THESIS OF THE DOCTORAL DISSERTATION

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Budapest

2024

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APPLE FRESH-CUT TECHNOLOGY DEVELOPMENT

DOI: 10.54598/004970

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2024

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1. INTRODUCTION AND OBJECTIVES

'Fresh-cut' is an internationally used term, which in Hungarian means washed, sliced and packaged fruit product.

World food production can be divided into two main parts. One is the group of food products sold fresh, the other is the group of products processed by the food industry. Food storage technology plays a crucial role in both food groups. The first group includes products from horticultural production, i.e. vegetables and fruit. The storage of horticultural raw material and finished products is of particular importance in the processing chain. There are now several options for the storage of horticultural products in combination with ripening inhibitors. In this case, the biological ageing process can be kept under a high degree of control. During my doctoral studies, I was involved in the development of product and production technology for freshly washed and sliced so-called fresh-cut apples, also taking into account the requirements of the Cooperative Doctoral Programme. The production, packaging and storage of fresh-cut fruits is a difficult and complex technological process due to the high respiration intensity during processing, the variability of many physical parameters affecting them and the storage sensitivity of the product. I have tried to find a complex solution to this problem. Freshly sliced, diced fruit products with a shelf life of more than 1-3 days are not available on the shelves of Hungarian supermarkets. During one of my conference trips abroad, I came across fresh-cut apples in PE bags, and after tasting them, I tasted an unpleasant aftertaste. Our world is moving towards convenience in the bumpy roads of food production and processing. Convenience, preservative-free, high nutritional content and freshness are all consumer demands for fresh-cut fruit products. Through the technology developed as a goal of my PhD work, I am confident that it will be possible to increase domestic fruit consumption, especially among young children and school-age children, even through the School Fruit Scheme. I have explored many areas of this technology and have demonstrated through experiments the factors that need to be taken into account when developing good production practices. In my thesis, I have tried to combine scientific research methodology with industrial production facilities and to approach the research topic in a complex way that can easily be applied in a real production environment.

During my doctoral training, my aim was to conduct research based on scientific approaches that could be easily transferred, as far as possible, to manufacturing technologies. In fact, my thesis is a product and technology development carried out with scientific rigour. The Cooperative Doctoral Programme is based on the principle of producing industrially applicable scientific research over the 4 years of the programme. To achieve this, I have set the following objectives:

- Development and development of processing and packaging technologies for fresh-cut apples, sliced, washed and packaged, with a minimum shelf-life of 12 days under refrigerated conditions, weighing 200 g ± 5 g.

- To prevent or reduce the browning of the flesh during processing and storage of fresh-cut apples using various substances approved for use in the food industry.

- Development of a packaging technology for fresh-cut apple products, determination of the optimal gas composition, design of micro-perforations of suitable size, comparison of the application of mechanically or laser produced micro-perforations, determination of the correlation of the specific gas permeation rate.

- Determination of the respiration intensity of sliced apples at different applied gas concentrations (reduced O_2) and exploration of the relationship between respiration and degree of processing.

- Validation of the production technology of the fresh-cut apple product as a final step in product development, in line with the requirements of the Cooperative Doctoral Programme.

2. MATERIALS AND METHOD

2.1. Apple

To determine the quality parameters, Idared apples (Malus domestica Borkh., cv. Idared) are the most abundant and best storable variety in Hungary, so I collected Idared apples from 4 different places in the country - specifically, Jánkmajtis, Vámosmikola, Pécs and Zalaszántó - to map the characteristics of the Hungarian raw materials as thoroughly as possible. From each area, I had 20 - 20 kg of control and 1-MCP (700 ppm) treated samples available for testing.

I also used Idared apple (Malus domestica Borkh., cv. Idared), provided by Agricolae Kft. (Jánkmajtis, Szabolcs-Szatmár-Bereg county, Hungary) for the study of respiration intensity and ethylene production.

For the colour fixation study, freshly picked fruit samples (Malus domestica Borkh., cv. Idared) were harvested in October 2022 at commercial maturity at the plantation of Agricolae Ltd. in Jánkmajtis, Szabolcs-Szatmár-Bereg county, Hungary. After harvesting, the samples were transported to the university laboratory.

To study the effect of altered gas concentration of sliced apple on respiratory intensity, samples (Malus domestica Borkh., cv. Idared) were taken from Zalaszántó (Zala county, Hungary). Control and 1-MCP (700 ppm) treated individuals were used in my research.

For the fresh-cut finished product, apples (Malus domestica Borkh., cv. Idared) were obtained from Agricolae Kft. (Jánkmajtis, Szabolcs-Szatmár-Bereg county, Hungary), which were control and 1-MCP (700 ppm) treated samples. The treatment was carried out within 36 hours after harvest. Approximately 4 months of refrigerated storage elapsed between treatment and experimental use.

2.2. Determination of raw material quality parameters with respect to geographical origin, anti-ripening treatments

Immediately after harvesting, the apples were placed in cold storage at 1°C, followed by 1-MCP treatment within 3-7 days. Treatment was carried out for 24 hours in closed, airtight cold stores. The concentration of the active ingredient was 700 ppm, calculated by the SmartFresh manufacturer's own system on the basis of the empty volume (m^3) of the cold room (manufacturer's recommendation). After treatment, control and treated samples were kept on a "counter" at 20±1°C for 14 days. Measurements of the initial parameters were taken immediately after harvesting, while the samples were remeasured on day 14 after storage on the counter.

Measuring of meat firmness was performed with an Effegi FT 327 (13 kg) penetrometer (Facchini, Srl., Alfonsine, Italy) using a 1 cm diameter print head (Hitka, 2011). The water soluble solids content was measured with an ATAGO Palette PR-101 (ATAGO CO., LTD., Tokyo, Japan) digital refractometer. The starch index was determined by Lugol's solution on halved fruits. The solution was a 1 litre aqueous solution of 10g iodine and 10g potassium iodide, in which iodide is able to lock the starch, thus giving a darker colour on the flesh where starch is present in higher concentrations. For the evaluation I used the CTIFL Starch Scale. Ethylene production was measured using an ICA-56 hand-held ethylene analyser (International Controlled Atmosphere Ltd., London, UK). The results were expressed in units of microlitres of ethylene produced per kilogram of fruit per hour ($\mu L \cdot kg^{-1} \cdot h^{-1}$) calculated on fresh weight.

2.3 Examination of respiration intensity and ethylene production as a function of processing degree and temperature

Respiration intensity and ethylene production of fruit samples were measured immediately after processing, at 60 min, so that in fact the direct dynamics of cellular respiration with respect to the degree of processing were investigated. For the degrees of processing (change in wound respiration surface), besides the control (unpeeled whole apples), measurements of respiration intensity and ethylene production of peeled whole apples, apple slices and apple cubes (1 cm · 1 cm · 1 cm) were performed at 1 °C, 5 °C, 10 °C and 20 °C. A distinction was made between control (denoted K) and SmartFresh™ (denoted SF) samples treated with 1-methylcyclopropene (1-MCP) as an anti-ripening agent. Carbon dioxide measurements were performed with FY A600-CO2H carbon dioxide sensors (Ahlborn Mess-und Regelungstechnik GmbH, Holzkirchen, Germany) and an Almemo 3290-8 data logger (Ahlborn Mess-und Regelungstechnik GmbH, Holzkirchen, Germany).

2.4. Colour fixation of sliced apples by solutions of different concentrations (salts, acid solutions)

I used citric acid (Lach-Ner s.r.o. Neratovice, Czech Republic), ascorbic acid (Chem-Lab NV, Zedelgem, Belgium), sodium chloride (Lach-Ner s.r.o. Neratovice, Czech Republic) and calcium chloride (Chem-Lab NV, Zedelgem, Belgium) as analytical grade. The concentration of the soaking solutions was adjusted between 0 and 10 g/L in 2 g/L increments. This meant that I prepared the following concentrations: 0 g/L, 2 g/L, 4 g/L, 6 g/L, 8 g/L, 10 g/L of each solution. The samples were soaked in the solution for 3 minutes and then placed in rows on a table.

The flesh color of the sliced soaked apples was measured using a Konica Minolta Chroma Meter CR-400 (Minolta Corporation, Osaka, Japan). To compare the color of two samples, I used the

color difference (ΔE*) calculation. Colour measurements were taken for 210 minutes. For the first 120 min, measurements were taken every 10 min, and for the remaining 90 min, the color of the sliced apple was recorded every 30 min.

Each treatment group was subjected to descriptive sensory judgement by myself and 8 colleagues.

2.5 Mapping, creation and testing of microperforation types (mechanical, laser)

The polypropylene trays (Linpac Packaging Ltd., Törökbálint, Hungary) were covered with polypropylene plastic film (Opalen layer thickness: 65 μm, type: HB AF PP width: 420 mm, Amcor plc, Melbourne, Australia). 1 microperforation was applied to the plastic film in each case.

The commercially available microperforated packaging materials were obtained from Kollár-Pakk Kft (Budapest, Hungary). The microperforations I created were made "cold" using a cylindrical mechanical microperforator attachment for the Multivac T200 (Multivac, Wolfertschwenden, Germany) semi-industrial packaging machine. The commercial microperforation was made by laser according to the dealer/manufacturer. The microperforations of the finished plastic packaging were examined under a digital microscope. I used a laser perforating machine (Laser plotter, Laser Engraving Machine, CO_2 50W DSP 40x60cm CL6040T, Shanghai ZX Trading co. ltd, Shanghai, China) to make the microperforations. Based on preliminary experiments, the optimal size of microperforation could be achieved with the following setup. One setting was used in my work. The program setting was set to 25 mm/s for speed, 100% for power and 0.101 mm for distance in both X and Y directions.

The microperforations were examined using a digital microscope (Dino-Lite Edge AM7515MT4A, AnMo Electronics Corporation, New Taipei City, Taiwan) and the captured images were evaluated using the accompanying software (DinoCapture 2.0). Before each series of measurements, a calibration was performed using the calibration ruler supplied with the instrument. 2.6. Az O_2 csökkentés hatásának vizsgálata a szeletelt alma respirációjára

2.6 Investigation of the effect of O_2 reduction on the respiration of sliced apples

For the gas flushing of the respirometer tanks, a gas mixer (Dansensor® MAP Mix Provectus®, Mocon Europe A/S, Ringsted, Denmark) was used to add mixed gas until the last tank had the desired gas composition. The designed O_2 gas concentrations were 20.9% O_2 (atmospheric), 15% O_2 in N_2, 10% O_2 in N_2, 5% O_2 in N_2, 3% O_2 in N_2, 1% O_2 in N_2. The air intensity was carried out as previously described and using the same apparatus. The gas concentration in the air space

was monitored with a gas analyzer (WITT Oxybaby 6i O_2 /CO_2, WITT-Gasetechnik, Witten, Germany) and the product was cooled with an ice agar.

2.7 Investigation of specific gas exchange rate as a function of gas concentrations for microperforations produced by laser of different sizes

In this study, I artificially created differences in O_2, N_2 and CO_2 gas concentrations in a microperforated foil sealed package using a modified atmosphere tube-sealing device. I then measured the gas exchange due to the concentration difference from the partial volume change with respect to the gas and the rate of gas exchange was given relative to the gas under test and the known microperforation surface area.

The packages were filled with an initial concentration of 97.9% CO_2 (Linde Gas Hungary, BIOGON C, Répcelak, Hungary) and 99.3% N_2 gas. For my experiments, nitrogen gas was produced using an N_2 generator (UHPLCMS 12E, Domnick Hunter Gas Generation Division, Gateshead, England).

For the preparation of the shielding gas packages I used a Multivac T200 (Multivac, Wolfertschwenden, Germany) packaging machine. The trays were stored at 22 °C ± 1 °C for 10 days.

After randomly selecting three trays, I measured the O_2 and CO_2 concentration of the package using a gas analyser (WITT Oxybaby 6i O_2 /CO_2, WITT-Gasetechnik, Witten, Germany). The sampler unit was inserted through the foil of the package and the gas composition of the package was measured. The maximum volume of gas required for sampling was 2 mL. The volume of the package was 642.27 ± 4.69 mL. The results were expressed as the percentage by volume of O2, N2 and CO2 in the package (Szabó et al., 2023).

The gas concentrations surrounding the packages in the storage room were O_2: 20.9 V/V% ±0.3%; N_2: 79.1% ±0.4% and CO_2: 0.00%. Combining 2 initial gas concentrations, 2 micro-perforation areas with a range of 2 measurements and 10 days of storage (measurement every 24 hours) with 3 replicates, a total of 120 samples were measured.

A laser perforating machine (Laser plotter, Laser Engraving Machine, CO_2 50W DSP 40x60cm CL6040T, Shanghai ZX Trading co. ltd, Shanghai, China) was used to make the microperforations. I placed 1 microperforation on each package foil. I made two kinds of adjustments on the machine. In the first setting, the speed was set to 25 mm/s, the power to 100% and the distance to 0.101 mm in both X and Y directions. In the second setup, the speed was 1 mm/s, the power was 80% and the distance was 0.101 mm in both X and Y directions.

The results showed an average ellipse/circle diameter of 170.4 ± 24.4 µm for SMP (smaller microperforation) and 221.6 ± 21.1 µm for LMP (larger microperforation).

The microperforations were examined using a digital microscope (Dino-Lite Edge AM7515MT4A, AnMo Electronics Corporation, New Taipei City, Taiwan) and the captured images were evaluated using the accompanying software (Figure 29) (DinoCapture 2. 0). The software gave an image of 2592x1944 pixels, the microscope was used at 457.7x magnification, and the image sharpening was adjusted using the mechanical fine tuning unit on the microscope stand. For the software image analysis, I used the "Line" function for elliptical shapes and the "Lasso" function for irregular perforations to determine the area of the perforations.

By specific gas exchange rate, I mean the inflow and outflow through the microperforation. The specific gas exchange rate is determined by estimating the partial volume change of the selected gas between two measurement times at constant pressure and constant temperature. During the gas exchange process, the higher concentration of O_2 or CO_2 molecules may flow towards the lower concentration in order to equalise the molecular concentration. The driving force is the concentration difference. This process also involves the collision of gas molecules, which also affects the rate of gas exchange.

The volume of the gases has not changed, so the pressure is constant. However, the partial volume of the gases changes, which gives the change in concentration. To prove this, Dalton's law is presented below.

The specific gas exchange rates for each measurement (for each microperforation area) were calculated as follows

$$.D = \frac{\Delta V}{t_{period} \cdot A_{perf}} \qquad [1]$$

where: D: estimated specific gas exchange rate (ml/(h·mm^2)), Aperf: microperforation area (mm^2), ΔV: estimated gas volume change between two measurements (ml), tperiod: time elapsed between two measurements (h).

2.8 Validation of the finished fresh-cut apple product

In the last chapter, based on my results so far, I made an attempt to prepare the finished product. Here I used the complete production technology and tested the storage samples along defined quality parameters.

I then applied a modified atmosphere during packaging. After packing, I conducted storage experiments and examined the changes in gas concentration in the atmosphere of the packages,

the colour (CIE L*a*b* colour space), consistency, pH, water soluble solids content, total bacterial count (presence of food safety) and organoleptic changes of the samples, the methodology of which is described in the following subsections.

The apples were washed with tap water, sliced using a large food processor, and after another wash with clean tap water, immersed in a solution of the specified concentrations (citric acid 4 g/L, ascorbic acid 4 g/L, sodium chloride 2 g/L and calcium chloride 6 g/L) for 120 seconds. Surface moisture was removed from the samples using a hand-held kitchen centrifuge, then placed in plastic trays and packed using a modified atmosphere (1% O_2 in 99% N_2). I then made a single laser microperforation (for both Control and 1-MCP samples) of the smallest possible size per package on the foil of the packages and stored refrigerated at 5°C. The parameters of water soluble solids content, meat firmness, packing gas concentration, pH, colour value and total bacterial count of the initial, control and 1-MCP treated samples stored for 6 and 12 days were then analysed.

2.9 Statistical methods

The data were processed using SPSS v.28 (IBM Corp., Armonk, NY, USA), but some data were evaluated in Microsoft Excel. Typically, I used one (or two) factor analysis of variance (ANOVA). I analysed the data sets for separate production sites, flock measurement, water soluble solids content and ethylene production and respiration intensity values, starch index, colour measurement values, control and treated samples, and for the final product validation, all measured results (colour, total germ, Brix°, precision flock measurement, gas concentration, pH). I also ran normality and variance homogeneity tests on the data series. If P-value > 0.05 for the Kolmogorov-Smirnov (or Shapiro-Wilk) test, I assumed a normal distribution. If P-value > 0.05 for the Levene test, then the assumption of homogeneity of variance is met. If the ANOVA (P-value<0.05) is significant, then I performed a post-hoc test, but if the condition of homogeneity of variance is violated, then I performed the Games-Howell test, but if the largest variance of the groups under study is divided by the smallest variance (varmax/varmin) and the ratio value of this is <2, then I could use the Tukey test. If the ANOVA was significant (P-value<0.05) and the homogeneity of variance was also met, then I used Tukey's test for statistical evaluations.

Measures of variance of microperforations were characterized by the range, mean absolute deviation, standard deviation and relative standard deviation.

The accuracy of the descriptive mathematics fit was given by the RMSE and R^2 measures.

3. RESULTS

In my doctoral thesis I worked on the following topics.

In my first experiment, I investigated the quality parameters of the raw materials for fresh-cut products. I investigated the possibilities of objective methods for measuring apples as a raw material, the effectiveness of the anti-ripening treatment, and the comparison of quality parameters by origin. Based on the flesh hardness and ethylene production of the raw materials, I propose to apply the 1-MCP treatment to all apple products intended for fresh-cut production. The determination of quality parameters yielded significant results for control and 1-MCP treated samples in terms of ethylene production and flesh hardness.

In my second study, I investigated the respiration intensity and ethylene production of 'Idared' apple fruit by increasing the surface area of the wound respiration (degree of processing) at different temperature ranges. My measurements showed that the inhibitory effect of 1-MCP treatment on ethylene production has a positive effect on the reduction of respiration intensity of the fruit. By evaluating my results, I obtained a clear answer that a higher degree of processing, in this case an increase in the cutting surface area of the fruit flesh, is associated with higher respiration intensity and ethylene production. When observing the respiration intensity during storage at 5°C, the respiration intensity was 7.2-fold higher for KOCKA (diced) control samples and 6.6-fold higher for 1-MCP samples compared to EAF (unprocessed) samples. Ethylene production in the 5°C storage test was 2.8-fold for KOCKA control samples and 4.3-fold for 1-MCP treated compared to the values for EHÉJ samples with the same degree of processing. After evaluation of my results, if the temperature factor is not taken into account, I conclude that the respiration intensity of fresh-cut (KOCKA) products is at least 4-fold and ethylene production at least 2-fold higher than that of unprocessed fresh (EHÉJ) apples.

In my third experiment, I used colorimetry and sensory tests to determine the optimal salt and acid composition of the soaking solution to inhibit surface browning caused by enzymatic oxidation of the product with high efficiency, thus increasing the shelf-life and consumer appeal of the product. The results of the colour-fixing study provided basic information on the colour-fixing effect of citric acid, ascorbic acid, sodium chloride and calcium chloride solutions at different concentrations (between 0 and 10 g/L in 2 g/L increments). Based on the results, the following solution formulation is recommended to effectively preserve the flesh colour of fresh-cut 'Idared' apples without adverse side-tastes: citric acid 4 g/L, ascorbic acid 4 g/L, sodium chloride 2 g/L and calcium chloride 6 g/L.

The fourth experimental phase focused on standardising the microperforation area (where gas exchange takes place) of the packaging films used. In my preliminary experiments, I observed that the area values of the mechanical microperforations vary widely, making the control of gas exchange difficult to describe. Thus, I investigated the mechanical-, commercial-, and laser-generated microperforated films I created. This experiment has greatly influenced the future of my research. The laser microperforation technology clearly proved to be the best in creating the right microperforation. The relative standard deviation showed the variance compared to the mean for different perforation techniques. Laser microperforated packaging gave the best result (11%) compared to mechanical (35%) and commercially sourced (51%) samples. For predictability, we recommend the use of laser microperforated films for fresh-cut apple packaging.

In my fifth study, I investigated the respiration of fresh-cut 'Idared' apples at different gas concentrations. In all cases, the respiratory intensity values of fresh-cut apples tested in modified atmosphere gave significantly lower results compared to those measured at atmospheric O_2 concentration. However, respiration intensity values measured at reduced O_2 concentrations of 15%, 10%, 5%, 3% and 1% showed no significant differences compared to each other. Reduced O_2 had a significant effect on respiratory intensity as early as 15% for both control and 1-MCP treatments.

In my sixth experiment, I determined the specific gas exchange rate of the selected microperforated film and expressed it using a descriptive mathematical function as a function of different gas concentrations. By fitting the mathematical function, a good approximation of the specific gas exchange rate as a function of the determined gas concentration was obtained. The descriptive function was verified by experimental measurements. Based on the fitted curve, the specific gas exchange rate (D) and the amount of gas exchange through microperforation can be calculated. The experimental results demonstrate a good fit between the measured and predicted values, and therefore the polynomial kinetic curve provides an accurate approximation to describe gas exchange as a function of gas concentration. There is no significant difference in the specific gas exchange rate between the smaller SMP (0.022 μm^2) and the larger LMP (0.037 μm^2) as a function of O_2 and CO_2 gas concentrations. When comparing the specific gas exchange rates of each gas compound, the rate parameters are λO_2: -0.031, λN_2: -0.0025 and λCO_2: 0.0015, which means that the gas exchange rate of O_2 has 11 times lower dynamics due to the smaller (20.9%) concentration difference. Although the constant value of N_2 is similar to that of CO_2, it is important not to ignore the difference in driving force. For N_2, the gas concentration difference is about 79.05%, while for CO_2 it is almost 98%. After comparing the velocity parameters of N_2

and CO_2, it was found that the dynamics of N_2 is about twice as small as that of CO_2. In conclusion, the polynomial curve fitting was successful for all experimental data.

In my seventh and final experiment, I performed a validation of my previous research results, in which I determined the effectiveness of my thesis work through packaging and storage experiments of fresh-cut apples as a finished product. In the last chapter, I investigated the quality parameters of the fresh-cut finished product and found that the quality of the fresh-cut apple apple was improved by using microperforation with a surface area of 2·10-2 ± 5.3·10-3mm^2 in 1.4% O_2 at 5°C storage with a soaking solution of citric acid 4 g/L, ascorbic acid 4 g/L, sodium chloride 2 g/L and calcium chloride 6 g/L. and 12 days, there was no significant difference from the initial samples in pH, water soluble solids content, sensory rating, total mesophilic aerobic bacterial count. During validation, the treatments (control, 1-MCP) showed significant differences in gas composition, precision meat hardness, colouring threshold. In all cases, the initial and stored quality parameters (meat firmness, colouring threshold, gas composition of the package) of the 1-MCP treated samples showed better results compared to the control (untreated) samples. 1-MCP was able to reduce the respiration intensity of fresh-cut apples, they were noticeably firmer and juicier, and the surface colour of the post-cut apple flesh was lighter in all cases compared to control apples that had not been treated with an anti-ripening treatment.

The 1-methylcyclopropene treatment slows down the respiration, ripening and ageing processes of the apples, the product retains its firmness, acidity and freshness better and its shelf-life is improved.

In conclusion, during my doctoral period, with the help of the existing university technological infrastructure and the scientific research methodology, I was able to define the basis for the development of a product with production technology, which contains information that can be used by industry and has a real market basis, since the development of a fresh, high nutritional value, convenience product was achieved during the research and dissertation phase of my doctoral period.

I believe that during my doctoral research I have been able to generate new scientific results that contain forward-looking scientific information that can be used by industry to achieve a higher added value level of fresh fruit and vegetable processing, even at the domestic level.

4. CONCLUSIONS AND RECOMMENDATIONS

In my PhD thesis, I have analysed in 7 separate sub-chapters the factors that critically influence the fresh-cut technology, taking into account the properties of the finished product.

In determining the raw material quality parameters used, I obtained significant differences between control and 1-MCP treated samples in terms of ethylene production and stock.

When investigating the effect of wound respiration, I found that the fresh-cut processing operation can increase the respiration intensity of samples several times compared to unprocessed (whole apple) samples. It is trivial that the effect of ethylene production and respiration intensity is significantly related to the degree of processing. An important scientific result from my research is that it is not necessarily evident that even a 15% reduction in O_2 concentration can reduce respiration intensity so significantly in sliced apples. Further research is needed here to draw longer term conclusions when investigating the relationship between respiratory intensity, wound respiration and reduced O_2 levels (lower O2 threshold issue, kinetics of anaerobiosis). It would be worthwhile in the future to investigate how wound respiration evolves over time from wound onset, and the extent to which it decays or remains constant over longer periods of observation. New questions arise about the effect on wound healing of the use of colour-fixing solutions.

I have explored a critical issue in manufacturing technology - colour fixation, i.e. oxidative flesh browning - using materials that can be considered as a sustainable solution for food manufacturing. My experiments have led to the development of a solution with effective colour-retaining properties, containing easily obtainable and harmless (and sometimes health-protective) substances, which, when used in the correct concentration, do not unpleasantly alter the initial sensory properties. Based on the results of my measurements, the most effective solution from all points of view contains the following proportions: citric acid 4 g/L, ascorbic acid 4 g/L, sodium chloride 2 g/L and calcium chloride 6 g/L. In the future, it would be worthwhile to carry out validation tests on the concentrations not only separately but also in combination (using solutions that produce effective colour retention). Alternatively, the use of citrates and ascorbates is a potential future research area, as lower ratios are required for their use. Last but not least, the question may arise as to what extent the colour-fixing liquid mixtures of different compositions may affect the respiration of sliced apples. Further research is needed to investigate this.

I also investigated the possibilities of producing microperforations. Experiments have been carried out to verify whether the production of microperforations using mechanical needles or lasers is more standardised. Using a digital microscope and statistics, it was possible to

determine that the production of laser perforations, although larger in size, can produce microperforations with a standardisation factor that is several times higher than that of mechanical microperforations. This has been statistically verified using several scattering metrics. In the future, it may be worthwhile to purchase a higher-quality, more accurate, more precisely controlled laser perforator, which could produce microperforations with a lower range of dimensions, even with smaller scattering metrics. There are a number of further opportunities in this area which could also facilitate manufacturing implementation.

During the packaging of apple slices, I investigated to what extent the reduced O_2 gas concentration can affect the respiration intensity of the fruit and whether the equilibrium can be achieved by microperforations when using EMAP technology. I obtained clear, statistically validated results on how the respiration intensity of wrapped, treated, sliced (fresh-cut) apples changed in an airspace with reduced O_2 concentration. Unfortunately, I was not able to verify that the respiration of the apple slices remained in equilibrium and that the dissolved oxygen in the slices did not interfere with the respiration process, but I plan to further enrich my research with gas chromatography measurements in the future.

Using microperforations, I applied a descriptive mathematical function to determine the specific gas exchange rate between the gases in the package (O_2, CO_2) and the environment. In my research, I was able to construct a descriptive mathematical function using a third degree polynomial equation to describe the relationship between the specific gas exchange rate and the gas concentrations under investigation. The third degree polynomial gave a good approximation to the mathematical description of the relationship. In conclusion, it may be worthwhile to develop a mathematical model, and to see how new model systems can be described by varying the current constants such as temperature and pressure. It has been previously discussed to what extent possible molecular collisions through microperforations may affect gas flow. Investigating this requires further and more in-depth research, involving other areas of science and engineering.

As a final step in my research, I have succeeded in validating a production technology recommendation whereby fresh-cut apples, packaged in a package, have maintained their quality up to the 12th day of storage. In the future, it may be worthwhile for the industry to develop and convert the developed technology to other packaging presentations and packaging materials (possibly pouches) that are more attractive. From here on, it will be easier to move into packaging technology directions for other larger-breathing fresh-cut fruits (plums, cherries, pears, strawberries, mangoes, etc.), since the principles are similar everywhere to what I have explained in my PhD thesis.

5. NEW SCIENTIFIC RESULTS

1. I have found that the respiration intensity of 1-MCP and control (untreated) apple (Malus domestica, Borkh., cv. Idared) at 1°C, 5°C, 10°C and 20°C increased at least 4-fold, while the rate of ethylene production increased at least 2-fold, with an increase in the respiratory surface area of 7.5-fold compared to untreated apple fruit.

2. I have found that reducing O_2 levels from 20.9% to 15% reduced respiration intensity of 1-MCP-treated sliced apple (Malus domestica, Borkh., cv. Idared) at 5°C to 66%, and reducing O_2 levels to 1.2% reduced respiration intensity to 55%.

3. I have found that the relative dispersion of the area of laser microperforations in polypropylene films, and thus their ability to be standardized, is 11%, which is lower than the area of individually created mechanical perforations (35%) or commercially available microperforated polypropylene films (51%).

4. In my research, I have succeeded in applying a well-fitting mathematical descriptor function using a third-order polynomial equation to describe the relationship between specific gas exchange rate and the gas concentrations under investigation. I have found that the specific gas exchange rate of O_2 is constant at -0.048, with an initial average of 99.3 ± 0.01% in N_2 and 97.9 ± 2.06% in CO_2 (for the same gas difference of 20.8 ± 0.09% O_2).

5. I have found that sliced apple (Malus domestica, Borkh., cv. Idared) proved to be effective in preventing browning of the flesh of sliced apples with a combination of citric acid 4 g/L, ascorbic acid 4 g/L, sodium chloride 2 g/L and calcium chloride 6 g/L, with a still acceptable degree of change in taste characteristics.

6. I have found that during the technology and product development of fresh-cut apples, industrially produced 1-MCP-treated sliced apples (Malus domestica, Borkh., cv. Idared) product, stored at 5 °C using a macerating solution of citric acid 4 g/L, ascorbic acid 4 g/L, sodium chloride 2 g/L and calcium chloride 6 g/L in polypropylene trays of 642,27 ± 4,69 mL volume, using microperforations of 2·10-2 ± 5,3·10-3 mm^2 surface area, retains its freshness after 12 days of storage.

6. LIST OF JOURNAL PUBLICATIONS IN THE FIELD OF STUDIES

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- Ha N.T.T., Pham T.T., Nguyen L.P.L., Mac H.X., Mónika Göb, Zoltán Sasvár, **Gergő Szabó**, Zsuzsanna Horváth-Mezőfi, Tamás Zsom, Géza Hitka (2023): Modelling of stiffness of 'Irene' apple during storage and shelf-life. Acta Horticulturae: Technical communications of ISHS 1382, p 157-162, **IF: 0,27; Q: Q4,** DOI: 10.17660/ActaHortic.2023.1382.20

- Ha N.T.T., Pham T.T., Nguyen L.P.L., Mac H.X., Mónika Göb, Zoltán Sasvár, **Gergő Szabó**, Zsuzsanna Horváth-Mezőfi, Tamás Zsom, Géza Hitka (2023): Carbon dioxide and ethylene production modeling of apricot at three maturity stages Acta Horticulturae: Technical communications of ISHS 1382, p 33-40 **IF: 0,27; Q: Q4,** DOI: 10.17660/ActaHortic.2023.1382.5

- Gergő Szabó, Flóra Vitális, Zsuzsanna Horváth-Mezőfi, Mónika Göb, Aguinaga Bosquez Juan Pablo, Tamás Zsom, Nguyen Lien Le Phuong, Géza Hitka, Zoltán Kovács, László Friedrich (2023): Application of Near Infrared Spectroscopy to Monitor the Quality Change of Sour Cherry Stored under Modified Atmosphere Conditions. Sensors, (23) 1, p 479. **IF: 4,35; Q: Q1,** DOI: https://doi.org/10.3390/s23010479

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