a high share of 'hidden' losses caused by inadequate transport conditions. Unprocessed agricultural products are in general not labelled with best-before / use-by dates. But they have a limited and often unknown shelf life. A red tomato might start to decay the next day or in two weeks. A green banana can start to ripen without an external trigger after a delay depending on harvest and transport conditions, but without any visible indicators for the duration of the remaining green life. Products with low shelf life are generally not detected during handling in the transport network, but they will be disposed of early at the store or consumer level without attaining the expected storage period.

Because manual quality inspection can hardly be carried out in each step of the supply chain, a reduction of the obvious and hidden transport losses can rather be achieved by a continuous and remote supervision of temperature deviation and risk assessment by biological and/or thermodynamic models. The freight operator should know the expected quality state of foods inside a truck or container without opening the doors, even before arrival. As a consequence, he can assign products with low remaining shelf life to a shorter distribution route. For example, such products can be sent to a shop with high turn-over to be sold faster (Scheer, 2006).

The design and implementation of such supervision systems require a multidisciplinary approach: Researchers from sensor technology, electronics, communication science, and food biology have to cooperate with practitioners from transport and food business. During the intelligent container project (Institute for Microsensors, 2013), sponsored by the Federal Ministry of Education and Research in Germany from 2010 to 2013 we were able to bring the required experts together. Six research institutes from electronics, logistic systems, agricultural technology and animal science cooperated with 14 partner companies covering fields from food suppliers, transport operators, container modification, truck and satellite telematics, wireless sensors, embedded software and data base services.

The main goal of the project was the construction of a container prototype for remote quality supervision and providing similar services for reefer trucks. In order to reduce communication costs, measurement data is directly processed in the container. The container only communicates warning messages if a critical state is detected. The sensor system of the intelligent container comprises a set of wireless temperature and humidity sensors to detect local maximal / hot spots and gas sensors for CO_2 and ethylene (Janssen, 2014), wherein the latter one is currently only available at lab-scale. Field tests were carried out for road transport of meat in North-Europe and for containerized transport of bananas from Central America to Europe. In this paper we will focus on topics that are special to the food chain for bananas, such as the high respiration activity during transport and the artificial ripening process, and on results from the related field tests.

TECHNICAL SYSTEM OF THE INTELLIGENT CONTAINER

The technical system of the intelligent container comprises interfaces for internal and external wireless communication as well as a Freight Supervision Unit (FSU) that links these two devices together and processes the sensor data (Fig. 1). The FSU is also able to access and control the setup of the cooling unit. The Thermoking Magnum Plus unit is equipped with an Advanced Fresh Air Management (AFAM) system, controlling a fresh air vent to attain a certain CO_2 level by self-respiration. Both the temperature and the AFAM settings can be adjusted by the FSU.

Two sets of wireless sensors with 20 devices each were packed inside the banana boxes. The sensors operated in the 2.4 GHz frequency range based on the 802.15.4 standard. The two sets enabled us to test and compare different network protocols including the proprietary BananaHop protocol (Jedermann, 2011), which was optimized for our experimental setup and a more general solution, which allowed IPv6 addressing of individual sensors from the external internet (Becker 2012).

The high water content of bananas and the high relative humidity between 80% and 100% in the container turned out to be a major obstacle to transmit sensor data from the inside of a pallet to the FSU mounted close to the cooling unit. Due to the high signal attenuation, messages had to be forwarded over multiple hops to reach the data sink. Even for distances of 50 cm, one third of all links failed, another third was only temporarily available and only the last third provided stable communication (Jedermann, 2011). An improvement is expected from using lower frequencies, such as the dash7 standard at 433 MHz, but related sensor notes are still under development.

The FSU processes the received sensor data and forwards generated warning messages over a commercial telematics unit, either by an Iridium satellite link or cellular GSM networks. Programming of the FSU can also be done remotely: The JAVA / OSGi (Open Source Gateway Initiative) framework (OSGi Alliance, 2013) enables one to administrate and update software components over the network, for example to install new quality supervision tools for a certain product. The temperature and quality data are made available by an internet service, either as web-page or as email notification. The server is also able to interconnect with company specific data bases.

QUALITY SUPERVISION FOR BANANAS

The transport and processing chain for bananas, which had been supervised in our field test, had the following structure: Harvest and packing at a farm in Costa Rica (~ 8 hours), transport to harbour (~ 12 hours), sea transportation to Antwerp under modified or controlled atmosphere and cooling from ~26°C to 14°C (2 weeks), handling and road transport to Germany (1 day), gasing with ethylene and ripening (6 days).

Quality problems became obvious mainly at two stages of the chain: At arrival in Europe and after the ripening process: a) A low percentage of containers arrived in a poor quality state. Besides infections with mould, an early start of the ripening process during transportation (turners) is the main quality problem in the banana supply chain. b) The goal of the ripening process is to produce bananas with an even ripening stage. Typically, the retailers demand a ripening stage of 4 (more yellow than green). Especially, if cooling was interrupted during transport, the ethylene induced ripening can produce large variations in the ripening stage at the end of the process, leading to rejection by the retailers. In order to detect related quality problems as early as possible, we evaluated possible influence factors to the ripening result in lab-experiments.

Influence Factors to the Ripening Result

'Cavendish' bananas from Costa Rica (Dole company) were transported by container shipment and truck to Germany (Potsdam) in order to estimate the influence of bunch position, bunch age at harvest and transport temperature on the ripening behaviour of the fruits. For ripening assessment, the parameter NDVI (normalized difference vegetation index) was measured with a hand-held spectrometer (Pigment Analyzer, CP Falkensee, Germany). NDVI reduction indicates chlorophyll loss in plant material and is calculated from the reflected light intensity in the following manner: NDVI= (I 780 nm – I 660 nm) / (I 780 nm + I 660 nm). Additionally other quality parameters have been measured like elasticity with a Texture Analyser (TA.XT.plus, Stable Microsystems, UK) and total soluble solids (TSS) with a digital refractometer (ATAGO PR 1, Leo Kuebler GmbH, Karlsruhe, Germany).

During 9 days after the ethylene treatment at 18°C temperature, the fruits changed from ripening stage 2 to stage 6. The NDVI decreased due to yellowing and TSS increased because of starch conversion to sugars (Fig. 2). Ripening behaviour of fruits from 14 week old bunches (time after flower emergence) did not differ from fruits of 15 week old bunches. No significant ripening retardation of the younger fruits from the bottom of the bunch (hand 7 & 8) could be observed compared to the older fruit at the middle (hand 4 & 5) or the top of the bunch (hand 1 & 2). Similar observations were made by Ahmad et al. (2001), who estimated that the ripening differences of the bunch position cannot be perceived in a commercial situation. Contrary to that, Mustaffa et al. (1998) found a significant influence of the bunch position on the ripening behaviour for fruits harvested between week 3 and 15, but probably due to the fact that in their experiment the fruits ripened on the bunch and not in a ripening chamber after ethylene treatment.

During an additional test, to determine the influence of transport temperature on the duration of the green life, the NDVI was measured using bananas from 20 transport boxes after a two-week container transport under modified atmosphere with 2% CO_2. The bananas were loaded with a temperature between 26.2°C and 26.9°C. Until unloading, the temperature decreased to values between 13.8°C and 14.7°C. Due to differences in the speed of cooling the average temperature during transport varied between 15.3 °C and 17.5°C. The NDVI of the green-ripe fruits after arrival in Potsdam varied between 0.16 and 0.41 and decreased during the following 3 weeks, but there was no relation between the average transport temperature and yellowing of the fruits (Fig. 3).

These results show that bunch position of the fruits, and moderate variations of bunch age at harvest and transport temperature had no measurable effect on the ripening behaviour of the fruits. The only measurable condition for a good ripening result is that the bananas are in a proper green-ripe maturity stage 2 (NDVI > 0), at which stage the bananas proved to be a stable product.

Automated Supervision

Bananas in the load with a higher respiration activity due to premature start of the ripening process, so called 'turners,' support the development of local hot spots in which the bananas produce more thermal energy than can be removed by the cooling unit. The resulting temperature rise leads to an even higher biological activity and production of ethylene which then can affect the whole container. A hot spot can be the trigger as well as the result of turners. The main task for an automated transport supervision system should be the detection of such critical states that can lead to a hot spot as early as possible. Prediction of such risks by warning messages transmitted before arrival of the ship in Europe is of high commercial value: Technical problems and power failures are detected immediately. In other cases, the information can be used to instruct the farmer to harvest at an earlier physiological stage to avoid further quality problems. Pallets with turners will be rejected by most customers. Early information about quality problems helps to organize a replacement delivery in time, especially if the banana boxes are branded for a certain customer.

Indicators for Turners by Temperature Measurement

Once the generated heat oversteps the energy removed by cooling, the hot spot can be easily detected by an increasing temperature curve. But in order to detect critical conditions before a hot spot arises, it is necessary to isolate these two effects from the resulting temperature curve.

Based on the measurements by the wireless sensors and additional data loggers during 1 test offshore and 2 tests ashore, we developed an empirical model (Jedermann, 2013), (Fig. 4) to predict temperature changes in the centre of a banana box as a function of air supply temperature as input and two variable parameters, which can be ascribed to respiration activity and effectiveness of cooling. The model contains two delay elements to represent the thermal capacity of approx. 18 kg bananas per box. The model has now been verified by 2 additional tests offshore and 3 tests ashore.

Although the model does not describe an exact physical representation, it turned out to be very useful to fit measured temperature curves in banana containers under various conditions such as normal/controlled atmosphere, initial temperatures between 14°C and 25°C, tests offshore and ashore, and step up/down changes of the set point. The part of temperature changes per hour that is caused by respiration ΔT_{Resp} can be calculated according to Eq. (1) with the proportional factor k_P. With a Q_{10} factor of 3 we achieved the best fit for the measured curves:

$$\Delta T_{Resp} = k_P \cdot e^{\ln(Q_{10})\cdot(T-13°C)/10} \quad (1)$$

A Matlab script was used to compute k_P as well as the parameter k_M as indictor for the effectiveness of cooling. Fig. 5 shows temperature curves recorded offshore / ashore and fitting by the model. By identification of k_P, it is possible to evaluate which share of temperature changes was caused by respiration. The part of temperature change ascribed to cooling ΔT_{Cool} can be calculated by subtraction of ΔT_{Resp} from the total temperature change. Multiplication with the constant C_P=930.5 W·s/(K·t), which includes the thermal capacity of bananas of 3,350 kJ/K and a conversion from hours to seconds, leads to a description of heat transfer in the unit of power (W/t). Example values for P_{Resp} and P_{Cool} calculated based on the measured temperature curves from various experiments, for a box temperature of 15°C and air supply temperature of 13°C, are given in Table 1. Depending on the conditions listed in Table 1, cooling can be very fast or fail completely. For example, under controlled atmosphere bananas produce 16.1 W/t heat by respiration. If the pallets are packed and loaded correctly to the container, the unit can remove 58.7 W/t which is far more than sufficient. If no atmosphere control is applied, the bananas produce 50.3 W/t heat; packing mistakes such blocked or closed gaps can lower the efficient cooling capacity to 41.6 W/t. The generated heat cannot be removed and a hot spot is created.

IMPROVEMENT OF PACKING AND CONTAINER RIPENING

Especially equipped chambers ashore are normally used for ethylene gassing and ripening of bananas. Shifting the ripening process into a container on board the vessel will bring large economical benefits in terms of saved time and equipment ashore. The main challenge in container ripening is the removal of the generated heat. Applying a reversed calculation of the model given in Fig 4 to the measured temperature curves resulted in heat production between 70 and 115 W/t at 15°C during ripening, which is up to 7 times more than under optimal controlled atmosphere transport conditions. Container ripening is therefore only feasible, if the efficiency of cooling system is improved. We introduced the following 4 measures to improve the air flow around and through the pallets and boxes: a) Spacers at the wall sides of the pallets prevent closed gaps. b) The loading scheme of pallets inside the container was modified to create 5 'chimneys' surrounded by 4 pallets each to increase the airflow between the pallets. c) A new box design was introduced by Dole with 8 additional 3.5 cm wide holes, the so called score vents. d) The packing of bananas inside the box was changed to enable an increased vertical air flow through the boxes. In total we could increase the amount of heat that can be removed from the bananas by 57% from 58.7 W/t to 92.1 W/t. If the set point is lowered by 0.5°C to 12.5°C, the heat removal can be increased to 114.6 W/t, which is sufficient to keep a temperature of 15°C.

From July 2012 to May 2013, three tests for container ripening were carried out with 8 pallets per container. Application of the measures described above to improve the air flow led to good ripening results with a ripening stage between 3 and 4 after 6 days, whereas the first test in which only a), b) and c) were applied had to be stopped one day ahead of schedule because the temperature rose above 18°C in some pallets. Careless packing during the last test also caused a temperature increase in some boxes up to 17°C, but no quality problems.

SUMMARY AND OUTLOOK

As long as hot spots can be avoided, bananas turned out to be a very stable product. Moderate deviations in bunch age and transport temperature had no influence on the ripening result. Hot spots can emerge during transport and particularly when the ripening process is carried out inside the container. The risk for hot spots can be predicted at an early stage by calculation of the thermal balance between generated and removed heat. The effect of modified packing schemes was evaluated by this approach. Cooling could be sufficiently improved to enable container ripening.

An enhanced system for banana supply chain supervision and planning should also include measurement of CO_2 production rate as an indictor of higher biological activity. A prediction of remaining green life at arrival in Europe can lead to a FEFO (First expired first out) strategy, in which containers in a critical state are assigned to immediate processing in facilities close by, whereas containers with a high predicted green life are used for intermediate storage or export to remote customers. These aspects will be discussed in a later paper.

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Tables

Table 1. Average values for generated respiration heat and removed heat per ton bananas under various conditions. All values are related to a box temperature of 15°C and supply air temperature of 13°C if not stated otherwise.

Category	Condition	Heat [W/t]
Respiration during transport of green bananas	Controlled atmosphere (CO_2 4.5%, O_2 3%)	16.1
	Modified atmosphere (CO_2 5%, O_2 16%)	32.5
	No atmosphere control	50.3
Ripening heat after ethylene treatment	Box temperature maintained at 15°C	70 … 115
	Box temperature 17°C	185 … 210
Removed heat by cooling	Standard packing	-58.7
	Pallets pressed to wall	-41.6
	Improved packing	-92.1
	Improved packing / Supply air 12.5°C	-114.6

Figures

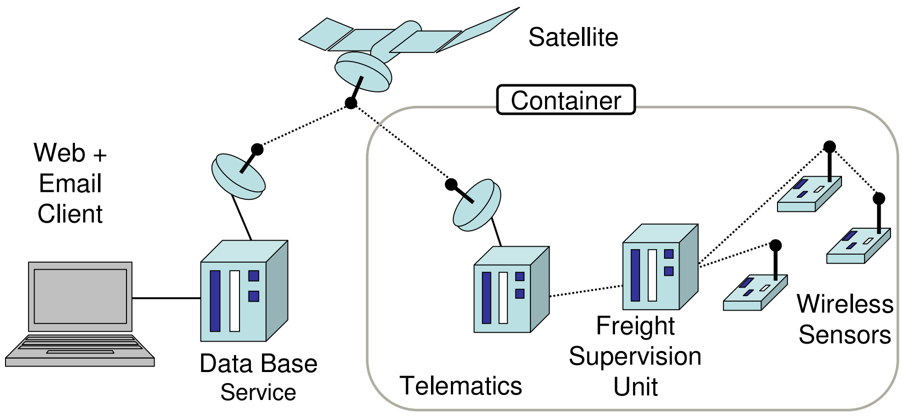

Fig 1: Communication system of the intelligent container

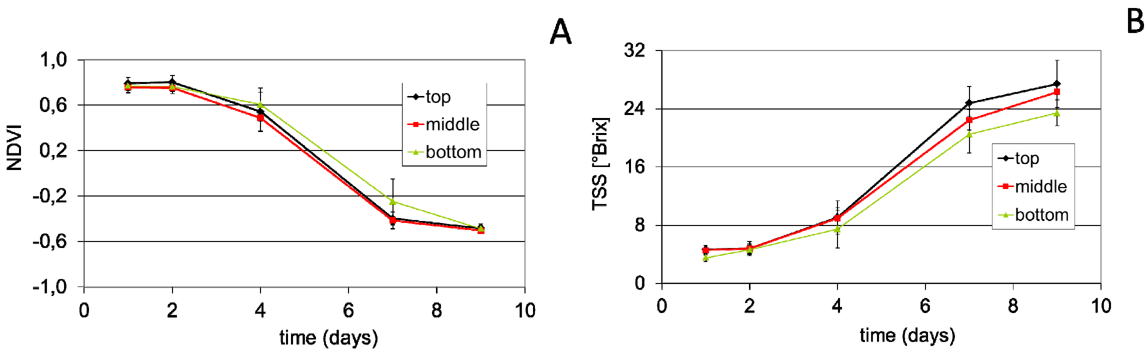

Fig 2: Change of NDVI (A) and TSS (B) of ripening bananas from different bunch positions after ethylene treatment at 18°C

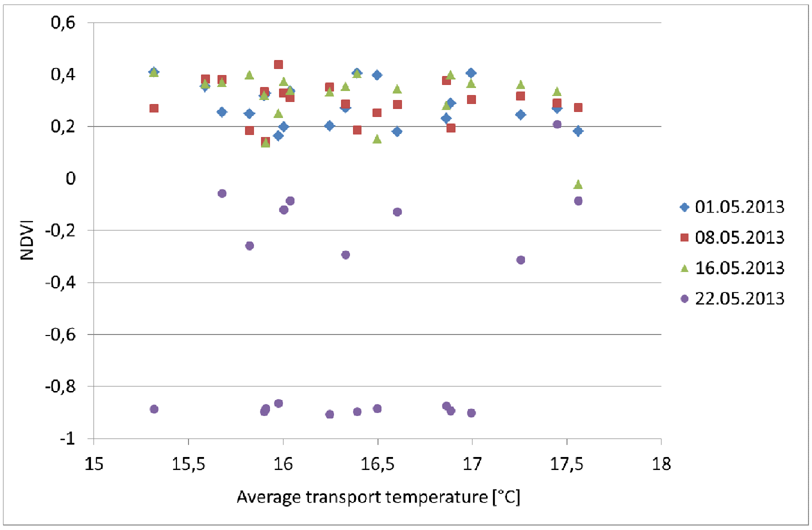

Fig 3: NDVI change of banana fruits during three weeks after arrival in Germany (1.5.2013) with average container transport temperatures in a range of 15.3°C to 17.5°C without ethylene treatment.

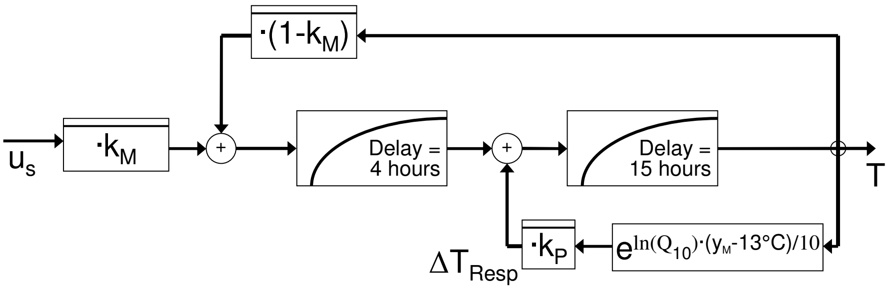

Fig 4: Model to predict box temperature T as function of air supply temperatures u_S and two variable parameters k_M and k_P.

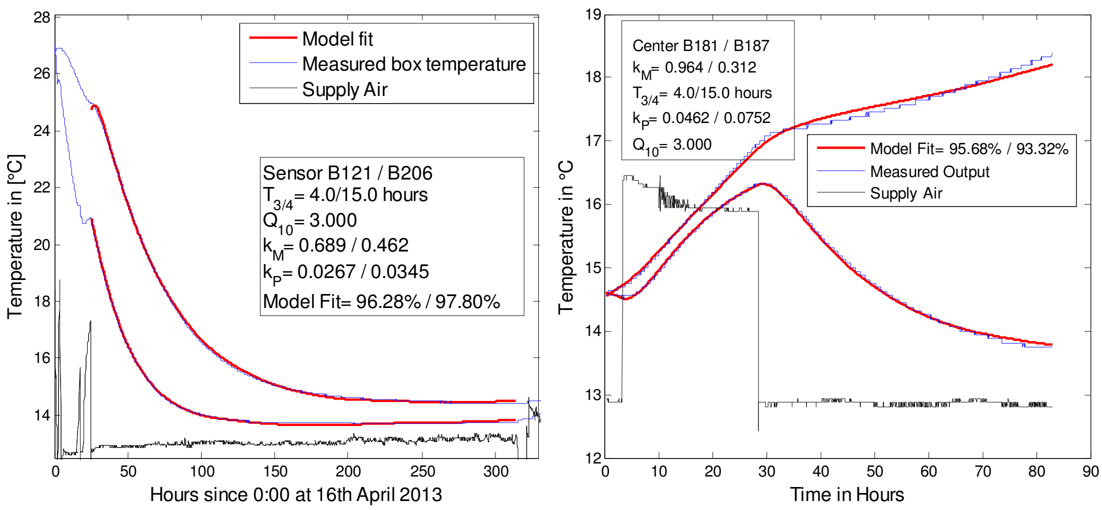

Fig 5: Comparison of measured temperature inside bananas boxes in different positions and fit by the model. Temperature variations offshore (left) and increase for a hot spot caused by simulated packing mistakes ashore (right).