LiVA™ Sticker and LiVA™ Ink

LCA Report

LiVA Bio-Protection Technologies Ltd (LiVA) is an Israel-based biotech company that has developed, patented and commercialized a prebiotic bio-protection sticker for fresh produce, labelled LiVA™ Sticker (LiVA-S). LiVA-S is a semi-synthetic product that comprises a patented blend of food-grade nutrients designed to selectively stimulate the native beneficial microbiome on produce surfaces, creating a natural bio-shield against spoilage. By harnessing and promoting beneficial microbial ecosystems rather than relying on traditional antimicrobial approaches, LiVA-S represents a next generation, sustainable bio preservation technology that prolongs shelf life, reduces food waste, and enhances food safety. LiVA-S is commercialised in round form for strawberries (this being currently the main production line) and rectangular form for mangoes packaging. LiVA is also developing a prebiotic, nutrient-based ink (LiVA-I) that can be seamlessly applied to plastic or biodegradable packaging materials, further extending the scope of microbiome-driven preservation across the supply chain.

LiVA's Claims

The current supply chain is featured by severe losses from farm gate to consumer and this share can be reduced by deploying LiVA-S and LiVA-I in conventional packaging systems. LiVA's innovations represent a systemic intervention to reduce reliance on fossil-based fungicides, mitigate risks linked to antimicrobial resistance, and advance the transition towards sustainable and resilient agrifood value chains. LiVA-S and LiVA-I products enable a substantial extension of shelf life and reduce spoilages in transportation and distribution while **securing a 25-75% reduction in pre/post-harvesting fungicide use** and moderating the stringent cold-chain requirements in terms of shipping and storage temperatures (**from zero to 4°C for strawberries and from 10°C to 12°C for mangoes**). The use of LiVA-S and LiVA-I allows for longer shelf life while securing the same level of quality of the fresh produce, securing a reduction in food waste and greenhouse gases (GHGs) emission throughout the value chain. The extension of shelf life means that consumers are more likely to consume the berries before they perish, while retailers can keep products on display for longer, increasing sales. **LiVA-S and LiVA-I bring a 20-40% reduction in waste** and are key elements to **reduce the need for overproduction**, avoid the associated upstream agricultural and logistical emissions, and limit downstream impacts from disposal. Therefore, besides the reduced use of fungicides, **the obtainable reduction of food waste represents a significant driver of environmental mitigation enabled by LiVA's product**.

Goal Definition	The present LCA aims to preliminarily evaluate the environmental performance of a novel, plastic-free ink formulation developed by LiVA (LiVA-I) to complement the already commercialised LiVA™ Sticker (LiVA-S), used as bio-shield against spoilage in fresh produce packaging. The assessment is therefore devoted to a thorough comparison of the environmental footprint of the current commercialised and future product compared with the existing bio-preservation solutions (i.e., fungicides used during the pre-/post-harvest phase to secure protection against common pathogens affecting fruit shelf-life). The assessment therefore considers LiVA's products as part of the packaging strategies to be implemented for guaranteeing the long-term preservation of strawberries and mangoes. Indeed, strawberries are widely regarded as one of the most perishable food products due to rapid softening, pectin de-esterification and susceptibility to grey mould, while mangoes are climacteric fruits, meaning they continue to ripen after being harvested and need to be kept at controlled temperatures (lower than 13°C). The environmental impacts of three alternatives (i.e., current scenario, LiVA-S scenario and LiVA-I scenario) per fruit have been compared throughout their entire life cycle to understand the extent to which LiVA's biotech-inspired solutions could effectively reduce the environmental externalities connected to the bio-preservation practices required to guarantee food safety. The inclusion and modelling of all stages from cradle-to-grave aims to validate the benefits arising during the transportation phase and consequent to the reduced food losses. Both LiVA-I and LiVA-S are indeed designed to enable a 2°C increase in the cold chain of both strawberries and mangoes, as will be further detailed later, thereby contributing to reduced energy consumption and greenhouse gases (GHGs) emissions during transport. Furthermore, the assessment is intended to quantify the actual benefits of LiVA-I over LiVA-S, as the ink formulation is a completely plastic-free product. Though in small amounts, the use of polypropylene (PP) in LiVA-S could undermine its overall beneficial contribution to the food handling value chain. The ultimate objectives of the performed LCA are: • To quantify and compare the potential environmental impacts of the LiVA-I with LiVA-S and the industry-standard benchmark products, these being Switch® and Scholar® for strawberries and mangoes, respectively. Both formulations are based on synthetic fungicides (i.e., a combination of cyprodinil and fludioxonil for the former, fludioxonil for the latter) and their production is featured by severe energy and fossil resource consumptions. Therefore, the carbon footprint of fungicide has been reported to be of 20.57 kg of $CO_{2,eq}$ per kg of active ingredient, while the average energy consumption during the manufacturing process is around 189 MJ per kg of active ingredients. Beyond GHG emissions, these fossil-based fungicides are persistent and can harm aquatic life and disrupt soil microbiota, and their repeated use contributes to the development of resistant fungal strains. Besides, though both have low acute toxicity in humans, long-term exposure raises concerns due to potential liver, kidney, and endocrine effects.

	• To identify the key stages of the life cycle and the environmental areas where LiVA's products can deliver improvements and where there is the need to streamline the process and mitigate impacts. • To support LiVA's decision-making processes with scientifically grounded evidence of environmental benefits and demonstrate alignment with EU goals for low emission, biotechnology-based food systems. **Further notes on the benchmarks** • **Switch®** is a co-formulation of cyprodinil (37.5 wt.%) and fludioxonil (25 wt.%) that has become a cornerstone in the management of grey mould (*Botrytis cinerea*) in strawberries, as well as other high-value crops such as grapes and vegetables. As Spain is the geographic scope for strawberry production, the application rate is assumed coherently with the indications of the Spanish official registration entry for Switch® (registered as n° 21714), which authorises its use at a field dose of 0.6-1 kg per hectare with spray volumes ranging from 500 to 1,000 L per hectare (up to 2,000 L per hectare in greenhouse). The register prescribes a maximum of 2 applications in open field and with a pre-harvest interval (PHI) of 3 days. • **Scholar®** is a post-harvest fungicide that is effective against the development and sporulation of major post-harvest pathogens, such as *Botrytis cinerea*, *Colletotrichum* spp. (anthracnose), *Lasiodiplodia* spp. (stem-end rot), *Penicillium* spp. (green mould) and *Rhizopus stolonifer* (rhizopus rot), thereby reducing losses during cold-chain transport and ensuring optimal product quality and safety. It is formulated as a suspension fungicide with a fludioxonil concentration of 230 g per L and can be applied adopting different approaches (e.g., hot dip, drench, or in-line spray). United States Environment Protection Agency (US EPA) label specifies that 32 fluid ounces of product should be added to 100 gallons of water. Converted into SI units, this means that for every 100 L of water, the operator must add approximately 2.50 mL of Scholar®. At this dilution rate, the solution contains approximately 0.61 g of fludioxonil per L.
Scope Definition	**LiVA's Products Functional Unit** The functional unit (FU) is defined as both "1 kg of nutrient blend formulation at vessel gate" and "1 unit of LiVA's product intended to preserve up to 1 kg of fresh product". As for the latter, LiVA-S is a sticker 35 mm disk weighing 90 mg (containing 9 mg of LiVA's formulate), while LiVA-I is a is bio-based ink that contains 0.05gr prebiotic formulation. **Strawberry and Mango Value Chain Functional Unit** The functional unit (FU) is defined as "1kg of fruit delivered at the consumer, including all necessary packaging and labelling and accounting for food chain losses". This unit has been chosen to reflect the overall function of LiVA's product, this being that of delivering a defined quantity of fruit to the consumer. The selected FU enables to effectively track the environmental

externalities associated with the investigated bio-preservation practices and spread throughout the value chain.

LiVA's Products System Boundaries

The assessment includes the formulation stages of both LiVA-S and LiVA-I, as these represent the sole additional environmental burdens that LiVA's products introduce in the value chain of fruits. The formulation of these nutrient blends has been modelled based on the actual composition of both the sticker and the ink. The modelling phase has been supported by the available documentation (Bill of Material, BoM) and the Material Safety Data Sheet (MSDS) of each single chemical used in the process, providing relevant information to get a preliminary understanding of the potential impacts based on chemical properties and hazard classification. The background processes for chemicals production have been therefore included to account for their related impacts and the production footprint in terms of resource-intensity, though the actual impacts generated by LiVA are mainly referred to the manufacturing process. The latter has been modelled in accordance with LiVA's industrial specifications and considering the amount of produced LiVA-S and LiVA-I alongside the energy demand for homogenisation, anticipated to be the major driver of indirect greenhouse gases (GHGs) emissions. Indeed, the homogenisation phase is common for both LiVA-S and LiVA-I and it is regarded as an essential step to ensure stability, uniformity and reproducibility of the active solution in large-scale production. To ensure comparability and consistency with LCA practices, the modelling of the manufacturing process for both LiVA-S and LiVA-I has been based on a per-item basis. To enhance reliability and robustness, representative data coming from forecasts of total production volumes have been considered for modelling purposes (i.e., the number of LiVA-S and LIVA-I items obtainable is based on annual production batches and batches production capacities). This scaling approach enables a per-item assessment grounded in industrial production conditions. While the initial phase is common for both products and foresees the preparation of the proprietary nutrient blend in an industrial emulsifying vessel, LiVA-S manufacturing involves die-cutting and printing and LiVA-I involves inkjet printing onto packaging. Therefore, different energy consumption figures have been considered for LiVA-S and LiVA-I based on literature estimates. According to LiVA projections, the manufacturing of LiVA-S and LiVA-I takes place in Italy and Germany, respectively. Therefore, each electricity-demanding application during the manufacturing process accounts for the electricity mix of the manufacturing region. This implies that the energy per-item estimates (for the blending phase, printing and die-cutting) are inserted into the LCI by considering local electricity grid mixes as providers. This approach enables to capture realistic carbon intensities and other environmental implications tied to the local grid supply situation.

Strawberry and Mango Value Chain System Boundaries

The system boundaries, equal for all the three alternatives, are cradle-to-grave, and encompass all stages of the life cycle:

- Cultivation phase, modelled according to available dataset considering the production of strawberries in open field crops in Spain and the cultivation of mangoes in the San Francisco Valley in Brazil. These inventories are provided by the adopted database as cradle-to-farm gate activities
- Post-harvest treatment and packaging of fruits according to the identified best practice for both strawberries and mangoes.
- Transport to distribution centres (DCs) and retail through refrigerated lorries or sea freights in case of strawberries and mangoes, respectively
- Household consumption and end-of-life (EoL) management

In case of mangoes, the transport from farm to harbour gate and the handling processes at DCs and retail level have been neglected due to the absence of adequate information or assuming that the energy and resource consumption in these stages is equal for all the investigated scenarios.

Geographical Scopes

- For strawberries, stages from production to consumptions have been considered to occur within Spain, with the exemption of EoL which has been considered on a Europe average basis.
- For mangoes, production has been considered to occur in Brazil, while distribution and consumption have been modelled using background data for The Netherlands context, as Rotterdam has been assumed as the reception location for imported mangoes. As for the case of strawberries, EoL for packaging was based on market averaged data for Europe.

Data Quality Statement

- Foreground data referred to the formulation and production processes have been provided by LiVA and are therefore regarded as high-quality data. The inventory data are not herein disclosed as the production process is patented.
- Foreground data referred to energy consumptions during transportation have been adapted either from literature or from the ecoinvent datasets to account for changes in handling temperatures (i.e., a 2°C increase in operating temperatures for all LiVA's scenarios). In case of electricity consumptions data, this have been readapted assuming an equal coefficient of performance (COP) for the refrigeration cycle and equal amounts of refrigerants. In case of transportation related data, diesel consumption has been adapted to refrigeration requirements assuming a 35.1% efficiency for power generation and emissions have been recalculated accordingly.
- Foreground data referred to food waste for strawberries have been gathered from literature. For all scenarios, a 2% loss has been considered for the DC stage (4% in case of corrugated cardboard packaging) and 10% loss for retail (15% loss in case of corrugated cardboard packaging). Based on Eurofins report, a 37.5% loss has been

	considered for untreated strawberries, and a 0% loss has been assumed for LiVA's scenarios. This data is regarded as a high-quality data since it comes from a third-party certifier. • Foreground data referred to food waste for mangoes have been gathered from literature. For all scenarios, the assessment considered mean losses at harvest of 14.4%, 5.3% at the packaging stage, 12.4% during international transportation. As for the untreated scenario, a wholesale/retail loss of 13.0% and a 12.0% loss at the consumer stage have been considered. These losses have been zeroed in case of LiVA's scenarios. • Background data related to the electricity mixes, material production, transport and EoL are sourced from ecoinvent, with preference given to datasets that reflect the geographical and technological context of the investigated scenario. EoL for biowaste rising from food losses has been considered as handle through anaerobic digestion using Switzerland based dataset in ecoinvent.
	Selected Impact Categories • **Climate change (GWP100)**. Captures energy use along cultivation, pre-cooling, cold storage, refrigerated transport and potential refrigerant losses. It is regarded as a main driver of both the cold chain system and the horticultural practices themselves, particularly for the case of strawberries. with very high GWPs. This is the principal driver for cold-chain systems. • **Ozone layer depletion (ODP, steady-state)**. Reflects burden associated with legacy service refrigerants to secure reliability across supply chains where residual ozone depletion substances can still be present. • **Photochemical oxidant formation (POF)**. Representative for emissions rising from diesel reefer units, on-road logistics and handling equipment in distribution platforms. • **Acidification (AP) and Eutrophication (EP)**. Sensitive to field emissions from fertiliser use in strawberry and mango production, and to additional upstream inputs rising from food losses. • **Abiotic depletion, elements (ADP-elements) and Abiotic depletion, fossil (ADP-fossil)**. Reflects packaging manufacturing, fuels and electricity consumptions. • **Human toxicity (HTP) and Ecotoxicity (FAETP, MAETP, TETP)**. Captures potential toxicological pressures from plant-protection substances and auxiliaries and upstream chemical synthesis. These categories are consistent with prior agri-food LCA that use CML for fresh produce, supporting methodological continuity and comparability.
	Database Selection Attributional modelling has been adopted for the purpose of the present assessment, with the ecoinvent 3.9 database and the allocation at the point substitution (APOS) system model being

	utilised. The attributional perspective has been selected because the objective of this study is to provide a comparative analysis of conventional pre/post-harvest practices versus the bio-preservation LiVA's product under current supply chain conditions. This is consistent with most published LCA studies on food supply chains, which describe the average environmental burdens per unit of product delivered, rather than exploring market-mediated consequences of large-scale adoption. Given the aim to ensure direct comparability and consistency with existing LCA studies, the utilisation of attributional datasets has been considered the optimal approach.
Life Cycle Inventory	**LiVA's Products** The Life Cycle Inventory (LCI) of LiVA's products includes compounds recognised under US food regulations and conventional commodity chemicals. A significant number of specialised media components are not equipped with dedicated ecoinvent unit processes. Nonetheless, omitting a substance due to database gaps can lead to a systematic underestimation of environmental burdens, especially in culture-media formulations where organic nutrients constitute a substantial fraction of mass and embodied energy. Their exclusion would systematically underrepresent resource and energy inputs for culture-media within the BoM, and these have therefore been substituted functionally and/or structurally with analogous datasets that replicate the dominant feedstocks and unit operations. Specialized media are not commonly available in ecoinvent datasets, and their modelling has been therefore anchored in their regulatory identity and typical feedstock origins to find a proper proxy. Industrial chemicals have been modelled by considering conventional chemical-synthesis inventories corresponding to the predominant industrial processes documented in chemical engineering literature and in process descriptions embedded in the ecoinvent database. All components have been accounted for as market activities, considering average Europe data. No further data on the LCI for LiVA's product is shared as these are confidential information for internal purposes only. **Fungicide** ecoinvent does provide a dataset for unspecified pesticide production which is based on 1 kg of active ingredient. The dataset reports raw materials computed based on stoichiometric calculations, while energy consumption is based on similar process and associated emissions are estimated. The dataset starts from the reception of precursors at the factory gate and ends with pesticides at the factory gate, including the input materials, energy uses, infrastructure and emissions. To discriminate the case of fungicides respect to the generic ecoinvent dataset, assumptions on energy consumption have been made. For generic pesticide, the ecoinvent dataset is built upon these assumptions: • **Electricity**: 1.927 kWh per kg. Average consumption of electricity and heat per kg of product (3.2 MJ per kg), and a resulting amount of electricity of 0.333 kW for every reaction step per kg reaction product, considering that the demand is made up of a mix that includes 38% electricity. Reaction steps are approximated with energy consumption data.

	• **Heat, district heating or natural gas**: 15.504 MJ. Originated from calculation of average consumption of electricity and heat per kg of product (3.2 MJ per kg), and a resulting amount of heat of 2 MJ for every reaction step per kg reaction product, considering that the demand is made up of a mix that includes 50% natural gas. • **Heat, district or industrial, other than natural gas**: 8.65 MJ. Originated from calculation of average consumption of electricity and heat per kg of product (3.2 MJ per kg), and a resulting amount of heat of 2 MJ for every reaction step per kg reaction product, considering that the demand is made up of a mix that includes 12% steam from external energy sources. The authors of the dataset stressed that reaction steps are approximated with energy consumption data, assuming that inventory flows can be estimated using process data for basic operation steps. The FAO methodological report summarizes legacy and contemporary sources, reporting class-level energy intensities to produce active ingredients (i.e. synthesis and work-up utilities), reporting: (1) 450 MJ per kg for herbicides; (2) 262 MJ per kg for insecticides; and (3) 189 MJ per kg for fungicides. The current generic dataset totals 31.095 MJ per kg (1.927 kWh of electricity, 15.504 MJ of heat, natural gas, 8.654 MJ of heat, other), which is a heuristic per-reaction-step multiplied by an assumed step count, not a class benchmark. To keep consistency with this construction, though far from FAO estimates, the values for fungicides were set to: (1) 1.84 kWh per kg of electricity; (2) 8.82 MJ of heat, district heating or natural gas; and (3) 2.09 MJ per kg of heat, district or industrial, other than natural gas. The modified dataset reflects generic fungicide production in the European context and has been used for the purpose of the present assessment. No further changes have been made to discriminate fludioxonil and cyprodinil, whose effect has been considered in terms of emission to soil and water for the strawberry and mango case, respectively. A further modification on the precursors share would have led to an excessive degree of uncertainties given that all production processes of synthetic fungicides are patented, and it is therefore not feasible to report actual production inventories. **Strawberry Value Chain** The assessment considers 1 kg of strawberries delivered at retail and available for consumer's purchase and accounts for any losses throughout the supply chain. Six scenarios are considered for comparison purposes, these being: • **Current**, the baseline scenario referred to the conventional pre-harvest fungicide treatment and a cold chain comprising cooling at 0°C, packaging in either plastic clamshells or cardboard, transportation at 2°C towards the DCs, temporary storage and distribution at 2°C towards retail. The current scenario sees pre-harvest fungicide treatment as the standard practice (i.e., Switch®, based on cyprodinil and fludioxonil, used to control the emergence of grey mould). Once harvested, strawberries are cooled to 0°C, sorted and packaged into either plastic clamshells or cardboards. Packaged

	strawberries are then distributed to be delivered at the DCs, then at retailers and eventually at consumers. In this scenario, temperature set-points are meticulously managed, and, alongside the fungicide regimen, these elements contribute to minimise spoilage and overcome the underlying perishability issues of strawberries. In both LiVA's scenarios, the chemical fungicide treatment is reduced by 50% by applying the LiVA-S or LiVA-I to the strawberry packaging. As both products are designed to provide a biological control over the outbreak of post-harvest diseases, their use widely reduce the need for synthetic fungicides and allows for less stringent cold-chain conditions (i.e., the lower risk of fungal spoilage make it possible for strawberries to tolerate warmer storage temperatures or longer storage durations without quality loss). Therefore, both LiVA's scenarios are featured by higher temperature setpoints (i.e., 2°C versus 0°C and 4°C versus 2°C in the farm to DCs and DCs to retail phases), less energy-intensive cooling steps, and lower spoilage and waste generation throughout the distribution chain. In order to structure the LCA, the strawberry supply chain is broken down into major stages and processes, with major inputs, output and emissions sources in each being detailed. • **Strawberry Cultivation**. Consistently with analogous literature works and with the intended market of LiVA, the assessment considered open-field strawberries cultivation in Spain as production process. The ecoinvent production process considers macro-tunnel cultivation along with all the average inputs related to agricultural operations, fertilizers and pesticides production and use, and machines used for soil inversion and irrigation. The ecoinvent dataset is representative representing strawberries produced in open fields in of Huelva (Spain) region and leverages a documented agronomy (project Worl Food LCA Database, WFLDB) referred to the 2006-2008 biennium, considering: (1) 45 ton per hectare annual yield obtained under irrigated conditions (annual amount of water 5,000 m3 per hectare); (2) mineral NPK fertiliser input is 150-100-200 kg per hectare (no organic fertilisers are applied); and (3) pesticide application referred to average active (ai) ingredients of about 26.3 kg of ai per hectare (plus 190.4 kg chloropicrin per hectare). Chemicals are modelled as market activities and, therefore, the inputs of packaging are considered. The production system has boundaries spanning from soil cultivation after the harvest of the previous crop to harvest and transport to the farm gate (storage is not included). In terms of machine operations, the dataset includes soil cultivation, fertilisation, pesticide application, harvesting, and on-farm transport. Direct field emissions and land use change are included as well. To incorporate Switch® without altering the spray-water or field-operation procedures, the respective amounts of both, modelled as described above, have been included in terms of both production and emissions to soil. The amounts of cyprodinil and fludioxonil have been calculated according to the above reported use indications and equal to 1.33E-05 kg and 8.89E-06 kg in the current scenario. Pesticide

usage have been modified accordingly. Reduction rates for LiVA's scenarios are based on the previously reported assumption.

- **Packing**. Harvested strawberries are cooled at either 0°C (0.0628 kWh electricity) or 2°C (0.0578 kWh electricity), packaged into either plastic clamshell (18.1g extruded HDPE film and 39.84g thermoformed PET per kg) or cardboard boxes (50g corrugated box and 1.8g extruded HDPE film per kg) and sealed (0.00854 kWh per kg). The same packaging is used in all scenarios, with either LiVA-S or LiVA-I being applied on the packaging considering the amount of strawberries to be handled. This stage includes the allocation of LiVA's products manufacturing according to their specific production process and use practice (direct energy and resource consumptions for LiVA's products applications are assumed to be negligible with respect to the considered stage). The number of either plastic clamshells or cardboard boxes varies with the amount of strawberries in input and it is therefore modelled to be dependent on food waste.
- **Cold Chain Transport and Storage.** Once packed, strawberries are transferred to the DCs through refrigerated lorries (100 km). The energy requirements for this refrigeration have been adjusted in terms of diesel consumption assuming that the available ecoinvent dataset is referred to a 10 °C mean temperature. Upon arrival, strawberries are cooled at either 2°C (0.0578 kWh electricity) or 4°C (0.0528 kWh electricity) and sent to retail through refrigerated lorries at the same temperatures (50 km). At retail, the assumed loss and a 0.016 kWh consumption for 24 hours is equally allocated for all scenarios.
- **Consumer**. A mean electricity consumption value of 350 kWh per annum has been considered alongside a storage duration of 5 days. Adopting a literature-based approach, the environmental burden has been allocated according to the economic value of strawberry and an allocation factor of 11.3% has been assumed.
- **EoL**. As packaging materials (i.e., plastic clamshells, corrugated boxes, food waste and LiVA's products) are included in the modelling, EoL pathways for each have been considered. Plastic clamshells and cardboard boxes waste handling is based on the market average for Europe, food waste is sent to anaerobic digestion and LiVA-S is handled according to market average treatments in Europe. Being completely biodegradable LiVA-I, EoL has been neglected for this scenario.

Mango Value Chain

The assessment considers 1 kg of mangoes delivered at retail and available for consumer's purchase and accounts for any losses throughout the supply chain. Three scenarios are considered for comparison purposes, these being:

- **Current**, the baseline scenario referred to the conventional post-harvest fungicide treatment and a cold chain comprising sea freight transport (10,000 km at 10°C) from Brazil to Rotterdam (The Netherlands, European Union). For this case, it is assumed that losses from the farm gate to the retail gate are of 32.1%, while losses at the

	retail/consumer stage are of 25%. More in detail, the current scenario sees post-harvest fungicide treatment as the standard practice (i.e., Scholar®, based on fludioxonil, used to control common mango rot diseases such as stem-end rot and anthracnose). Considering the hot water treatment technique, mangoes are immersed in a heated solution to suppress spoilage organisms and then washed with a Scholar® solution dried, sorted and packaged into cartons. Packaged mangoes are then shipped in refrigerated containers by sea to be delivered at the DCs, then at retailers and eventually at consumers. In this scenario, temperature set-points are meticulously managed, and, alongside the fungicide regimen, these elements contribute to minimise spoilage and overcome the underlying perishability issues of mangoes. In both LiVA's scenarios, the chemical fungicide wash is reduced by 50% by applying the LiVA-S or LiVA-I to the mango packaging. As both products are designed to provide a biological control over the outbreak of post-harvest diseases, their use widely reduce the need for synthetic fungicides and allows for less stringent cold-chain conditions. Both LiVA's scenarios are featured by higher temperature setpoints (i.e., 12°C versus 10°C), less energy-intensive cooling steps, and lower spoilage and waste generation throughout the distribution chain. In order to structure the LCA, the mango supply chain is broken down into major stages and processes, with major inputs, output and emissions sources in each being detailed. • **Mango Cultivation**. Mangoes are assumed to be cultivated in open-field orchards in Brazil and the ecoinvent dataset is selected accordingly. As discussed, this stage includes the production and use of conventional fertilizer, alongside related N_2O emissions (and, therefore GHG emissions), irrigation, on-site fuel use for farm machinery, and other agrochemical products used in the pre-harvesting stage. The cultivation phase remains unaltered for both LiVA's scenarios as it is a baseline that is set to represent the main burdens related to food waste. Eventually, it must be noted that as mango trees do sequester CO_2 during their growth, this might offset emissions, though this uptake is allocated over the lifetime of the orchard and severely depends on EoL. • **Post-harvest**. After harvest, mangoes are transported to a designated packhouse where they undergo a thorough cleaning, treatment, and packing process. In the baseline scenario, this stage is modelled through the available ecoinvent dataset, adjust to include Scholar® treatment to deactivate spores on the fruit skin. The available dataset in ecoinvent for hot treatment is adequate for mangoes intended for export. The process includes mangoes washing, hot treatment and both wax (not included in the inventory as the inventory of the Carnauba wax, equal to 8.33E-03kg, is not available) and fungicides applications. ecoinvent dataset includes a loss of 5%, referred to mangoes being regarded as not compliant with the quality requirements. This data has been adjusted to reflect the above-mentioned literature evidence. Based on dataset description, effluents from washes and phytosanitary treatments are treatments

	disposed of in soil without treatment, and it therefore assumes that all chemicals are released in them. The current dataset has been modified to account for the use of Scholar®, a post-harvest fludioxonil-based fungicide commercialized by Syngenta and compatible with the already included line sprays. Scholar® has been considered as a baseline for the conditioning process, retaining the assumption that the chemical inputs are discarded to the soil through the effluents (emission to water, unspecified, equal to the applied active mass and therefore not accounting for the on-fruit retention and the degradation factors). The application rate is assumed of 1.25 L per ton of product and data on water consumption have been adjusted accordingly. • **Packing**. Treated mangoes are packaged in corrugated cardboard cartoons. The boxes themselves typically weigh around 400 g each, including any HDPE liners (assumed equal to 5 g), which works out to roughly 100 g of cardboard per kg of mango. The same cardboard packaging is used in all scenarios, with either LiVA-S or LiVA-I being applied on the packaging considering the amount of mangoes to be handled. This stage includes the allocation of LiVA's products manufacturing according to their specific production process and use practice (direct energy and resource consumptions for LiVA's products applications are assumed to be negligible with respect to the considered stage). The number of cardboard boxes varies with the amount of mangoes in input and it is therefore modelled to be dependent on food waste. • **Cold Chain Transport and Storage.** Once packed, mangoes enter the international logistics chain, and a strict cold chain is maintained throughout the supply chain. The cold chain requirements for mangoes are strict, since they are a chilling-sensitive climacteric fruit. Refrigerated container ships are used to transport mangoes Brazil to Rotterdam (The Netherlands, Europe). A reefer container uses fuel or electricity to maintain a temperature of 10°C for current scenario and 12°C for LiVA's scenarios. The energy requirements for this refrigeration have been adjusted in terms of diesel consumption assuming that the available ecoinvent dataset is referred to a 10 °C mean temperature. Upon arrival, mangoes have been transferred to retails by means of refrigerated lorries at different temperatures. • **Consumer**. A mean electricity consumption value of 350 kWh per annum has been considered alongside a storage duration of 5 days. Adopting a literature-based approach, the environmental burden has been allocated according to the economic value of mangoes and an allocation factor of 17.5% has been assumed. • **EoL**. As packaging materials (i.e., corrugated boxes, food waste and LiVA's products) are included in the modelling, EoL pathways for each have been considered. Cardboard waste handling is based on the market average for Europe, food waste is sent to anaerobic digestion and LiVA-S is handled according to market average treatments in Europe. Being completely biodegradable LiVA-I, EoL has been neglected for this scenario.

	Further notes on post-harvest mangoes handling ecoinvent also includes a further potential conditioning treatment for mangoes after harvest, this being the wax treatment coupled with fungicide application. The available dataset includes activities spanning from mangoes washing to wax and fungicides applications and, as for the hot treatment, it is assumed that chemicals are discarded into the soil through the effluents without further treatment. While it is described as a valid treatment for both internal and external market, it must be noted that wax treatment can be regarded as not sufficient to satisfy the quarantine requirements for most export destinations, including the EU, which requires a phytosanitary certificate to enable the access to the market (i.e., the operators need to demonstrate mangoes are free of quarantine pests). The current EU regulation does not prescribe a single treatment, such as hot water, but instead requires proof of freedom from pests through inspection and an approved systems approach. Therefore, to ensure compliance, exporters mostly use hot water treatment though not formally mandatory, as destined for the EU can be destroyed at the expense of the exported if a single fruit fly is detected.
Impact Assessment Method	The CML v4.8 2016 midpoint method has been adopted for the present assessment due to its status as a mature, transparently documented and widely implemented LCIA framework, with stable characterisation factors that are suitable for attributional LCA in agri-food and cold-chain contexts. The 2016 release consolidates the CML Baseline categories and remains available from the originating institution (Leiden University), ensuring the traceability of factors and method notes.
Results	**LiVA's Products** Results for LiVA's formulations support the introduction of their novel LiVA-I, as it enables a 40.27% average reduction in environmental burden per kg of nutrient blend considering 2028 and 2030 forecasts. On the other hand, it must be underlined that impacts on a per kg basis are substantially low (GWP of 1.19 kg of $CO_{2,eq}$ per kg and 0.83 kg of $CO_{2,eq}$ per kg for the sticker and the ink formulation, respectively) and are mostly driven by electricity consumption and certain nutrient media which have been modelled through proxies. On the other hand, impacts of a per-item basis further support the introduction of LiVA-I, bringing a substantial reduction with respect to the LiVA-S format intended for mangoes preservation. Normalising the results with respect to the LiVA-S format intended for strawberries, average impact reduction is of approximately 76.86%. Further insights are provided in the interpretation section. **Strawberry Value Chain** The comparison across current scenarios with different packaging materials (i.e., plastic clamshells and cardboard boxes) clearly highlights the benefits of LiVA's products in terms of overall environmental footprint reduction. With reference to the plastic clamshell baseline, LiVA-S brings a 25.94% average reduction in the investigated impact categories, while LiVA-I scenario is featured by an average reduction of 27.19%. Upon considering the cardboard boxes scenario,

mitigation effect is similar (25.18% and 26.60% for LiVA-S and LiVA-I, respectively). Considering the overall comparison, LiVA-S and LiVA-I enable the development of a carboard box-based value chain guaranteeing an overall mitigation of the environmental externalities of 31.54% and 32.86% on average, respectively. These outcomes outline the capacity of LiVA's products to prompt a massive shift towards less energy and resource intensive packaging materials and support the replacement of plastic in the sector. Cardboards are nature-based packages whose adoption is currently hindered by the material acting as a substrate for microbial growth and favouring moisture absorption. Despite the assessment was performed by assuming higher losses through the chain, the cardboard box scenarios still outperformed the plastic clamshells ones, and it must be noted that LiVA's products might also lead to further enhancements as cardboard conditions prompts their action, making them a unique solution to overcome adoption barriers.

In detail, for the plastic clamshells scenarios, GWP contributions are as follow:

- **Current Scenario**. 44.75% from strawberry production, 26.02% from electricity consumption at household, 8.56% from clamshell EoL, 6.69% from clamshell manufacturing, 5.21% from transportation and 4.52% for biowaste treatment.
- **LiVA-S**. 45.07% from strawberry production, 25.83% from electricity consumption at household, 8.62% from clamshell EoL, 6.74% from clamshell manufacturing, 5.17% from transportation, 3.28% for LiVA-S manufacturing, 1.29% for biowaste treatment and 0.03% for sticker EoL.
- **LiVA-I**. 46.61% from strawberry production, 26.71% from electricity consumption at household, 8.92% from clamshell EoL, 6.97% from clamshell manufacturing, 5.347% from transportation, 1.33% for biowaste treatment

As for the cardboard box scenarios, the contributions for GWP result as follow:

- **Current Scenario**. 50.62% from strawberry production, 28.33% from electricity consumption at household, 5.91% from transportation, 5.36% from biowaste treatment, 3.83% from carboard box manufacturing and 0.85% from cardboard box EoL.
- **LiVA-S**. 50.94% from strawberry production, 27.93% from electricity consumption at household, 5.68% from transportation, 3.85% from carboard box manufacturing, 3.71% for LiVA-S manufacturing, 2.04% for biowaste treatment, 0.86% from cardboard box EoL and 0.03% for sticker EoL.
- **LiVA-I**. 52.91% from strawberry production, 29.01% from electricity consumption at household, 6.06% from transportation, 4.00% from carboard box manufacturing, 0.89% from cardboard box EoL and 2.12% from biowaste treatment.

For both cases, LiVA-I does not add substantial contribution to the resulting GWP, while LiVA-S has a share lower than 5% that rises almost completely from the sticker being modelled as a market activity (LiVA-I on the other hand has been supposed as applied directly to the packaging). A notable exception in the comparison across plastic clamshell and cardboard boxes

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is represented by higher impacts in the AD, ODP and POF, connected to the higher demand for upstream production (average share for strawberry production of 59.91%, 96.92% and 57.10%, respectively).

Mango Value Chain

The comparison for the mango value chain supports the above-reported findings. LiVA-S brings a 19.75% average reduction in the investigated impact categories, while LiVA-I scenario is featured by an average reduction of 20.31%. GWP contributions are as follow:

• Current Scenario. 32.93% from electricity consumption at household, 22.72% from sea freight transportation, 14.29% from cardboard box manufacturing, 10.69% from mango production, 2.80% from inland transportation, 1.20% from carboard EoL and 1.17% from biowaste treatment.
• LiVA-S. 36.87% from electricity consumption at household, 20.98% from sea freight transportation, 14.16% from cardboard box manufacturing, 10.59% from mango production, 2.73% from inland transportation, 1.34% from carboard EoL.
• LiVA-I. 37.12% from electricity consumption at household, 21.12% from sea freight transportation, 14.26% from cardboard box manufacturing, 10.66% from mango production, 2.75% from inland transportation, 1.35% from carboard EoL.
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<tr><td>Interpretation</td><td>
The outcome of the present investigation reflects a preliminary assessment on both the manufacturing process of LiVA’s products and the potential changes in the environmental profile of certain supply chain that could derive from a widespread adoption of both LiVA-S and LiVA-I into the fresh produce market. The performed assessment confirms the claim of LiVA and underscores the outstanding benefits that their bio-preservation solutions could bring in the food chain. The capacity of LiVA’s product of abating losses and food waste throughout the chain represent a game changer in the segment, as the reduction in waste represent a lever to avoid overproduction and horticultural-related impacts. Moreover, the introduction of LiVA’s products into the market does not bring any relevant added burden to the chain, as the entire production process under LiVA’s control is based on nature-based solution and the use of industrial chemicals is minimal. The following limitations underlying the present investigation must be underlined:

• Assumptions have been taken from literature, particularly with reference to upper chain losses and electricity consumptions. Future updates of the present investigation should include primary data collected by acting in synergy with sectoral stakeholder to further validate the obtained outcomes.
• The production process of LiVA-S intended for mangoes suffer from the adoption of literature-based evidence related to the die-cutting and printing processes. The allocation of a high energy demand for the final stage could be far from the actual demand and will therefore need a readaptation by gathering on-field data upon the final establishment of the production line.
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	• Outcomes reflect the adopted geographical scope and are likely to slightly change by considering different background data for the electricity mix and other market activities. The environmental footprint of all the investigated scenarios is likely dependant on site-specific conditions and, as such, future updates of the present investigation should decline the performed analyses in different settings. • The recyclability potential of certain material such as PET, HDPE and paperboard has been only partially addressed by considering market averaged inputs for granulates and raw material. Future updates of the present assessment should gather segment-specific data to further validate the obtained outcomes. **Further notes on fungicides** The modelling of the fungicide production suffers from inherent limitations deriving from high uncertainties on the manufacturing process, as most formulations are covered by patents and create tailored dataset would lead to severe uncertainties and potential misleading. The current approach based on existing dataset adaption is extremely conservative, as literature and statistic data have been adapted to the available ecoinvent datasets, which adopts a substantially low energy consumption figure that does not reflect data coming from relevant institution such as the Food and Agriculture Organization (FAO). Despite this conservative approach, LiVA's solution demonstrates to outperform the capacity of conventional fungicide to extend fresh produce shelf life. Nonetheless, the benefits brought by LiVA's products are likely to go beyond the ones here obtained, and further confirmation could come upon establishing an in-depth cooperation with sectoral association and industries which could provide more reliable data.
Data Availability Statement	LiVA's product data constitutes proprietary and commercially sensitive information. Detailed, process-level results and datasets have been disclosed exclusively to LiVA and used solely for internal process optimization activities and continuous improvement of production lines. No external dissemination of these detailed outcomes will occur without LiVA's prior authorisation, and any necessary external reporting will be limited to aggregated or anonymised summaries that do not reveal confidential information or trade secrets. Further information might be provided upon request if concern the outcomes referred to the fruit value chains
Authors Declaration	This assessment was prepared by Lira Ltd through an independent, science-based evaluation of the production process and a critical, systematic review of the current technical and peer-reviewed literature. The work was carried out in accordance with recognised LCA principles and good reporting practice, with methodological choices and assumptions selected for coherence with the technological, temporal, and geographical representativeness of the underlying data. Lira Ltd hereby affirms the professional independence of the analysis and the absence of undue influence by LiVA over methodological decisions, data treatment or interpretation of results.

Table 1 Impacts per kg of nutrient blend intended for either LiVA-I or LiVA-S applications.

Impact Category	Unit of measure	LiVA-I formulation (2028)	LiVA-I formulation (2030)	LIVA-S formulation (2026)	LiVA-I formulation (2030)
AP	kg SO_2-Eq	2.17E-03	2.16E-03	6.28E-03	6.22E-03
GWP	kg CO_2-Eq	8.28E-01	8.21E-01	1.20E+00	1.18E+00
FAETP	kg 1,4-DCB-Eq	8.01E-01	7.88E-01	1.47E+00	1.45E+00
MAETP	kg 1,4-DCB-Eq	8.45E+02	8.08E+02	1.61E+03	1.55E+03
TETP	kg 1,4-DCB-Eq	2.11E-01	2.11E-01	2.30E-01	2.30E-01
ADP, fossil	MJ	5.65E+00	5.58E+00	1.43E+01	1.41E+01
EP	kg PO_4-Eq	2.03E-03	2.00E-03	4.06E-03	4.04E-03
HTP	kg 1,4-DCB-Eq	1.32E+00	1.31E+00	2.71E+00	2.69E+00
ADP, element	kg Sb-Eq	4.25E-06	4.17E-06	1.20E-05	1.18E-05
ODP	kg CFC-11-Eq	1.68E-06	1.68E-06	1.75E-06	1.75E-06
POF	kg ethylene-Eq	4.50E-04	4.50E-04	5.10E-04	5.10E-04

Table 2 Impacts per LiVA's unit (each unit of product is intended to preserve up to 1kg of fresh produce).

Impact Category	Unit of measure	LiVA-I applied (2028)	LiVA-I applied (2030)	LiVA-S rectangular (2026)	LiVA-S rectangular (2030)	LiVA-S round (2026)	LiVA-S round (2030)
AP	kg SO_2-Eq	1.09E-07	1.08E-07	2.21E-05	2.21E-05	2.50E-06	2.50E-06
GWP	kg CO_2-Eq	4.14E-05	4.11E-05	6.16E-03	6.16E-03	7.20E-04	7.20E-04
FAETP	kg 1,4-DCB-Eq	4.01E-05	3.94E-05	8.00E-03	8.00E-03	7.90E-04	7.90E-04
MAETP	kg 1,4-DCB-Eq	4.23E-02	4.04E-02	2.10E+01	2.10E+01	2.04E+00	2.04E+00
TETP	kg 1,4-DCB-Eq	1.06E-05	1.06E-05	4.35E-05	4.35E-05	6.43E-06	6.43E-06
ADP, fossil	MJ	2.80E-04	2.80E-04	8.64E-02	8.64E-02	1.33E-02	1.33E-02
EP	kg PO_4-Eq	1.01E-07	9.98E-08	7.76E-06	7.76E-06	8.33E-07	8.33E-07
HTP	kg 1,4-DCB-Eq	6.60E-05	6.54E-05	8.98E-03	8.98E-03	9.20E-04	9.20E-04
ADP, element	kg Sb-Eq	2.12E-10	2.09E-10	7.10E-08	7.10E-08	7.23E-09	7.23E-09
ODP	kg CFC-11-Eq	8.39E-11	8.39E-11	1.53E-10	1.53E-10	2.92E-11	2.92E-11
POF	kg ethylene-Eq	2.27E-08	2.26E-08	1.46E-06	1.46E-06	1.73E-07	1.73E-07

Table 3 Impacts per 1 kg of strawberries consumed across six scenarios (3 with plastic clamshells, 3 with cardboard box packaging).

Impact Category	Unit of measure	Current - Clamshell	LiVA-S - Clamshell	LiVA-I - Clamshell	Current - Cardboard	LiVA-S - Cardboard	LiVA-I - Cardboard
AP	kg SO_2-Eq	6.57E-03	4.93E-03	4.81E-03	6.70E-03	5.08E-03	4.95E-03
GWP	kg CO_2-Eq	1.38E+00	1.02E+00	9.90E-01	1.29E+00	9.66E-01	9.30E-01
FAETP	kg 1,4-DCB-Eq	1.72E+00	1.25E+00	1.24E+00	1.25E+00	9.13E-01	9.02E-01
MAETP	kg 1,4-DCB-Eq	2.33E+03	1.73E+03	1.71E+03	1.85E+03	1.39E+03	1.36E+03
TETP	kg 1,4-DCB-Eq	2.72E-02	2.02E-02	2.01E-02	2.49E-02	1.87E-02	1.86E-02
ADP, fossil	MJ	1.58E+01	1.21E+01	1.16E+01	1.51E+01	1.16E+01	1.11E+01
EP	kg PO_4-Eq	3.98E-03	2.78E-03	2.74E-03	3.78E-03	2.67E-03	2.63E-03
HTP	kg 1,4-DCB-Eq	3.05E+00	2.27E+00	2.25E+00	2.80E+00	2.11E+00	2.08E+00
ADP, element	kg Sb-Eq	3.48E-05	2.59E-05	2.58E-05	3.03E-05	2.28E-05	2.27E-05
ODP	kg CFC-11-Eq	5.34E-06	3.98E-06	3.98E-06	5.46E-06	4.12E-06	4.12E-06
POF	kg ethylene-Eq	4.09E-04	3.04E-04	2.94E-04	4.13E-04	3.11E-04	3.00E-04

Table 4 Impacts per 1 kg of mango consumed across three scenarios.

Impact Category	Unit of measure	Current	LiVA-S	LiVA-I
AP	kg SO_2-Eq	8.47E-03	6.62E-03	6.59E-03
GWP	kg CO_2-Eq	1.35E+00	1.07E+00	1.07E+00
FAETP	kg 1,4-DCB-Eq	8.75E-01	7.14E-01	7.04E-01
MAETP	kg 1,4-DCB-Eq	1.51E+03	1.25E+03	1.23E+03
TETP	kg 1,4-DCB-Eq	2.14E-02	1.70E-02	1.70E-02
ADP, fossil	MJ	1.56E+01	1.27E+01	1.26E+01
EP	kg PO_4-Eq	4.72E-03	3.60E-03	3.59E-03
HTP	kg 1,4-DCB-Eq	2.92E+00	2.36E+00	2.35E+00
ADP, element	kg Sb-Eq	9.97E-06	8.33E-06	8.25E-06
ODP	kg CFC-11-Eq	3.90E-08	3.17E-08	3.16E-08
POF	kg ethylene-Eq	5.45E-04	4.21E-04	4.19E-04

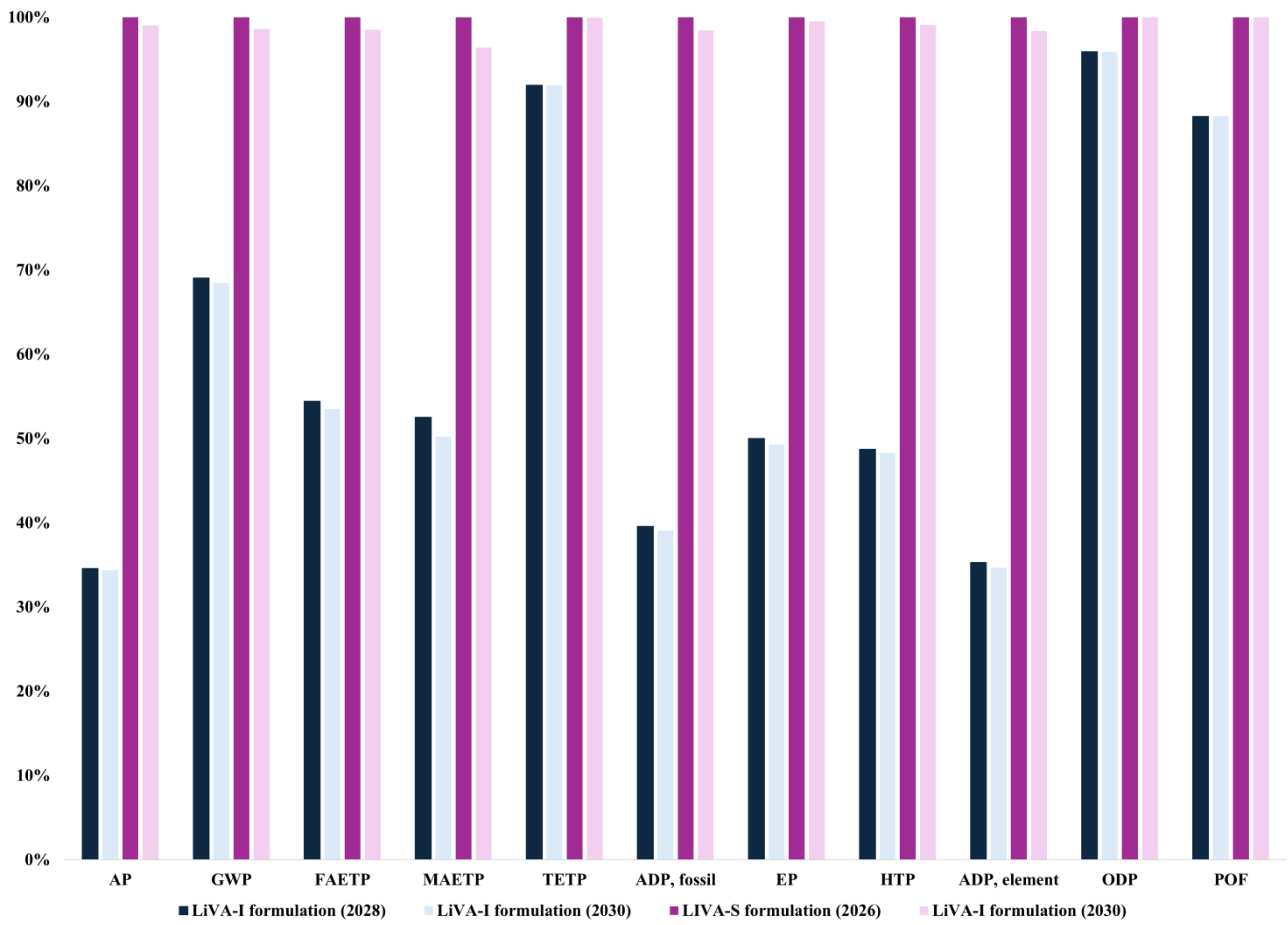

Figure 1 Impacts comparison per kg of nutrient blend intended for either LiVA-I or LiVA-S applications.

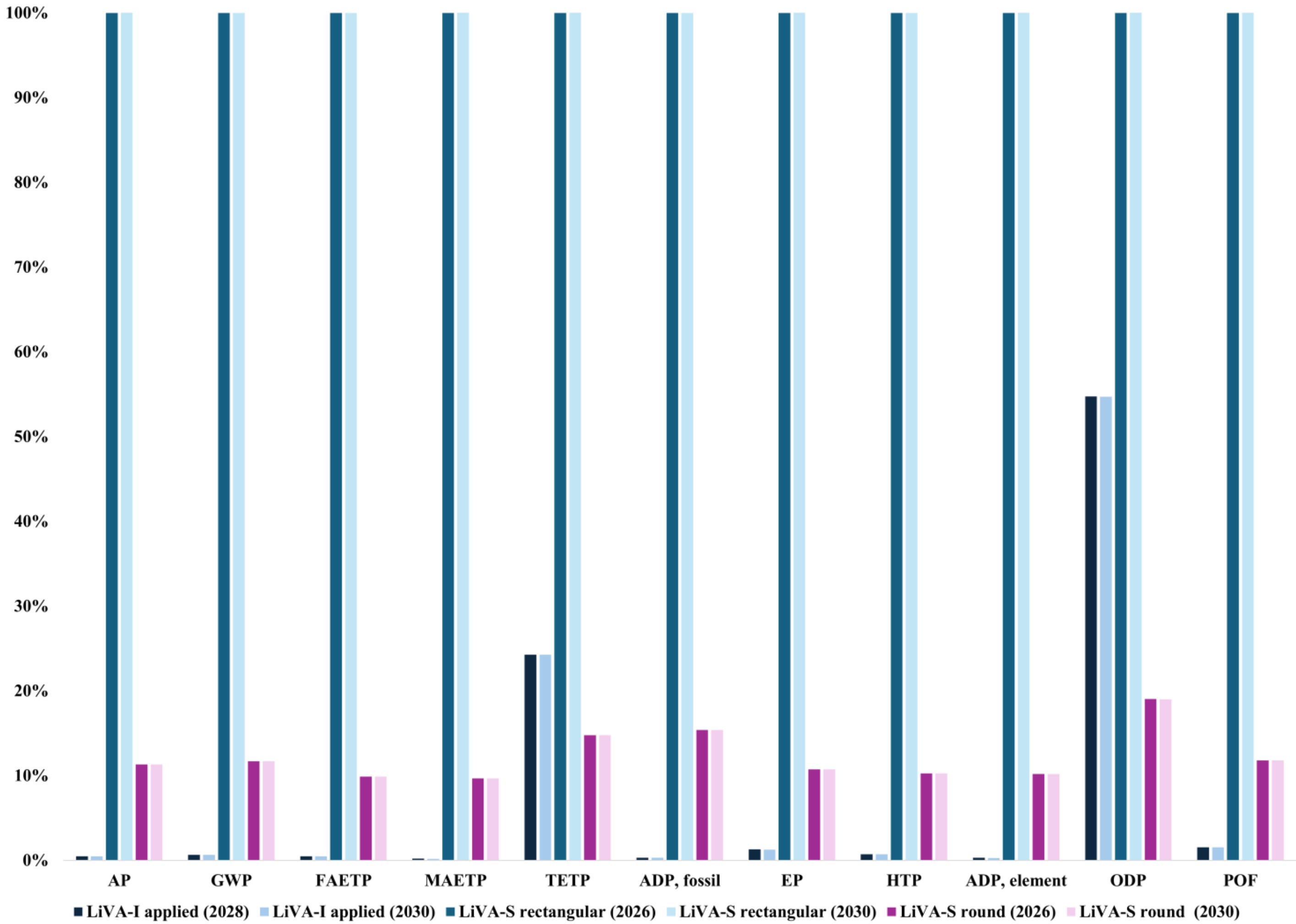

Figure 2 Impacts comparison per LiVA's unit (each unit of product is intended to preserve up to 1kg of fresh produce).

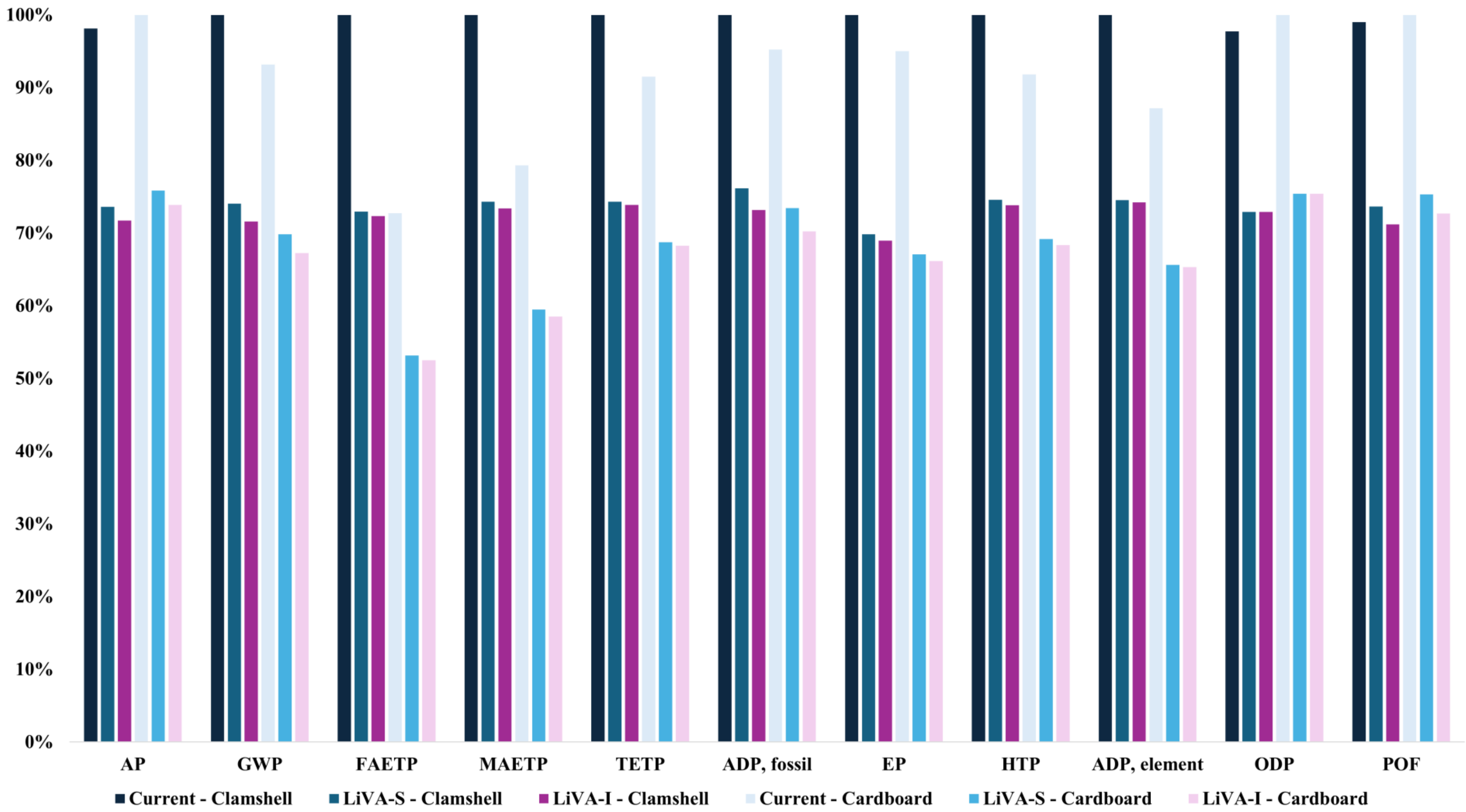

Figure 3 Impacts comparison per 1 kg of strawberries consumed across six scenarios (3 with plastic clamshells, 3 with cardboard box packaging).

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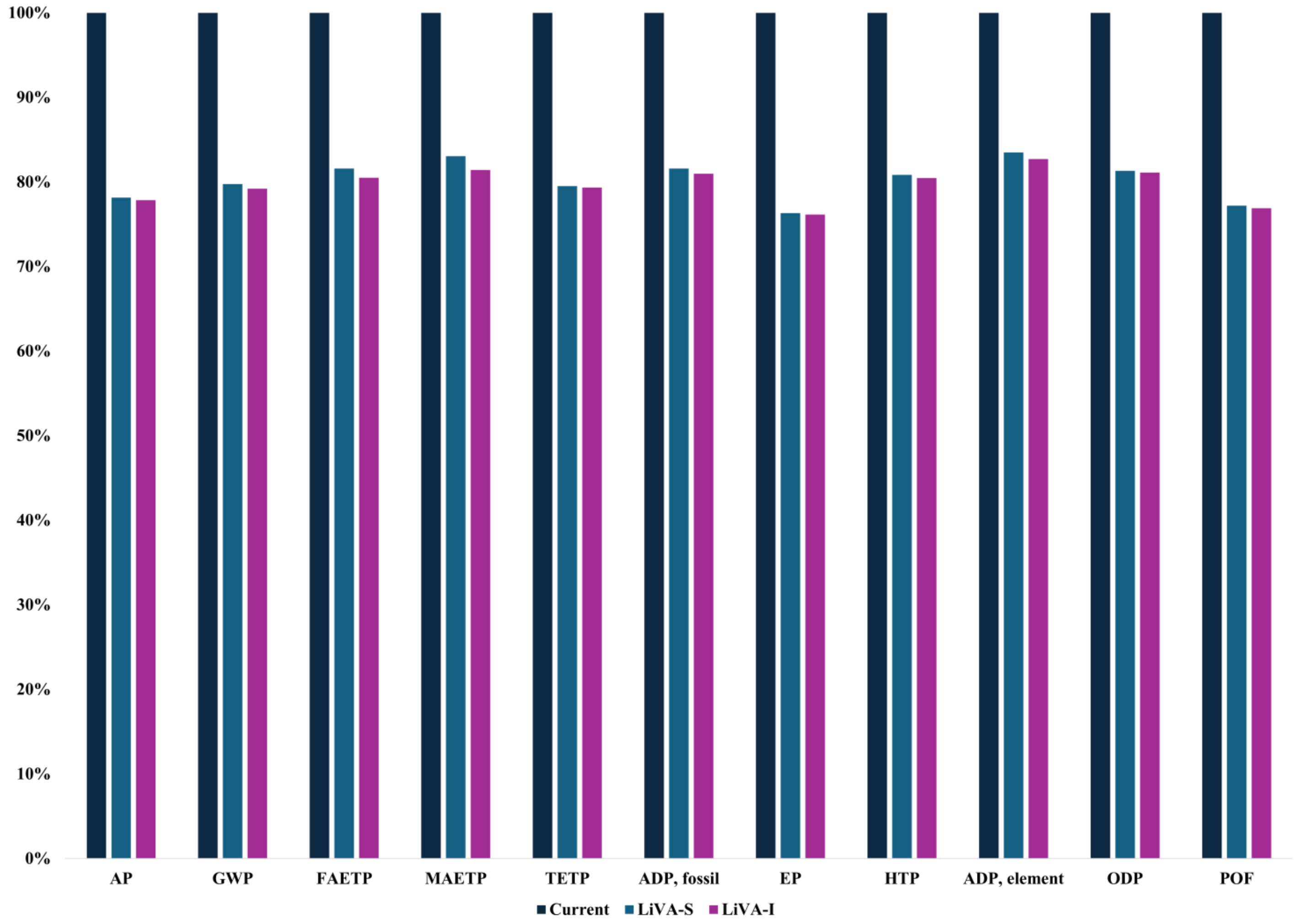

Figure 4 Impacts per 1 kg of mango consumed across three scenarios.

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