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Report on Fruit and Vegetables demonstrators

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OVERVIEW ON TASK 6.4

1 GENERAL SUMMARY

Emissions savings in the fresh fruit and vegetables sector are targeted from the perspective of energy savings and preserving quality for reduction of losses in the supply chain, which often encompasses (long-term) storage, transport and shelf life.

In this task there are two demos with respect to this target:

- Demo 5: Energy-efficient DCA
- Demo 6: Climate Neutral Packaging

In demo 5 on Energy-efficient DCA, a new technology for long-term storage of fruit is demonstrated in the practical context of long-term (up to 9 months) storage of Conference pear fruit. Conference pears are a major pome fruit produced in different regions in Europe and exported world-wide throughout the year after storage in large cold rooms. The specific technology of the demo encompasses a Dynamic Controlled Atmosphere (DCA) applied in these cold rooms. Here, the oxygen concentration in the room is specially adapted to minimize the respiration metabolism of the fruit. Low respiration rates are required to minimize fruit ripening that will lead to quality loss quickly recuing shelf life and leading to losses due to senescent breakdown. In DCA, this means that the oxygen concentration in the room is lowered to very low values (close to or even below 1% for Conference pear) to reduce respiration rates to as low as possible levels, while avoiding a too low concentration that could lead to fermentation and consequent development of off-flavours and internal damage of the fruit. Using gas sensors, in DCA the respiration and fermentation rates are continuously monitored to prevent having too low concentrations. As the fruit respiration changes during storage, the oxygen levels are continuously adapted, which is why the methods is called 'dynamic'. In the demo, the method is compared to more conventional ultra-low oxygen (ULO) storage, that also uses low but fixed predetermined oxygen levels that are typically higher than in DCA (typically 3% for Conference pear). In the demo we monitored quality changes over time in the two systems as well as the energy use of the respective cold rooms in a commercial storage facility at a fruit grower, based on differences in respiration rates that affects heat production of the fruit that needs to be removed by the cooling system. We have successfully demonstrated that for long-term storage, DCA technology leads to less energy needed for cooling while maintaining fruit quality better and avoiding more food losses, compared to ULO. The DCA method is currently being commercialized by partner Optiflux (Figure 1).

Figure 1: Energy efficient DCA (master module and field node attached to the cold room)

In demo 6 Climate Neutral Packaging sustainable packaging for soft fruits have been tested, using bio-sourced materials to extend shelf life and reduce the carbon footprint. Applying sustainable packages reduces plastic waste, but for extremely perishable produce might increase fruit losses. The best packaging solution will depend on the product and the shelf life required. Different options (Figure 2) were considered in shelf-life tests and evaluated against the quality change kinetics of the packaged fruit. Evaluations were performed on both blueberries and strawberries, two perishable fruit.

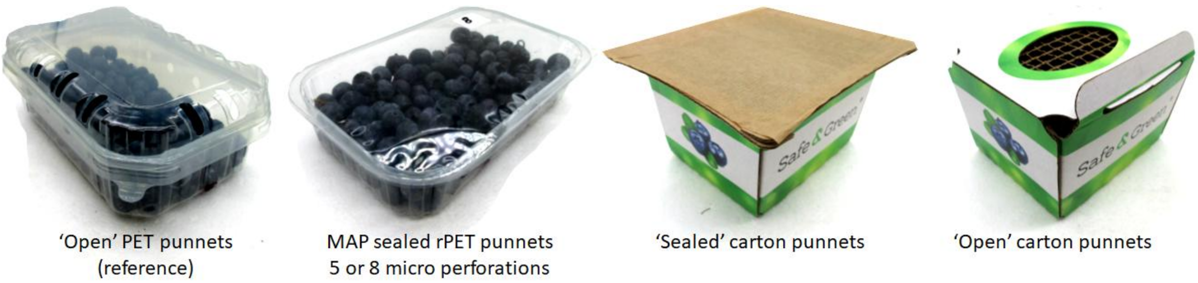

Figure 2: Sustainable blueberry packages evaluated for blueberry packaging

2 RECOMMENDATIONS

For demo 5, Energy-efficient DCA, the following recommendations could be made:

- Industry
  - DCA is a successful alternative for conventional ULO storage for long-term preservation of pears, as well as other fruits and vegetables, and commercial systems are available.
  - Quality preservation after long-term storage is significantly better after DCA compared to ULO.
  - Energy savings in DCA have been demonstrated to amount up to 15% due to reduction of respiration heat.

- Academia
    - Application of DCA can be explored for many other crops and applications can be also extended, for example to DCA transport, or smaller units such as pallet covers, which is convenient for storage of soft fruits.
- Society
    - DCA is a clean energy-efficient technology for long-term storage of fruit and vegetables that does not require specific chemical treatments. It is thus very suitable for storage of organic products. It also makes it possible to provide local products to consumers year-round and avoids emission-intensive imports.
- Policy makers
    - Energy-efficient technologies for better quality preservation, such as DCA, contribute to reduce food losses in the supply chain.

For demo 6, Climate Neutral Packaging, the following recommendations could be made:

- Industry
    - Recycled PET showed better performance than a plastic packaging reference and was approved as potentially useful by industry end users that confirmed an interest in testing for replacing existing plastic unit containers.
    - Paper based punnets performed similar to the plastic reference.
    - The successful introduction of biodegradable polylactic acid (PLA) based packaging, while having good potential as replacement for common plastic materials, suffers from practical issues related to material stability (affecting stock management) and its waste management (need for a dedicated waste stream separate from current plastic waste and compost streams).
- Academia
    - Further studies are required to develop packaging alternatives that have similar barrier properties and stability as conventional plastic packages, considering important economic requirements such as availability, simplicity, stability and waste management.
- Society
    - Prefer recycled PET as consumer package of fruit and vegetables.
    - Perishable foods such as fruits and vegetables require a dedicated cold chain to prolong their shelf life.
- Policy makers
    - Raise awareness about packaging for reducing food losses of fruit and vegetables.
    - Develop measures that facilitate waste management of biodegradable packages.

3 DESCRIPTION OF THE SECTOR

According to Eurostat data[a], fresh vegetables in the EU are worth 60 billion Euro in yearly production value, and fresh fruits 30 billion Euro. Yearly production volumes reach 60 million tons for vegetables and 40 million tons for fruit. To maintain good quality supply to consumers throughout the year after harvest and be able to compete on the world market, advanced storage methods are implemented in cool rooms accommodating between 100 and 500 tons of product each. Storage times can be between 1 day and 1 year long. It is estimated that between 30 and 50% of fresh fruit and vegetable supply is refrigerated, thus the total cooling infrastructure for fruit and vegetables consists of roughly 100000 cool rooms across the EU, not counting for cooling infrastructure for imported fresh produce (imports are valued another 20 billion Euro). Peak loads per cool room are up to 50 kW, while yearly energy consumption of cool stores is on average 300 kWh per ton of produce (based on measured data from apple and chicory root storage cases in Belgium, VCBT, personal communication). Extrapolation to the whole EU sector this would represent an order of tens of TWh, and several millions of tons of CO_2 equivalent greenhouse gas emissions using non-renewable energy sources (Current renewable energy use is between 10 and 50% at commercial packing houses in Belgium). Up to 80% of energy costs of packing houses and storage facilities for fruit and vegetables is attributed to cooling and controlled atmosphere conditioning so any energy use reduction, or improved energy efficiency will have a direct positive measurable effect not only on emissions but also on profitability of a sector working at low margins and under price pressure. For fruit and vegetables, quality is a main driver that determines price. Top quality produce easily sells at prices that are 20% higher than that of suboptimal quality. Therefore, to be successful any technology needs to be benchmarked against strict quality constraints. ENOUGH will thereto provide novel dynamic controlled atmosphere solutions using digital twins to drive the sector to become climate neutral. Finally, new technologies will also need to minimize food losses. It is estimated that in EU, current losses of fruit and vegetables in the supply chain can amount to 10%. Avoiding these losses by improved technology and smarter management, will allow to contribute significantly to loss of energy use and costs. Packaging for highly perishable fruit and vegetables (estimated 50% of total) has been shown to represent on average 210 g CO_2 equivalent GHG emissions per kg[b]. ENOUGH aimed to reduce the impact by 50% by using suitable (i.e. reducing food losses) sustainable alternatives (such as biodegradable, reusable or reprocessed) to current wasted packaging, represents a potential reduction of another 10 million of tons of CO_2 equivalent greenhouse gas emissions annually.

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[a] https://ec.europa.eu/eurostat/

[b] *Poore, J., & Nemecek, T. (2018). Reducing food environmental impacts through producers and consumers. Science (New York, N.Y.), 360(6392), 987–992. https://doi.org/10.1126/science.aaq0216*

4 DESCRIPTION OF THE TECHNICAL SOLUTIONS

After harvesting, vegetables and fruit are subject to a loss of quality. To counteract these post-harvest losses, proper large scale storage (Demo 5) and small scale packaging (Demo 6) are typically applied.

In Demo 5, an Optiflux add-on hardware unit and accompanying software was installed on an existing installation of 28 rooms for Ultra Low Oxygen (ULO) storage of pome fruit, enabling them to perform Dynamic Controlled Atmosphere (DCA) storage with the aim to reduce the need for cooling while maintaining product quality.

In Demo 6, the current packaging situation of soft fruits was evaluated to see whether traditional plastic packaging materials can be replaced by more sustainable options commercially available at the start of the project, but not properly tested for fruit packaging performance. The aim was to match or improve upon the current situation with regard to preserving major quality traits.

PRESENTATION OF DEMONSTRATORS

5 DEMO 5 -RQ-BASED DCA STORAGE

5.1 Description

Controlled atmosphere (CA) storage of fruit is carried out in cool rooms where in addition to the low temperature of about -1 to 3°C, the atmosphere is changed and controlled to relative low levels of oxygen (O_2) of around 1 to 3%, and elevated carbon dioxide (CO_2) levels (also around 1 to 3%) depending on the fruit and cultivar stored. Especially for apple and pear, storage period will be several months and typically 9 months but can be up to more than 10 months. Berries, depending on the type, can be stored for weeks to several months. This is the widespread today's solution.

With dynamic controlled atmosphere (DCA) storage, demonstrated here, savings can be made for needed cooling energy while retaining better fruit quality. Using DCA storage O_2 levels are not kept fixed but will vary dynamically based on real-time measurements of the low oxygen stress response of the fruit. To detect low O_2 stress, measurements of the Respiratory Quotient (RQ) i.e., the ratio of the CO_2 production rate and the O_2 consumption rate of the fruit are used.

Based on RQ measurements, the O_2 level in the room is gradually decreased, until low O_2 stress detection by RQ exceeding a present threshold value. Subsequently, the O_2 level is slightly increased until relief of the low O_2 stress (Figure 3). As such, the fruit is stored at the lowest O_2 level possible, ensuring maximal quality retention without inducing storage disorders or off flavours. Moreover, by decreasing the O_2 level in the storage rooms, the respiratory heat production of the fruit is reduced, resulting in less cooling interventions eventually leading to energy savings.

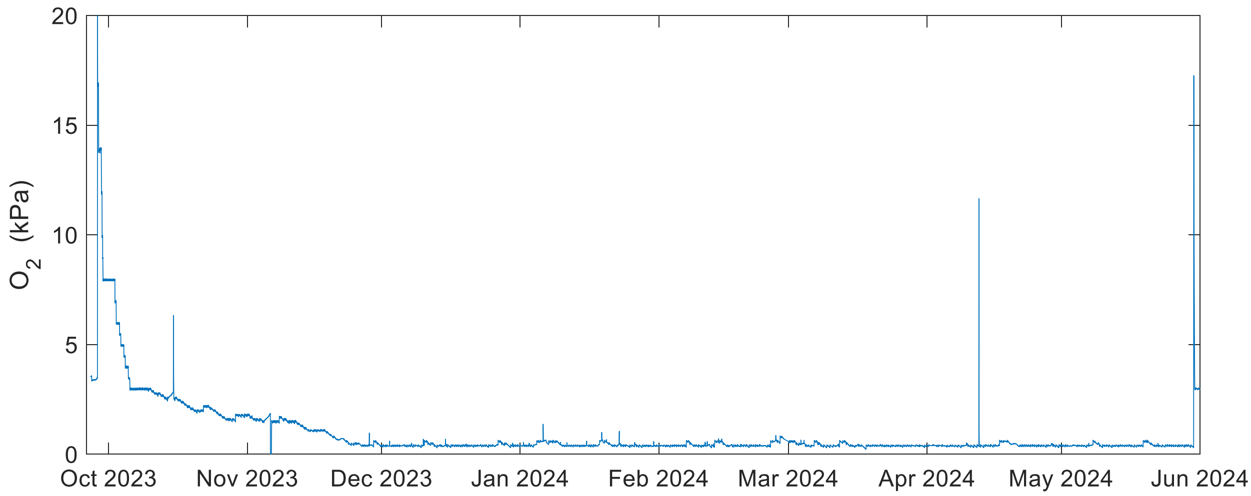

Figure 3: Realised oxygen (O_2) levels during storage of Conference pear with DCA. At the beginning of storage (end of September) O_2 levels are decrease in about a week to 3 kPa. Subsequently the DCA controller takes over and reduces the O_2 levels further until a stress level is reached (December).

Because the respiration rate of the stored product is decreased, also its metabolism is decreased leading to better quality retention (Figure 4). Better quality retention leads to longer shelf life at the market and the consumer resulting in lower waste losses.

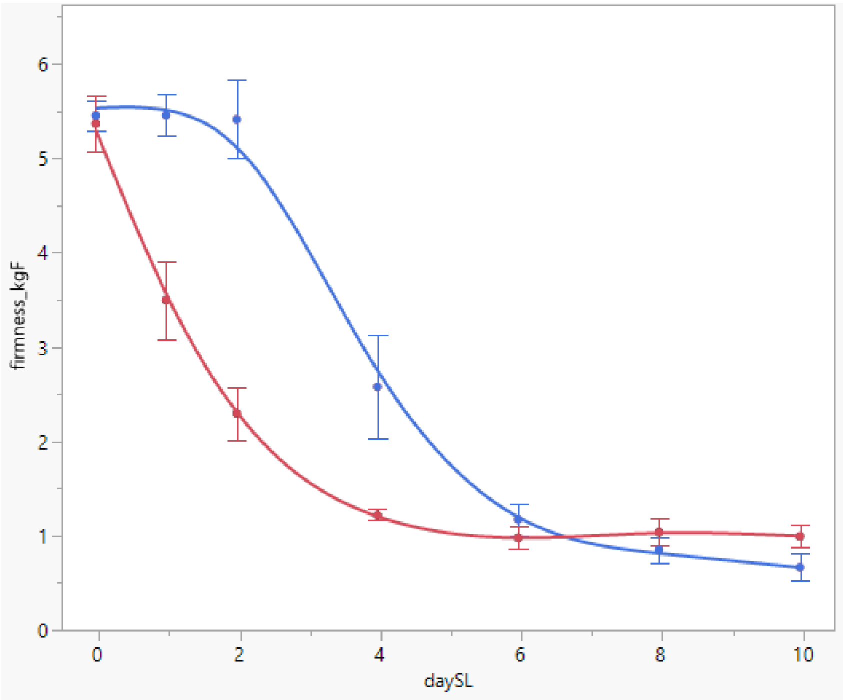

Figure 4: Evolution of fruit firmness during a shelf life simulation at 18°C after 8 months of storage in DCA (blue line) and ULO (red line). The DCA stored fruit retains its firmness 2 days longer compared to fruit stored in the classical ULO conditions.

At the start of the project, the DCA technology had already been demonstrated in relevant industrial environments. The target set in this project was to further qualify the system and prepare for full commercial deployment. Optiflux offers, installs and maintains DCA systems at customers in Europe and abroad. The target sectors are:

- Fruit producers, cooperatives and wholesalers running small, medium and large scale controlled atmosphere storage facilities
- Research organisations advancing controlled atmosphere storage knowledge and technology

5.2 Application methodology and assessment

DCA technology was developed into an industry solution comprising robust, reliable and safe to use sensor and control systems that can be easily integrated into existing and new storage facilities. The operational performance and the impact on fruit quality and energy use reduction is measured and analysed at an industrial storage facility of a Belgian fruit grower running a pear fruit storage facility, representative for the EU fruit sector.

The DCA system is actually an add-on to controlled atmosphere (CA) storage facilities. Such facilities could contain one to several tens of storage rooms with a capacity of 50 to 500 tons of fruit stored in bins. Each room is equipped with an evaporator, used for cooling, and gas sampling/supply (O_2, CO_2, N_2) which are individually controlled from a central control hubs. For DCA, each room is equipped with a dedicated sensor and gas sampling unit that is connected to a central DCA controller. Additionally, a CO_2 scrubber is part of the basic CA installation to remove excess of CO_2 from the storage atmosphere. The system is flexible and can be implemented for any number and size of CA storage rooms. Also smaller stand-alone units were developed that can service customers requiring lower volumes (e.g. for soft fruit producers, or for research purposes).

5.3 Results

Demonstrated advantages of the system include:

- Up to 15 % lower energy consumption compared to conventional storage technology (ultra low oxygen (ULO) storage)
- 100 % organic (no chemical treatments needed during storage)
- Eliminating fruit disorders such as superficial scald
- Tailored to each specific batch of fruit
- Longer shelf life compared to ULO storage

Identified KPIs

- Energy consumption (kWh/kg fruit) of a DCA storage room in comparison to normal CA storage room
- GHG emissions (kg CO_2eq/kg fruit) of a DCA storage room in comparison to normal CA storage room
- Change of quality expressed by firmness (N) and colour (hue value) of fruit after DCA storage in comparison to normal CA storage, and remaining shelf life (days)
- Duration of storage (days) of fruit predicted as function of changing quality for management of demand and supply

The baseline is the commercial standard for controlled atmosphere (CA) fruit storage under ultra low oxygen (ULO) conditions, which is already an advanced solution with respect to normal air low temperature storage that already saves 50% of CO_2 and heat production by reducing the oxygen concentration from 21% to levels as low as 1-3%. The baseline case is part of the demo: one room operates in DCA, one room operates in CA. Alternatively, the KPIs can be calculated based on the differences in respiration rate of the fruit stored in either DCA or CA conditions, based on the respective levels of temperature, O_2 and CO_2 in the two systems. The comparison was carried out in the storage season 2023-2024 and repeated in season 2024-2025.

Measured energy savings of the two seasons were comparable but are somewhat lower than expected. This is partly due to the difficulty in measurement of energy use of CA rooms in practice, as they are part of a larger refrigeration system with multiple cool rooms operating in different conditions and with different batches of fruit. Also, while we demonstrated that respiration heat significantly reduces, other energy consumers in cooling such evaporator fans may not be used optimally yet.

Results:

For Conference pear :

- Relative savings DCA with respect to ULO on fruit heat production: 10-15%
- Relative savings DCA with respect to ULO on scrubbing energy use: 10%
- Relative savings DCA with respect to ULO on total energy use: 5-10%

  Scaled to CO_2 emissions of cooling rooms, we can make the following calculations. According to our standard calculations (with reference to the calculations explained in the technology reviews of the storage roadmap WP2[c]), standard ULO of pome fruit has the following emissions from electricity use, in Belgium assuming a grid emission factor of 110 g CO_2-eq/kWh:
- For cooling 225-233 g CO_2-eq/ton fruit/day depending on the cultivar

[c] https://enough-emissions.eu/download/68169/?tmstv=1752070085

- For scrubbing 3.7-29.2 g CO_2-eq/ton fruit/day of storage depending on the cultivar

Corresponding maximum savings by implementing DCA according to the above results are thus:

- For cooling 34-35 g CO_2-eq/ton fruit/day (15%)
- For scrubbing 0.4-3 g CO_2-eq/ton fruit/day (10%)

Total savings expected for the Belgian (BE) pome fruit sector alone on a year basis, for switching from ULO to DCA are estimated as follows:

- Total BE production of apple and pear in 2023 (Eurostat): 584 000 ton
- Fraction of ULO storage (estimate): 50%
- Average duration of ULO/DCA storage (estimate): 6-9 months
- Total average potential emission savings by DCA storage in BE: 1 813-2 720 tonCO_2eq.

Total pome fruit production in the EU was close to 14 million ton in 2023 (Eurostat). Using the same assumptions as above but using the country specific emission factors, for the main pome fruit producing countries in the EU, the following savings could be estimated (Table 1):

Table 1: Estimation of savings for main pome fruit countries in Europe

	Production of pome fruit 2023, kton	Emission factor 2021, ton CO_2-eq/MWh	Average annual savings, ton CO_2-eq
BE	584	0.17	1813-2720
IT	2523	0.285	13133-19700
DE	979	0.383	6348-10273
NL	552	0.331	3337-5006
PO	3974	0.779	56543-84814
FR	2021	0.068	2510-3765
ES	850	0.175	2717-4075
Total	**11483**		**86902-130353**

5.4 Impacts

- The standard method of ULO is already very energy-efficient, using advanced flooded refrigeration systems with climate friendly refrigerants in well insulated air-tight rooms. Still, it was found, from demonstration in commercial storage rooms, that relative savings of DCA with respect to ULO on pome fruit respiration heat in storage is 10 to 15%, with added savings due to reduced CO_2 scrubbing that amount to 10%. Overall, taking into account all energy loads of the refrigeration system, relative savings of DCA compared to ULO for total energy use were found to 5-10% over a full storage period of 9 months.
- Quality preservation of fruit, expressed by fruit firmness and colour, after 9 months of DCA storage was higher than from ULO storage. Subsequent average shelf life was found to be 6.5 days after DCA, compared to only 4 days for ULO, a 60% increase. This allows a potential reduction in losses in the supply chain and reduced waste at consumer end.
- Fruit quality models implemented as digital twins allow for better management of storage.
- Emission savings per DCA room (200 ton of fruit) amount to 1.2-1.9 ton CO_2-eq per year.
- On EU scale this means that replacing ULO with DCA will directly save more than 87-130 ktons of CO_2-eq emissions per year through the reduction of electric energy use for the total of pome fruit production in EU.

- Reduced waste impact on emissions was not yet precisely calculated. 1% reduction of waste of pome fruit in EU equals approx. 23-46 ktons CO_2-eq per year. The extension of shelf life by DCA will contribute to achieving this. It allows for a 60% longer time between storage and consumption before the fruit is wasted.
- The DCA technology is readily available for other respiration intensive commodities that benefit from CA storage. This includes products like Kiwifruit, Plums, Berries, Cherries, Bananas, Cabbage, Cauliflower, Broccoli, Onions and Potatoes.
- Impacts on energy savings for these products could be higher with applying CA than for apple and pear, as ULO is not yet the standard for these products.
- A simple proportional production volume calculation indicates potential direct emission savings of at least more than 500 000 ton CO_2-eq. for all these fruit and vegetables together on EU scale.

5.5 Business potential

The DCA method demonstrated in ENOUGH is now being commercialized by Optiflux. They offer systems that can be added onto commercial CA and ULO storage rooms, as well as smaller scale flexible units for storage of smaller volumes of products, as well as for research purposes. Their product portfolio contains (see www.optiflux.world):

- The OptiPallet system consists of three main parts:
  - Pallet bags: for airtight storage of fresh fruit and vegetable samples under CA, ULO or DCA while maintaining easy access to the cold store. Pallets can be placed in any type of cold store.
  - OptiSense: measurement and control system. Precise measurement and control of gas composition with minimal usage of gas and energy. Available from 10 to 200 storage units.
  - OptiControl: The ultimate software to configure and manage your storage experiments and related data.
- The OptiRoom system consists of three main parts:
  - CA cold stores: for airtight storage of fresh fruit and vegetable samples under CA, ULO or DCA.
  - OptiSense: measurement system. Precise measurement of gas composition. Available from 10 to 200 storage units.
  - OptiControl: The ultimate software to manage your storage.
- The OptiLab system consists of three main parts:
  - Optiflux' laboratory storage units: for airtight storage of fresh fruit and vegetable samples under CA, ULO or DCA while maintaining easy access for sample collection. Storage containers can be placed in any type of storage room.
  - OptiSense: measurement and control system for laboratory containers. Precise measurement and control of gas composition with minimal usage of gas and energy. Available from 5 to 200 storage units.
  - OptiControl software: The ultimate software to configure and manage your storage experiments and related data. All data on storage conditions, post-harvest treatments, quality assessments and experiment logbooks in one place for easy visualisation, analysis and reporting anywhere anytime.

Optiflux is a spin-off company of ENOUGH partners KU Leuven and VCBT that specializes in data-driven fruit quality and storage optimization. Since its founding in 2021, raising a seed funding of €600 000 from capital investors, it has steadily grown to a Belgium based company that is today employing 10 people and is serving growers, cooperatives and traders in different regions in the world. Their patented algorithms assess quality, colour, size, and shelf life. With the help of the developments and demonstration of ENOUGH they have created a non-chemical system to fine-tune storage and transport atmosphere based on fruit respiration.

6 DEMO 6 -CLIMATE NEUTRAL PACKAGING

6.1 Description

To counteract post-harvest losses, especially in the case of highly perishable soft fruits, plastic packaging is often used to influence the environmental conditions of the product in a favourable way. Sustainability of the current situation can be improved by replacing traditional plastic packaging materials by more sustainable options and by further improving the performance of the packaging system minimising food losses. These alternative packaging materials were commercially available at the start of the project, but not yet properly tested for fruit packaging performance in relevant conditions.

6.2 Application methodology and assessment

Both recycled PET (polyethylene terephthalate) and biodegradable PLA (polylactic acid) with microperforated top seal foils and paper based punnets (Figure 5) were identified as suitable and available alternatives to plastic materials for fruit consumer packaging which can be relatively easily implemented in current supply chains. These new materials were approved as potentially useful by industry end users (Belgian fruit cooperatives) that confirmed an interest in testing for replacing existing plastic unit containers. Microperforated films with different perforation levels were included to further improve the performance of existing packaging systems by generating modified atmosphere conditions.

Blueberries and strawberries were chosen as commodities for testing because of their high commercial relevance and their high sensitivity to decay in suboptimal conditions. Eventually the PLA-based packaging was not feasible to implement as their commercial availability for testing was hampered by the current lack of industrial interest due to practical issues related to material stability and its waste management. While performance of this PLA-based packaging is expected to be as good as the recycled PET version when applied to soft fruit like strawberry or blueberry, they are considered less sustainable than recycled PET[d].

Commercial fruit were obtained through the auction, at different time points throughout the commercial blueberry and strawberry season involving different commercial growers. Packaging materials were supplied to the packing station of the auction. Fruit were commercially handled and packaged at the auction using the packaging materials supplied. To monitor fruit quality over time, the packages were stored at the pilot scale storage rooms of VCBT. KU Leuven has measured and analysed quality indicators (decay and weight loss) at different time points during typical supply chain conditions (Temperature and Relative Humidity) for standard plastic and alternative packaging as to compare the alternatives to the baseline condition.

[d] Rybaczewska-Blazejowska, M., Mena-Nieto, A., 2020. Circular economy: Comparative life cycle assessment of fossil polyethylene terephthalate (PET) and its recycled and bio-based counterparts. Manag. Prod. Eng. Rev. 11, 121–128. https://doi.org/10.24425/mper.2020.136126

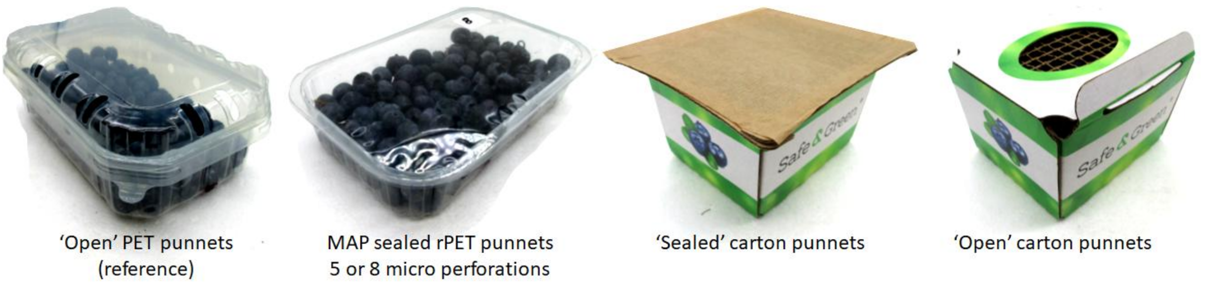

Figure 5: Sustainable blueberry packages evaluated during the 2024 trial. Similar packaging concepts were applied to strawberry as well.

INRAE has developed a model to predict heat and mass transfer in a container filled with blueberries considered as a porous food medium. Parameters were determined and validation tests performed. The model simulates temperature change as well as evaporation and condensation on the surface of stored product stacks at the container (punnet) scale with respect to the outside conditions, and the presence of vent holes.

6.3 Results

For both blueberry and strawberry, it was shown that the MAP sealed rPET punnets were able to further reduce fruit losses in terms of suppressing weight loss and better maintaining overall fruit quality. The added effect of MAP was due to the clearly increased CO_2 levels and reduced O_2 levels as compared to regular air. The carton punnets were in their performance more similar to the reference. While overall the different packaging systems performed similar when applied to different batches of fruit, large differences existed in the quality levels between the batches tested, depending on the moment of the season and the grower from which the fruit were obtained.

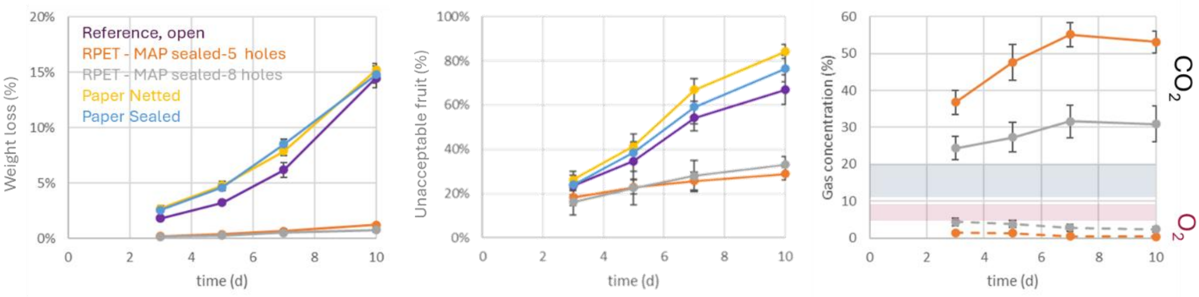

Figure 6: Exemplary data on blueberry showing the difference in weight loss and overall quality expressed as the percentage unacceptable fruit (showing signs of microbial decay), during a 10 days exposure to 18 °C shelf life conditions. Additionally the gas conditions inside the two microperforated package systems are shown.

INRAE developed a simulation model to study the impact of temperature dynamics, moisture migration and condensation on fruit mass loss (Nuangjamnong et al. 2025). The model has a very good agreement with the experimental results. Different vent holes in the packaging will be studied regarding their influence on condensation at the fruit surface.

Eventual confirmation of the results in realistic supply chains will be required by industry to guarantee quality and shelf life. We will have to study different scenarios combining type of packaging, temperature and humidity levels, losses of product and the impact on GHG emissions for each packaging.

Shelf-life models have been implemented as part of the Enough simulation tool which is freely accessible to the industry[e]. Currently the packaging has been tested in combined industry/lab tests. The results have been shared with the industry through an industry journal (Meesters et al. 2025) and during the Enough industry workshop (September 18, 2024, Leuven, Belgium). It is up to the industry to decide to implement the packaging materials and replace conventional plastics were feasible. Given the packaging materials tested are readily available, uptake by the industry can go rapidly, reaching higher TRL quickly.

We used literature data of emissions of different packaging materials. Using the data from the ENOUGH tool, we assessed the emission factors of the different packaging used in this trial. Table 2 gives the mass and estimated emission of each package displayed in Figure 5.

Table 22: mass and emission of packages

	g	kg CO_2-eq/ton	g CO_2eq/unit	Reduction of emissions wrt PET
PET	11.43	4032	46.1	
rPET	11.43	2000	22.9	50%
sealed carton	35.82	829	29.7	36%
open carton	31.8	829	26.4	43%

6.4 Impacts

- Alternative packaging for berries were selected and successfully tested. These included recycled PET (rPET) with sealed micro-perforated top foil, open carton punnets and sealed carton punnets. Using shelf-life tests, modified atmosphere packaging in rPET showed, compared to plastic punnets, a reduction of weight loss from max. 15% to less than 2% and rejection rates (considered as waste) could be reduced from 70% to 30% after 10 days of shelf life.
- Carton packaging gave similar or higher weight loss and rejection rates as a reference plastic punnet.
- Direct energy use savings could not yet be demonstrated for using these novel packaging in supply chains. A temperature-controlled supply chain is the best guarantee for minimal food losses, so we expect energy use is similar to that of classic packaging.
- Tools were developed to optimize design of packaging to reduce quality losses due to transpiration and condensation.
- Emission savings of packaging material are expected as follows:
  - Reference virgin PET: 46.1 g CO_2-eq per unit punnet
  - rPET**:** 50% lower than virgin PET
  - Carton: 36-43% lower than virgin PET

[e] https://frisbee-etool.inrae.fr/

6.5 Business potential

In ENOUGH, no new packages were developed, but only tested in close cooperation with potential end users in the fruit and vegetable sector. Several EU based companies are supplying sustainable packaging solutions that are fit for fruit and vegetables.

For the end users, rPET is often the best transitional option towards sustainable packaging: it balances improved sustainability with minimal disruption or increased cost. Cardboard offers the strongest branding and sustainability alignment, but has higher costs (20–50% more) and needs moisture protection (coatings or liners). Conventional PET remains common but may face regulatory risk and consumer backlash by 2026+ under EU Packaging and Packaging Waste Regulation (PPWR).

The best choice also depends on the required shelf life, with paper based solutions perfectly suitable for short chain applications while rPET/MAP based solutions become more relevant for longer handling chains where perishability becomes limiting.

A quantitative estimation of costs is given for end users in Table 3. Cardboard could be double the cost of PET.

Table 3: Estimates of costs of punnet packaging for berries using different materials (per 1000 punnets)°

	PET	rPET	Cardboard
Base Material + Lid	€50	€60	€100
Branding/Print	€10	€15	€25
Eco-Certification Costs	–	–	€10–€15
Total Packaging Cost	€60	€75	€135–€150

°Sources (used by ChatGPT for the cost estimates above):

1. Packaging supplier catalogs and quotes (e.g., Stora Enso, Repaq, Ecolean, Mondi, Guillin Group)
   - Many list unit prices in B2B trade portals or provide ballpark pricing upon inquiry.
   - Cardboard punnets: ~€0.06–€0.10
   - rPET punnets: ~€0.04–€0.07 depending on recycled content and format
   - Conventional PET: ~€0.03–€0.05 (widely validated)
2. Retail and produce industry publications:
   - Fruitnet, FreshPlaza, and Eurofruit Magazine often cite packaging costs in interviews with suppliers and packers.
3. Tradeshows & circular economy case studies:
   - Case studies from Interpack, Fruit Logistica, and packaging innovation reports (like those from WRAP UK, Ellen MacArthur Foundation, or EU-funded projects like REFRESH).

The Europe fresh food packaging market size reached approximately € 9.6 Billion in 2024 (Anon. 0, 2025). Within fresh food packaging (including fruit & veg), revenue of cardboard packaging was ~USD 9.6 billion in 2024, with a projected 2.6–3.4% CAGR to 2032–34 (Anon. 0, 2025). The Food Grade rPET Market was valued at € 5.4 Billion in 2024 and is forecasted to grow at a CAGR of 7.5% from 2025 to 2032, reaching € 7.24 Billion by 2032 (Anon. 1, 2025).

Important drivers for this growth of sustainable packaging solutions are

- EU regulations under the Packaging & Packaging Waste Regulation (PPWR) (Anon. 2, 2025).
- Producer Responsibility (EPR), which is a policy tool that extends the producer's financial and/or operational responsibility for a product to include the management of the post-consumer stage, in order to help meet national or EU recycling and recovery targets (Anon. 3, 2025).
- Advances in mechanical and chemical recycling improve rPET purity – essential for safe food-contact uses (Anon. 1, 2025).
- Recyclability rates for cardboard in Europe are high.

Challenges include quality variability at RPET, odor, color consistency, sorting of multilayer packaging still hinder circular uptake and cardboard is typically more expensive than plastic

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GENERAL CONCLUSIONS

7 GENERAL KPIS/IMPACT

Fresh fruit and vegetables are highly perishable foods, with generally short shelf life, that require a controlled storage and cold chain to provide year-round supply to consumers. It was demonstrated here that emissions in storage can be reduced significantly by using advanced storage technology and sustainable packaging. The savings emerge both from reduced energy use (DCA storage) as well as reduced losses (DCA storage and packaging). Direct emissions savings are expected as follows:

- Relative savings of DCA compared to ULO for total energy use were found to 5-10% over a full storage period of 9 months.
- Emission savings of sustainable packaging materials are 50% lower for rPET and 36-43% lower for carton compared to virgin PET.

Potential direct emission savings of at least more than 500 000 ton CO_2-eq when implementing DCA storage for all suitable fruit and vegetables on EU scale. Using shelf life tests, modified atmosphere packaging in rPET showed, compared to plastic punnets, a reduction of weight loss from max. 15% to less than 2% and rejection rates (considered as waste) could be reduced from 70% to 30% after 10 days of shelf life.

8 DISSEMINATION AND COMMUNICATION

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9 GENERAL FUTURE OUTLOOK

DCA is a more sustainable alternative for conventional ULO storage of fruits. Benefits are clearly shown in the ENOUGH demonstrator and commercial systems are now provided. Still, continued research and demonstration will be required to convince stakeholders of the commercial benefits, across applications and products, in a sector that is very price sensitive with strong international competition.

Concerning packaging, sustainable alternatives are already available, but continued research is needed to demonstrate their performance in real life cold chains under fluctuating conditions, and practical hurdles need to be resolved. These include technical challenges concerning sealing permeable transparent top films on carton packages in a sustainable way and prevent excessive dehydration in carbon packages, for instance by developing sustainable coatings.