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RESEARCH ARTICLE

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Abstract

The objective of this work was to propose an environmental scoring tool for food packaging based on the assessment of three key pillars of packaging sustainability: Materials, Functionality and Post-Usage fate. A participatory process involving relevant food-packaging experts and end users was applied to define the relevant criteria for each pillar. Each criterion was translated into a question for users, and the answers are converted into a score between 0 (*worst option*) and 1 (*best option*) per pillar. For the Materials pillar, two scores were computed from a streamlined calculation of resource (CEENE) and carbon footprints (IPCC) while for the Functionality and Post-Usage pillars, scores were computed from Yes/No answers provided by the users. A fourth pillar considers the potential risk of long-term environmental pollution. Then, the packaging options for the same food are ranked according to the Borda voting rule, considering the individual rankings obtained for the various pillars. The proposed methodology was applied to three commercial (milk and sugar) and non-commercial (strawberry) packaging case studies. The obtained ranking is discussed with respect to current knowledge in the field. The provided methodology is easy to understand, science based, and combines quantitative and qualitative assessments. The developed tool could be handled by non-experts in environmental sciences such as food manufacturers, packaging converters and policy makers. The resulting indicators provide answers to user concerns regarding the environmental impacts of food packaging and guide their choice of the most sustainable option. The proposed scoring method considers the functionality of the packaging with respect to preserving food and reducing food waste, which is rarely considered in packaging environmental assessments.

KEYWORDS
environmental score, packaging usage benefit, qualitative assessment, streamlined resource and carbon footprints, sustainability

1 | INTRODUCTION

By preserving food from deterioration, packaging plays a key role in minimising food loss and waste (FLW) and the enormous concomitant impact of FLW on the environmental footprint of the food industry.[1,2] However, food packaging is mostly perceived as an environmental problem because its production and disposal are associated with numerous environmental impacts, notably the unresolved issue of post-usage plastic packaging that is associated with serious health and ecotoxicology risks.[3–5] Food packaging prevents FLW and enables the efficient distribution of products, thereby contributing to sustainability by providing indirect positive environmental impacts.[6–8] These positive impacts may even counterbalance the direct environmental impacts caused by the production and disposal of packaging.[6,9,10] However, based on the pioneering works of Wikström and Williams,[11,12] the balance between positive and negative impacts of food packaging is rarely included in environmental assessments, although it is necessary for directing evidence-based packaging selection and identifying the optimal trade-off between product protection and preservation and the environmental footprint.

Life-cycle analysis (LCA) is one of the most widely used standardised methodologies for assessing the environmental impacts of a product throughout its lifecycle,[13] but it generally focuses only on the direct environmental impacts of food packaging. If the indirect environmental impacts, such as FLW reduction, are included in some LCA studies, the analysis is still insufficient for the numerous cases where the FLW reduction largely compensates for or overcomes the negative impacts. Another drawback of LCA-based assessments is that they cannot be easily used in the packaging-design step because limited data is usually available (e.g., lack of information on material properties and difficulty defining the functional unit and reference flows, two essential elements of LCA methodology[14]). In addition, the quantity and quality of input data needed to conduct a reliable LCA limit the use of this method for analysing several packaging options at the same time, which would otherwise be very useful for the decision-making and packaging eco-design steps.

To overcome the issue of LCA complexity, less resource-demanding eco-design tools that can be used to select and/or compare different packaging material options have been developed. An overview of these tools, not restricted to the case of food packaging, can be found in previous studies.[15,16] The development of eco-design tools is still being intensely studied, especially early-stage assessments[14] including multicriteria approaches where the economic aspect is considered in addition to environmental performance.[17] In the specific case of food packaging, packaging evaluation tools have been proposed by several research groups. However, because of the many indicators that need to be included in these tools, their application scope varies significantly. For example, the Packaging Scorecard[18] maps the performance of packaging based on key aspects of the supply chain (e.g., product protection, volume, weight efficiency and minimal waste generation). However, due to the lack of data and user expertise to properly evaluate some of the criteria, the evaluation could be influenced by subjective judgement.[19] Another study[20] used an analytical hierarchy process to analyse and assess the packaging of fast-moving consumer goods, focusing on five evaluation areas, including environmental aspects. This method did not include the functionality of the packaging that may reduce FWL. Guillard et al.[21] proposed a multi-criteria decision-support system that considers several stakeholder requirements to help the user select suitable packaging for their application. Even if this tool considers food preservation via the choice of an appropriate barrier property for the targeted food application, it is restricted to fresh food that requires a breathable packaging and includes a limited set of criteria. Along with holistic tools that include some environmental criteria, simplified evaluation tools and approaches have been proposed to assess the environmental impact of food packaging (Table 1). The most sophisticated eco-design tools are mostly based on streamlined LCA (e.g., Piquet, Compass, Bee and ECO-Design of Packaging) and provide environmental-impact data for some packaging categories. The most recent and complete methodology[19] evaluates packaging systems based on four categories (material production, transport, household and end-of-life). To the best of our knowledge, this is the only existing tool to include the influence of packaging on food waste in households. Although this tool provides a comprehensive overview of the environmental performance of food packaging, it does not allow the aggregation of results into a single score, which may limit the decision-making process.

Based on this background, to address the need of food and packaging companies for a simple, easy-to-handle evaluation tool that considers both direct and indirect packaging impacts (e.g., FWL reduction), this study aimed to develop a scoring methodology using a co-creation process involving experts and stakeholders in the food/packaging chain. This study was conducted within the framework of the GLOPACK (Granting Society with Low Environmental Impact Innovative Packaging) H2020 European project (2018–2021). The objective was to consider the important life-cycle phases of the packaging including its functionality (usage benefits), focusing on the ability of the packaging to protect food and its long-term fate in the environment. The developed tool does not integrate the impact of the food itself, to avoid biasing the decision-making process. The tool should consider all kinds of materials, not solely plastics. Finally, a final single score must be obtained to easily rank the packaging alternatives and facilitate the decision-making process. No existing tools include all of these criteria.

Target users of the GLOPACK packaging score tool are food companies that use packaging materials. The tool could also be very useful for manufacturers that provide packaging to food companies and more generally for other stakeholders involved in packaging decision-making. The tool focuses on comparing existing packaging formats but could also provide guidance in the packaging optimisation steps to evaluate the sustainability of a new packaging solution.

TABLE 1 Summary of available tools for environmental assessment of packaging.

Type	Tool (developer)	Description/objective	Limitations/missing information	Advantages
Eco design tool	EEFP tool (Environmental Evaluation Tool for Food Packaging)[19]	Packaging assessment areas: (1) material, (2) transport efficiency, (3) influence on household food waste, and (4) end-of-life options. Each assessment area contains several performance criteria. For each criterion, there are five defined environmental performance levels, where level 5 indicates the best performance.	No score aggregation between performance criteria, which may limit analysis and decision-making when comparing alternatives. Tool developed in collaboration with Orkla Foods, largest business unit for food supplies in the Nordics, Baltics, and Central Europe. Thus, the tool is restricted to Orkla Foods packaging.	Considers the most important life-cycle phases of packed products. Includes the functionality of the packaging (influence on food waste). Publicly available (published paper). Could be used by non-experts in LCA.
	Eco-score: environmental impact of packed food products (https://docs.score-environnemental.com/)	Procedure to calculate a single score that is printed as FOP labels on the consumer sale unit. The score can also be viewed on a smartphone by scanning the bar code. Includes LCA of the food product itself (from Agribalyse project): 14 impacts are aggregated into one global score. Additional criteria considered as bonus or malus are then used to refine the global score: (1) production mode (bonus is given to organic, fair, sustainably certified production modes), (2) origin of the ingredients (a bonus is given depending on the origin of the ingredients and the environmental policy of the origin country), impact on biodiversity (a malus is provided to ingredients identified to have an significant impact on biodiversity), and (4) packaging (a malus is calculated based on the type of resource, for example, fraction of recycled material, use of renewable materials, and sustainable management of resources), and end-of-life options (recycling, biodegradation, or incineration).	This score considers only two aspects of packaging: (1) type of resources and (2) end-of-life treatment, which is restricted to only three options (recycling, biodegradation, and incineration). The lowest malus is for recyclable materials followed by biodegradable ones and then incineration, indicating a clear bias for recycling strategies. Functionality of the packaging (and its effect on food waste reduction) is not considered.	Method publicly available. Single score, easy to understand by consumers (score printed on the package as an FOP label; the final score out of 100 is converted into a letter between A (best environmental score) and E (worst score).

(Continues)

TABLE 1 (Continued)

Type	Tool (developer)	Description/objective	Limitations/missing information	Advantages
		Final score (out of 100) = LCA global score + bonus − malus		
	BEE: Bilan Environnemental des Emballages (CITEO) https://bee.citeo.com/	Online tool for quantitative environmental assessment of user's packaging based on stream-lined LCA, Considers 4 environmental impact factors of packaging from the extraction of raw materials to their end-of-life management.	Strictly limited to production and post-treatment of packaging French market only Extensive information needed on weights and size of primary and secondary packaging. Functionality of the packaging not considered.	Free interactive tool. Methodology guide publicly available.
	ECO-Design of Packaging - A Toolbox for Professionals (Fost Plus, Prevent Pack) https://ecodesign-packaging.org/	LCA-based tool to evaluate environmental impact of pre-defined packaging types (plastic, glass, metal, etc.). 3 impact factors considered. Allocates the results to different life-cycle stages.	Materials already predefined, no flexibility for, for example, multilayers. Several life cycle steps are excluded (disclaimer in the FAQ section). Functionality of the packaging is not considered. Seems not available anymore	Free interactive tool. Focused on food packaging. Provides potential actions that can be implemented in the 4 life-cycle stages (Raw materials, Manufacturing, Distribution, End-of-life)
	FEEL: Facilitateur d'Éco-conception En Ligne (CITEO) https://feel.citeo.com/	Eco-design online tool based on a check list Questions are grouped into 5 categories: Conception, Production, Transport, Communication, and End-of-life. to identify a short action plan to improve packaging sustainability.	For packaging and papers. Does not provide a score but an action plan. Functionality of the packaging is not considered.	Free, easy to handle. Provide a short action plan.
	Nordic Swan Ecolabelling (Nordic Ecolabelling) http://www.nordic-ecolabel.org	LCA-based eco-design tool. Ecolabelling scheme for the Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden) All kinds of goods, not only packed food products. More than 25 topics covered (primary packaging, raw material constituents, chemical products and substances, quality and regulatory requirements). Could be used to help companies select or design more sustainable solutions.	Only 3 types of food contact materials are considered: packaging for liquid foods, disposables for food, grease-proof paper. A lot of information and certificates of compliance are required. Functionality of the packaging is not considered.	Link to certification (for Nordic countries). Can be used as an eco-conception tool out of certification framework. Details of the criteria and background methodology available.
	EcoImpact-COMPASS (Sustainable Packaging Coalition) https://trayak.com/compass-enhancements	Streamlined LCA tool for assessing the environmental performance of packaging designs 9 impact categories. Covers a broad range of packaging materials and different EOL options (recycling, landfilling, etc.	Only for packaging material; business tool Functionality of the packaging is not considered.	Evaluate simple to complex packaging scenarios. Identifies hotspots where there is an opportunity to reduce environmental impact

TABLE 1 (Continued)

Type	Tool (developer)	Description/objective	Limitations/missing information	Advantages
	PIQUET Sustainable Packaging Alliance https://piqet.com/	Streamlined LCA tool for assessing the environmental impacts and resource consumption profiles of different packaging options. Covers a broad range of packaging materials, life-cycle stages (transport, retail, consumer), product losses, and different EOL options (recycling, landfilling, littering, etc.	Only for packaging material (not specifically food packaging) A lot of detailed input data is required. Business tool. Functionality of the packaging is not considered.	Identification of hotspots to improve sustainability throughout the supply chain. Possible to compare and benchmark design options and improvements. Tool to communicate environmental benefits effectively.
	PackScore (British Plastics Federation [BPF]) https://www.bpf.co.uk/design/packscore/what-is-packscore.aspx	Simplified eco-design tool based on a set of questions to be answered by the user on the packaging design. Visual grading of recyclability (A – F) (similar to Recyclass grades, see below) and enables indication of light weighting, re-use, and bio-based materials. The objective of the tool is to visualise a sustainability checklist.	Mainly an evaluation of recyclability. Business tool. Functionality of the packaging is not considered.	
Bioplastic assessment	Bioplastic Tool (Association of Organic Food Producers [AÖL]) https://biokunststofftool.de/?lang=en	Internet tool providing information on the five most important commercial material groups (Bio-PE, Bio-PET, cellulose, PLA, starch blends). 5 criteria considered: ecology, society, safety, technology and quality aspects. Further sub-criteria are land utilisation, life cycle assessments, social standards and migration. A checklist is provided as a tool for decision making.	Only applicable to bioplastics. Only available in German. Functionality of the packaging is not considered because it is outside the scope of the tool.	Evaluation of each category of criteria rated according to the quality/quantity of data available (3 categories considered *Extensive database*, *Limited database* or *Very small/no database*. Information presented by group of substances or by type of packaging. Comparison of two or more substances side by side.
Recycling tool	RecyClass (Plastics Recyclers Europe) http://www.recyclass.eu/en/home/	Online tool that evaluated the recyclability of a certain package by answering a questionnaire. Results are expressed in a scale rating from 'A' to 'F'.	Only applicable to plastics. Functionality of the packaging is not considered because it is outside the scope of the tool.	Free, interactive online tool. Guide is provided to correctly answer each question and understand results. Recycled content certification possible.

(Continues)

TABLE 1 (Continued)

Type	Tool (developer)	Description/objective	Limitations/missing information	Advantages
	TREE: Test de la Recyclabilité des Emballages (CITEO) https://tree.citeo.com/	Online tool to evaluate material recyclability. Quickly diagnoses the recyclability of a packaging and give suggestions for optimisation.	Developed for the conditions in France. Organic recycling not considered. Functionality of the packaging is not considered because it is outside the scope of the tool. Only for Citeo's clients	Applicable to all types of packaging materials (including plastics). Requirements guide publicly available.
	Pack4Recycling (Fost Plus) https://ecodesign-packaging.org/en/tools/pack4recycling/	Internet tool enabling companies to test the recyclability of their packaging: plastics, steel, aluminium, paper-cardboard, glass and other materials Focused on the situation in Belgium.	Only recyclability assessment. Developed for the conditions in Belgium. Materials are already predefined. Functionality of the packaging is not considered because it is outside the scope of the tool. Seems not available anymore.	A short explanation of the result and some advice to ensure/improve recyclability are provided.
Guidelines	APR Design® Guide for Plastics Recyclability (Association of Plastic Recyclers) https://www.plasticsrecycling.org/apr-design-guide/apr-design-guide-home	Online resource outlining the recommendations of the plastic recycling industry. Helps packaging designers create the most recyclable plastic packaging that complies with the capabilities of the recycling infrastructure.	Only relevant to plastics. Based on the North American plastic recycling infrastructure. Functionality of the packaging is not considered because it is outside the scope of the tool.	Available online or as a pdf. The information is clearly presented in tables and explained in detail for each plastic material. Different features are analysed (raw polymer, barrier layers, coatings, additives, colour, dimension, etc.)
	Recyclability of Plastic Packaging (Comité Technique pour le Recyclage des Emballages Plastiques) http://www.elipso.org/wp-content/uploads/2018/04/Cotrep_-_guide_EN.pdf	Easy-to-use summary of studies conducted by COTREP and its members that outlines the main principles of recyclability and includes technical material profiles to foster innovation without compromising on packaging recyclability.	Only applicable to plastics. Developed under the French policy framework. Functionality of the packaging is not considered because it is outside the scope of the tool.	Checklist composed of questions, information and guides, and examples.
	Sustainability Checklist for Packaging (Food and Drink Federation [FDF] and INCPEN – the Industry Council for Research on Packaging & the Environment) https://incpen.org/fdf-and-incpen-publish-sustainability-checklist-for-packaging/	Guidance questions on functionality of packaging, re-use, recovery, recycling, and transport to ensure packaging is sustainable and environmentally conscious. Helps companies choose and optimise their packaging.	Only guidelines. Written primarily for users of packaging placing products on the UK market.	Focused on food packaging. Applies both to packaging intended for consumer goods as well as business-to-business.

TABLE 1 (Continued)

Type	Tool (developer)	Description/objective	Limitations/missing information	Advantages
	Eco-design of plastic packaging Checklists (German Industrial Association for Plastic Packaging) http://eco-alpha.ecodesign-packaging.org/en/guidelines-and-toolbox/checklists-examples-factsheets-toolbox/checklists	Contains direct links to the latest collection of guidelines, useful tools and helpful information for eco-design of plastic materials.	Currently only tools and guidelines in German. Only applicable to plastics, although some concepts are applicable to other materials. Functionality of the packaging is not considered because it is outside the scope of the tool.	All guidelines and tools available are listed with direct links to the related webpages.
	Design for Recycling Guidelines for PET bottles (European PET Bottle Platform [EPBP]) https://www.epbp.org/design-guidelines/products	Guidelines on numerous elements of PET bottle design that can impede the PET recycling process or reduce the quality of the recycled PET.	: Only applicable to PET bottles: transparent clear/light blue; transparent coloured; opaque. Functionality of the packaging is not considered because it is outside the scope of the tool.	Summary table: full compatibility, limited compatibility and low compatibility; and specific details through hyperlinks.
Hazardous chemicals assessment	SIN List and SINimilarity (ChemSec) https://sinlist.chemsec.org/ http://sinimilarity.chemsec.org/	SIN List: Provides companies with a list of hazardous chemicals that have been identified by ChemSec as being SVHCs, based on the criteria defined within REACH. SINimilarity: SINimilarity shows if a substance is structurally similar to a substance on the SIN List; helps to avoid substituting one problematic chemical with another.	No environmental assessment.	Regularly updated. Search engine or full list in Excel file (SIN List).

2 | ENVIRONMENTAL SCORING TOOLS FOR FOOD PACKAGING

Table 1 provides examples of methodologies and tools currently available in the food-packaging sector for rapid and simple environmental assessment of packaging. These tools were developed mostly for use by research and development teams in food and packaging companies. Table 1 also summarises the main advantages, drawbacks and application areas of these tools.

The tool presented by Molina-Besch and Palsson[19] evaluates a packaging system according to criteria sorted into material production, transport, household and end-of-life groups. The metrics are evaluated over five levels, from level 1 (*no improvement of relevant packaging attribute(s)* to level 5 *documented by consumer tests that relevant user-friendliness attribute(s) are improved*). This methodology was established for the internal use of the petitioner (Orkla Foods) and may be difficult to extrapolate to other users. In addition, it is difficult to identify cases of overpackaging (excessive packaging attributes for a specific food) or underpackaging (packaging performance that does not meet the needs of the food).

Another eco-score calculation approach was recently developed by a French consortium, which is intended to be used to develop front-of-package labels for communicating packaging scores to consumers. Their methodology is based on an LCA of the food product and integrates some additional bonus–malus criteria. A score for the packaging material is calculated and applied as a malus to the overall food-product score from the LCA. The packaging malus is the average of scores related to the origin of the material (e.g., percentage of recycled material in the packaging, certified sustainable paper and use of renewable resources) and its post-usage fate (recyclability, …). This eco-score does not consider the functionality of the packaging on FLW reduction. This eco-score calculation method is based on information from the Agribalyse database that has been expanded from the farm to consumer's plates including all stages of the food cycle.[22]

Most of the tools listed in Table 1 (BEE, ECOdesign of Packaging, FEEL, COMPASS and PIQUET) permit the evaluation of several aspects of the packaging lifecycle, such as resource use, manufacturing and post-usage recyclability, but generally focused on one packaging attribute (e.g., minimising the packaging weight). These tools are applicable for users who need a simple tool to quantify the environmental impact of this modification. However, these tools are insufficient for a global assessment of the environmental impact of different packaging alternatives and could introduce bias into the decision-making process. In addition, they do not consider the packaging functionality.

The tools in Table 1 with the lowest resource demand are based on qualitative or semi-quantitative guidelines (e.g., the APR Design® Guide for Plastics Recyclability), checklists (e.g., Sustainability Checklist for Packaging), or analytical tools that focus on single aspects, such as selecting a bio-based resource (e.g., Bioplastic Tool) or assessing packaging recyclability (e.g., Recyclass). Although less complex, the assessment is oversimplified by focusing on the single criteria of packaging life, for example, resources or recyclability. Our review of existing packaging eco-design tools showed that most available tools are focused on plastic packaging. Except a recent study,[19] these environmental-assessment tools do not consider the positive indirect impact that packaging may have on FLW reduction and rather focus on direct environmental impacts due to material production or post-usage fate. The post-usage fate is often limited to the recyclability of the material, without considering other post-treatment (e.g., home composting or anaerobic digestion). Although these tools are based on LCA, they cannot evaluate the entire cycle because one or several stages of the packaging life are not considered.

3 | METHODOLOGY

3.1 | GLOPACK packaging score specifications (Step 1)

The developed methodology was based on a co-creation process involving various actors in the food-packaging chain. The main specifications of the packaging score were first discussed within the GLOPACK consortium, a European project that gathered 16 partners from seven countries, among them 11 companies in the food or packaging sectors. The 16 partners contributed to defining the specifications. After several rounds of discussion, a consensus about the following specifications was reached and used as a starting point for defining the scores.

- score only the primary packaging, independently of the food product itself;
- consider the most important packaging life phases (pillars) and evaluate both direct and indirect environmental impacts;
- one final score per pillar, as a percentage or scale;
- aggregation between scores to easily compare different packaging solutions;
- applicable to every type of food packaging material: for example, plastics (including bio-based materials), metals, paper, cardboard, glass and multi-materials;
- simple but science-based methodology;
- user-friendly: the methodology must provide an environmental evaluation of food packaging from easily available information;
- public availability: the methodology must be transparent and available to all stakeholders;
- updatable with new knowledge and technologies: the scoring methodology must evolve along with the new developments in the packaging field to provide reliable and accurate evaluations over time; and
- target audience: food and packaging manufacturers and users, packaging developers, policymakers, staff of technical centres and packaging-development projects.

3.2 | Building a list of relevant criteria (Step 2)

The second step of tool development was to build a list of relevant criteria for the environmental evaluation of food packaging (e.g., origin of the resources, recyclability rate and oxygen barrier properties) according to the specifications defined in Step 1. To this end, eight qualitative interviews among experts and stakeholders of the food/packaging chain were performed: two academics, two representatives from food companies, one representative from a food technical centre, two representatives from waste-management companies and one environmental engineer. Face-to-face, video, or phone interview sessions were organised individually with each representative. Each interviewee was asked to freely explain their opinion about the most important criteria for evaluating food-packaging sustainability. To help the interviewee, they were prompted with the steps in the life cycle of packaging materials (resources, usage and post-usage fate) to initiate discussions around the key pillars of packaging sustainability. Arguments provided by interviewees to justify their choice of criteria were also collected and then discussed and validated within the GLOPACK consortium (50 people) during dedicated working sessions. There was some overlap between responses and the arguments that were categorised during these working sessions. Only the most commonly cited criteria from the interviewees were kept.

In parallel, a careful analysis of the state-of-the-art knowledge related to the environmental sustainability of food packaging was performed to evaluate the most-common criteria cited by the interviewees considering current scientific knowledge. It was important to choose criteria that can be easily estimated and are not dependent on obscure data that is not easily available to the user. In general, the data for finalised packaging formats are easier to find than those for formats under development. It was also important to not select criteria based on preconceived ideas or misinformation about food-packaging sustainability. Analysis of existing tools described in Table 1, including their limitations, was also used to build the list of criteria considered in the GLOPACK packaging score. We also tried to identify the source of the limitations of other methods, such as misinterpretations or ignorance of the concepts by users, or a lack of scientific knowledge.

Then, the criteria were sorted into categories. All criteria related to the origin of the resources and their transformation were placed in the category Materials; all criteria related to food shelf-life were placed in the Functionality category; and all criteria related to post-usage fate were placed in the Post-Usage category. The independence of each criterion was carefully checked to ensure the reliability of the answers and avoid double scoring. Validation of the final choice of criteria was finalised during plenary meetings of the GLOPACK consortium (50 people).

3.3 | Building the score (Step 3)

Each criterion selected in Step 2 was converted into a question for the user and the questions were grouped into a checklist (one per category). Each criterion is evaluated either by making a quantitative assessment (if feasible and necessary, e.g., for the Materials pillar where a qualitative assessment is irrelevant) or by a qualitative assessment based on a binary Yes/No answer. The answer 'Yes' generally implies a positive environmental attribute while 'No' implies a negative attribute. In both quantitative and qualitative questions, the user has the option to answer 'I don't know', to enable the users to obtain a score even if some information is missing. The answer 'Does not apply' is available if the question is not relevant to the user. The answers to all questions are then converted into a score between 0 (*worst option*) and 1 (*best option*) considering environmental sustainability. A reliability index is calculated for each final score, which is the uncertainty related to the amount of 'I do not know' answers to specific criteria.

3.3.1 | Building the score for quantitative assessment (Materials pillar)

To calculate the score for the Materials pillar, both resource and carbon footprints are calculated. The life-cycle impact assessment method CEENE (Cumulative Exergy Extraction from the Natural Environment) is used to quantify the resource footprint from the cumulative amount of exergy extracted from nature to produce the final product.[23,24] The resources are expressed in terms of exergy, which is based on the second law of thermodynamics and includes both the quality and quantity of the resource.[23] This method is one of those recommended for computing the resource footprint in terms of thermodynamics.[25] The carbon footprint is calculated using the IPCC database (v1.03) using a 100-year timespan.[26] The inventory data were retrieved from the Ecoinvent database v3.5 (Swiss Centre for Life Cycle Inventories, 2018), using the software Simapro v9.0.0.47. In the case of plastics, the processing of the raw materials (first transformation, such as pellet production from fossil/bio-based plastic materials) and packaging manufacturing (second transformation, such as extrusion or blow moulding) appear separately, while for other materials the final product appears in the database without a distinction between the first and second transformation. Therefore, plastic processing steps were categorised into raw materials (including the first transformation, e.g., pellets) and manufacturing (including the second transformation, e.g., films).

Next, the transport of the packaging materials to the food company is considered assuming various distance ranges: short (0–299 km), medium (300–1000 km) and long (>1000 km). For long distances, 2000 km was selected as a proxy. The impact of transport was obtained from the Ecoinvent database for each transport method for a specific mass and distance. Finally, three geographical regions where processing activities (e.g., production of pellets) and the corresponding supply chain are located were considered. The options are Europe, rest of the World (outside Europe) and Global (Europe + rest of the World). The resource and carbon footprints per component of a specific packaging are computed as follows:

$$\textit{Resource footprint} = \sum_{i=1}^{n} CEENE_i \times mass_i \quad (1)$$

where $CEENE_i$ (MJex/kg) is the resource footprint of component *i* and $mass_i$ is its mass (kg).

A similar calculation was performed for the carbon footprint:

$$\textit{Carbon footprint} = \sum_{i=1}^{n} IPCC_i \times mass_i \quad (2)$$

Where $IPCC_i$ (kg CO_2 eq/kg) is the carbon footprint of component *i*.

To translate the absolute ***Resource footprint*** and ***Carbon footprint*** into a score between 0 and 1, a function $f(x)$ (Equation 3) was used.

$$f(x) = \frac{p}{p+x} \quad (3)$$

Here, $f(x)$ is the ***Resource footprint score*** and ***Carbon footprint score***, *x* is the absolute ***Resource footprint*** and ***Carbon footprint*** values per packaging and *p* is a fitting parameter with no physical meaning that controls the slope of the function, that defines the decrease rate from 1 to 0 with respect to *x*.

3.3.2 | Building the score for qualitative assessments (Functionality and Post-Usage pillars)

To calculate the score for the qualitative assessments (Functionality and Post-Usage pillars), the sum of all 'Yes' answers was calculated and divided by the total of all answers:

$$\textit{score} = \frac{N^\circ \textit{ of } \textbf{Yes} \textit{ Answers}}{N^\circ \textit{ of } \textbf{Yes} \textit{ Answers} + N^\circ \textit{ of } \textbf{No} \textit{ Answers}} \quad (4)$$

A reliability index is used to quantify the uncertainty of the score calculated for the specific pillar:

$$\textit{Reliability index} = \frac{N^\circ \textit{ of } \textbf{Yes} \textit{ Answers} + N^\circ \textit{ of } \textbf{No} \textit{ Answers}}{N^\circ \textit{ of } \textbf{Yes} \textit{ Answers} + N^\circ \textit{ of } \textbf{No} \textit{ Answers} + N^\circ \textit{ of } \textbf{I Don't know} \textit{ Answers}} \quad (5)$$

3.3.3 | Comparison of packaging scores (Borda methodology)

For each of the three pillars, we obtain a score between 0 and 1. This is interesting as an absolute comparison of the packaging for each pillar but does not enable an overall comparison. However, aggregating the evaluation results directly (e.g., by means of an average) does not necessarily make sense since they represent different and quite orthogonal aspects of the environmental impact. To address this, we used a voting rule,[27] which is a function that takes a set of individual rankings of some alternatives as input and outputs a global ranking that represents a collective choice. In our context, each pillar produces a ranking of the packaging alternatives to be compared, from best to worst, where aggregation of these rankings enables a comparison of packaging alternatives considering all pillars. From the many existing voting rules, we chose the Borda count. For each ranking, an alternative *A* is assigned several points equal to the number of alternatives that are ranked lower than *A*; summing the points across all rankings gives an overall score of each alternative and their final ranking.

Given a set of alternatives $\mathbf{A} = \{A_1, ..., A_n\}$, a ranking or preference P_i is a linear preorder. For a set of rankings $\mathbf{P} = \{P_1, ..., P_n\}$ where $P_1, ..., P_n$ are the individual rankings of *n* voters, the score of an alternative *A* is defined as:

$$\textit{score}(A) = \sum_{P \in \mathbf{P}} |\{X | (A > X) \in P, X \in \mathbf{A}\}| \quad (6)$$

This rule considers the rankings in their entirety while still being quite easy to compute and tends to favour consensus among the voters (i.e., pillars in our case). Alternatives that are acceptable to all voters, rather than those preferred by the majority, tend to be selected, which makes sense in the context of environmental assessments.

For instance, assuming four alternatives A_1 to A_4 and the following three rankings: $A_1 > A_2 > A_3 > A_4$, $A_3 > A_4 > A_2 > A_1$ and $A_2 > A_1 = A_3 > A_4$. Alternative A_1 obtains three points from the first ranking, since it is ranked higher than the three other alternatives, zero points from the second ranking as it is last and one point from the third ranking (since it is only better than A_4). Similarly, A_2 has six points, A_3 has five points, and A_4 has two points. With these scores, we compute the final ranking: $A_2 > A_3 > A_1 > A_4$. Here, A_2 wins the vote and is the collective choice of the voters.

3.3.4 | Testing the tool (Step 4)

The tool was finally tested on a range of food packaging already available on the market. Three food case studies were selected (1) milk containers, (2) trays of fresh strawberries, and (3) sugar packs. The five containers selected for commercially available ultra high temperature (UHT) treated milk were: (1) opaque PET bottle with HDPE cap, (2) HDPE bottle with an HDPE cap and aluminium-based lid, (3) multilayer carton with cardboard/plastic and HDPE cap, (4) multilayer carton with cardboard/plastic/aluminium and HDPE cap, and (5) multilayer carton with cardboard/plastic/aluminium and no cap. The three packaging solutions selected for strawberries were (1) PET tray and PET flow pack with a plastic pad in the bottom of the tray, (2) cardboard tray (non-commercial) and cellulose-based lid film, and (3) cardboard tray and PET flow pack. The three packaging solutions selected for sugar were (1) paper-based sachet, (2) cardboard box, and (3) multilayer plastic bag ('doypack') with a plastic cap. The two first containers are for 1 kg of product, while only a 750 g doypack is commercially available. The three packaging solutions were also evaluated using the French Agribalyse-based eco-score tool using only the part dedicated to packaging evaluation.

4 | RESULTS AND DISCUSSION

This section is divided into three parts. First, the selection process to determine the set of criteria used to compute the score is presented. The second part discusses the list of questions, which are associated with the criteria for the three pillars. In the last part, the scores are presented for the three case studies and compared with the results obtained from French Agribalyse-based eco-score tool.

4.1 | Qualitative interviews

In total, 93 responses were collected from the eight qualitative interviews with experts and stakeholders in the food/packaging chain. Anonymous raw data can be downloaded from https://doi.org/10.57745/SVFQL2. Note that 27% of the arguments cited were linked to the functionality of the packaging (Figure 1), highlighting that this aspect is considered important, although it is often neglected in most existing assessment tools (Table 1). Criteria such as 'protection', 'shelf-life', 'protection against physiological degradation', 'against drying' and 'against oxidation' were frequently quoted by the interviewees, who argued that 'the packaging must have the correct functionality to protect the product'. A criterion cited six times was 'informs about the conditions of preservation and use', confirming the importance of labels explaining the storage conditions to ensure the full functionality of the packaging to preserve the food. Other criteria mentioned were '(re)sealability', 'sales unit' and 'individual portions' (to avoid leftovers and FLW).

The second-most quoted category of arguments was the end-of-life category (26%, Figure 1), highlighting the stakeholders' concerns related to post-usage fate of the material; 'recyclability', 'potentially recyclable', 'effectively recycled', 'actually recycled' were cited half the time, followed by 'biodegradable', 'compostable', 'duration after use/persistence', 'sorting' and 'separation', which were each mentioned more than three times. It seemed important at this stage that the scoring tool differentiates *recyclable* and *recycled*. Indeed, *recyclable* refers to the capability of the material to be recycled, but does not guarantee that the material will be effectively recycled. This depends on the sorting and recycling facilities available in the region or country of disposal. In contrast, *recycled* means that the material is recyclable and was effectively recycled in an appropriate post-treatment facility. *Recycling* is a broad term describing several processes, which could be mechanical recycling and refer to either a closed-loop process where uncontaminated material with properties close to that of virgin material is recovered or an open-loop process where the material is downcycled into lower-quality products. A broad definition of recycling may also include the recovery of chemical constituents or chemical recycling and energy recovery.[28,29] In the answers of the interviewees, we did not notice any distinction between recycling types, but we clearly understood that recovery of energy by incineration was not included in their definition of recycling. Currently, mostly mechanical recycling (closed-loop or open-loop processes) is implemented at the plant scale, so we assumed that 'recycling', as understood by the interviewees, means mechanical recycling. Finally, the interviewees also highlighted the importance of packaging labelling with clear instructions about the sorting conditions.

The third-most quoted category of arguments was Raw Material & Resources (20%, Figure 1). 'Origin of the materials', 'geography', 'geographical origin', 'origin of the resources', 'bioplastics' and 'recycled materials' were all quoted several times. Other arguments referred to the ethical aspect of the production 'In all stages, the working conditions must be optimal (e.g., no child labour and gender equality) and the social-societal side must be taken into account' or the origin of the biomass in case of bio-based plastics should not have 'competitive uses (e.g., animal feed, compost)' and should not increase pressure on land and food resources. Another category of arguments related to raw materials refers to controversial substances (such as GMO and chemical solvents) that may be found in packaging formulations or chemical products/solvents that may be used to produce or extract the raw material used in the packaging.

The fourth and fifth categories of responses (Figure 1) are respectively, the first transformation (13%) and the second transformation (14%), that is, shaping of the raw materials into final packaging. Energy consumption and its impact on climate change was the most quoted concern related to the first and second transformations.

For the sake of clarity and to simplify the tool, we decided to use three pillars and split the criteria among them as follows:

- Materials: resource extraction, transformation processes (first and second) to obtain the final packaging and transport to the food company.

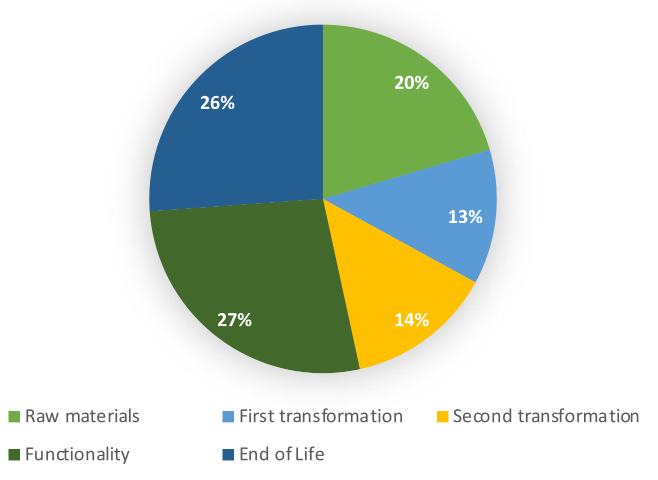


FIGURE 1 Categorisation of the 93 responses provided by the interviewees.

- Functionality: beneficial characteristics of the packaging that enable a longer shelf life of the product and prevent food waste.
- Post-Usage: potential and currently applied treatments to process the material after its use as food packaging.

4.2 | Analysis of the literature

The three considered pillars were coherent with the findings in the scientific literature. Approximately 20 documents were consulted. The scientific review can be downloaded at https://doi.org/10.57745/SVFQL2. Many of these papers deal with LCA of bioplastics, packaging items, or processes. The categories covered by the scientific papers overlapped with those identified during the analysis of the interview content (functionality, post-usage options, raw materials and second transformation), confirming that our selection of pillars was sufficiently exhaustive.

Topics extracted from the scientific literature for the Materials pillar were generally focused on case studies and were mostly based on LCA results comparing two alternatives (e.g., biobased vs. conventional plastic bottles).[30–35] Although generalising the conclusions of particular cases is not straightforward, the literature review confirmed that the origin of the raw material and its first and second transformations are important and that transport cannot be neglected. It was also concluded from the analysed papers that a quantitative approach based on a life-cycle inventory database could be applied to evaluate the environmental impact of the pillar, providing that extensive data are available. As a result of the preliminary analysis, the Materials pillar included the following sub-items: (1) raw material (origin, nature of resources and first transformation); (2) manufacturing (second transformation); and (3) transport of the packaging material to the food company.

Topics extracted from the scientific papers were in line with the results of the interviews. Considering the Functionality pillar, several papers confirmed the relevance of considering the indirect positive impact of packaging on FLW reduction and the overall environmental balance.[1,2,19,36,37] Packaging contributes to decreasing FLW and the corresponding negative impact that producing and distributing uneaten or inedible food has on our environment and economy. FLW reduction is first a matter of packaging functionality (e.g., barrier properties) that maintain a modified atmosphere suitable for food preservation (e.g., avoid the remoistening of a crispy, dry product),[2] but also a matter of ease of use (e.g., individual-serving portions, the packaging should be easy to open, to empty).[38] Using packaging of individual serving sizes reduces the risk that leftovers from a larger family-size package are incorrectly stored after the first use and finally never consumed and discarded.[37,39] However, individual-serving packaging also uses more material proportionally to pack the same quantity of food and thus has a higher environmental impact than larger packages.[32,40] In addition to food protection, waste reduction and convenience, food packaging must provide information such as the product identification and preparation and storage conditions, which are also important to mitigate food waste at the household level. Finally, one criterion highlighted in the literature, but not mentioned by the interviewees, was 'utilisation and handling, including providing for transport and retailing'.[37] We decided to add this criterion to the Functionality pillar, resulting in the following sub-items: (1) transport/distribution (supply chain only); (2) food preservation and food waste; and (3) food storage and preparation by households (convenience, ease of use and information).

Analysis of the arguments for the Post-Usage pillar confirmed that post-usage treatment facilities are regionalised and the regulations concerning waste collection, sorting and treatment depend on the region or country.[41–43] For instance, Rossi et al.[44] stated that 'Although composting and anaerobic digestion were considered as potential end-of-life options for biodegradable materials studied, many sites currently available for composting and anaerobic digestion do not accept packaging materials.' In addition, Italian and UK regulations authorise the collection of compostable packaging materials as bio-waste, while in France this is not the case. It was also concluded that a quantitative approach for calculating the environmental footprint of this pillar could not be conducted in the developed scoring tool because it would require too many inputs that would be not known a priori and could not be included in a user-driven tool.[45] Finally, another important aspect is the risk associated with post-usage treatment, such as persistent particles/microplastics or toxins (such as dioxins) in the environment.[3,46–48] A recent study showed that it is necessary to consider the impact of the long-term fate of plastics in the environment during decision-making processes.[48] They recommended adding a plastic particulate footprint as a midpoint impact indicator in the LCA. The specific case of plastic materials and their long-term potential for damaging the environment and human health were considered in our methodology by adding a dedicated criterion in the form of a risk warning.

As a result of the preliminary analysis, the Post-Usage pillar was designed with the following sub-items: (1) general aspects related to the sorting of the material (including sorting instructions); (2) post-usage treatments (potential and existing methods); and (3) post-usage risks (e.g., long-term fate and microplastic generation, mis-sorting leading to recycling disruption).

4.3 | Building the tool: Checklist & list of questions

The scoring tool comprises a list of questions for each pillar and its sub-items to be answered by the user. The questions should cover all the necessary topics for calculating the final score. For instance, in the case of raw materials, it is important to know the type of resource and its origin. This information could be obtained by asking two questions 'where does the material come from?' and 'what is the resource type (e.g., plastic, paper, glass)'? From the answers to these two questions, we compute the environmental cost of the resource related to extraction and processing, which depends on the country of origin of the raw material, and also the environmental cost of transport. For each pillar and sub-item, the same approach was followed to build the tool.

4.3.1 | Materials

Two indicators, ***Resource footprint*** and ***Carbon footprint***, were used to quantify the environmental impact of the materials. To calculate these indicators, the minimum amount of required information was retrieved from the answers to five questions provided by the users (Table 2). A list of possible answers for each question is proposed in a scroll-down menu. These questions must be answered for every constituent of the packaging since it may be made from more than one material. As all possible combinations of answers to the five questions of the Materials pillar are known, resource and carbon footprints for 1 kg of material were calculated in advance and stored in a database, in the background of the template, from which they are retrieved when needed.

For the resource type, eight options are available, which cover most common packaging materials: (1) plastic, fossil-based recycled; (2) plastic, fossil-based, virgin; (3) plastic, biobased, biowaste; (4) plastic, biobased, food/feed; (5) glass; (6) aluminium; (7) paper-based, recycled, and (8) paper-based, virgin.

For the manufacturing (second transformation), the user can select from 10 options, covering most of the relevant packaging manufacturing processes: (1) extrusion of plastic sheets and thermoforming, inline; (2) extrusion, co-extrusion of plastic sheets and thermoforming of plastic sheets (not inline); (3) extrusion, plastic film; (4) blow moulding; (5) injection moulding; (6) stretch blow moulding; (7) glass production; (8) aluminium production; (9) paper/cardboard production, using recycled; and (10) paper/cardboard production, using virgin material. For the origin of the material, and the transport the user can also answer 'I don't know' and the least favourable option is considered by default in the following calculations as a precautionary principle.

After all five questions in Table 2 have been answered, the corresponding resource and carbon footprint values for 1 kg of material (in MJ_{ex}/kg and $kgCO_2eq$/kg, respectively) are retrieved from the database for each packaging component and multiplied by the mass of each component (Equation 1, Equation 2) to obtain ***Resource footprint*** and ***Carbon footprint*** for the packaging system considered.

To translate these footprints into a score (0–1), Equation (3) is used with a fitted p parameter equal to 1 for the ***Resource footprint*** and 0.1 for the ***Carbon footprint***. The p-values were identified based on an ideal best- and worst-case scenarios for food packaging. Best-case and worst-case packaging must have a score close to 1 and 0, respectively. Based on data extracted from Ecoinvent, the best-case packaging was considered to be a recycled cardboard tray (16 g) sealed using a cellulose-based lid film (0.55 g). The ***Resource footprint*** (3.5 MJex/kg) and ***Carbon footprint*** (0.1 kg CO_2 eq/kg) for the best-case scenario are among the lowest considering the CEENE and IPCC values per kg of recycled paper-based material and should correspond to the highest score. The worst-case packaging was arbitrarily chosen as an aluminium box with an over-dimensioned weight of 300 g to ensure an extreme condition. Although unrealistic, this material was selected because it has the highest environmental impact considering the CEENE and IPCC values per kg (103.8 MJex/kg and 4.3 kg CO_2 eq/kg, respectively) and was assigned the lowest score of 0. Combining these two relations (one couple per indicator) in Equation (3) did not give a unique solution and a trade-off between the minimum and maximum p-values obtained for each indicator had to be determined by testing several p-values until a desirable solution was obtained. The best trade-off was $p = 1$, giving a ***Resource footprint score*** of 0.72 for the best case and 0.02 for the worst case, while $p = 0.1$ in Equation (3) gave a ***Carbon footprint score*** of 0.87 for the best case and 0.04 for the worst case. The use of this approach with the other case studies (milk and sugar packaging in the next section) confirmed that using $p = 1$ and 0.1 in Equation (3) to convert absolute values of ***Resource footprint*** and ***Carbon footprint***, respectively, gave meaningful [0,1] scores. The best-case score converged to 1 but did not reach this value, keeping a window of improvement for the material.

TABLE 2 List of questions to complete for the Materials pillar.

Questions		Example answer
1. Raw material		
1.1.	**Origin of the raw material**	
1.1.1	Where does the raw material come from?	Europe
1.2.	**Resources characteristics**	
1.2.1	Select the most appropriate option for each packaging component:	Plastic, fossil-based, virgin
2. Manufacturing		
2.1	Select the most appropriate processing step in the scroll-down menu:	Injection moulding
3. Transport of the packaging material (to the food company)		
3.1.	Select the average distance travelled by the packaging in Europe, before arriving to the food company (in km)	300–1000
3.2.	Select the main transport type	Road, unspecified

4.3.2 | Functionality

The most important aspects related to the functionality highlighted by the experts were the ability of the packaging to prolong the shelf life of the food, facilitate usage and re-usage of the product (for multi-portion products), facilitate transport and inform the consumer. As these aspects are all difficult to evaluate quantitatively, a qualitative approach was used. A list of questions was developed to obtain responses relevant to all aspects of functionality, especially how the packaging material meets the preservation needs of the food. For the sub-items 'Transport/distribution', Food waste/food preservation', and 'Food transport, storage and preparation by households', the user must answer 'Yes', 'No', 'I don't know', or 'Does not apply' to every question (Table 3). These questions are answered once for the full packaging.

The item 'Food waste/food preservation' evaluates how well the packaging material meets the food preservation and storage needs of the food. This aspect is strongly dependent on the nature of the food (e.g., sugar powder, fresh meat and vegetables do not require the same protection during storage). To evaluate how the packaging meets the food requirements without overpackaging (too much functionality compared to the requirements of the food) or under-packaging (not enough protection for the food), a first question is related to the food itself—for example, 'Can the product dry out or loose crispiness during storage?'—and a mirror question enquires about the same aspect of the packaging a second time—for example, 'Does the packaging provide protection against humidity/dryness?' We proceed similarly for five different aspects of food preservation (Table 3). Then, depending on the answers to these two mirror questions, the 'Yes' or 'No' value is assigned and the final score for the pillar is computed according to the rule explained in Table 4.

To evaluate the sensitivity of the product toward oxidation and the ability of the packaging to protect it against oxidation, we proceeded slightly differently. Two questions were asked about the

TABLE 3 List of questions for the Functionality pillar.

Questions		Example answer
1. Transport/distribution		
1	Is the packaging efficient/optimised for transport, retailing, and distribution? (shape, weight)	Yes
2. Food waste/food preservation		-
2.1	**Questions related to the food product**	-
2.1.1	Does the food require extra mechanical protection? (e.g., *eggs, dry biscuits, …)*	No
2.1.2	Can the product dry out or lose crispiness during storage?	Yes
2.1.3	Is the product susceptible to odour absorption?	Does not apply
2.1.4	Is the product susceptible to discolouration or light oxidation?	Yes
2.1.5	Is the product packed under MAP or vacuum?	Yes
2.1.6	If the product is air packed, is it susceptible to oxidation?	Does not apply
2.2	**Questions related to the primary packaging**	-
2.1	Does the packaging provide extra mechanical protection? *(e.g. egg box, dry biscuit package, strawberry tray* etc.*)*	No
2.2	Does the packaging provide protection against humidity/dryness? (*for water-sensitive products, such as dry, crispy food products or moist, savoury pastries, cakes, is the WVTR value on technical sheets in agreement with the food needs?)*	Yes
2.3	Does the packaging provide protection against odours?	Does not apply
2.4	Does the packaging provide protection against light? *(e.g., opaque material when needed for a light-sensitive product)*	Yes
2.5	Does the packaging provide a good gas barrier? (*for oxygen-sensitive products, principally products containing vitamins, unsaturated fats, dry products with risk of rancidity, is the OTR value on technical sheets in agreement with the food needs?)*	Yes
2.6	Is the packaging solution designed at the just necessary/optimal level? *(are there any attempts using modelling tools or experimental approaches to optimise the pack, reduce the number of components, or decrease the packaging thickness to achieve the same food shelf life and standard conditions of use; does the packaging contains the right amount of product)*	Yes
3. Food transport, storage and preparation by households		
3.1	Does the packaging provide storage information? (*conditions of conservation before and after opening, duration, temperature)*	Yes
3.2	Is the packaging easy to reseal/reclose? (for multi-portion packs)	Yes
3.3	Does the packaging facilitate use and consumption? (*easy to grip, open, dose)*	Yes
3.5	Is the packaging easy to empty (e.g., is it easy to remove every food from the packaging)?	Yes

TABLE 4 Rules used to obtain final 'yes' or 'no' values for the 'Food waste/food preservation' item in the Functionality pillar.

Question about the food *can the product dry out or lose crispiness during storage?*	Mirror question about the packaging *does the packaging provide protection against humidity/dryness?*	Final value	Explanation
Yes	Yes	Yes	If the food is sensitive to humidity, it needs protection against moisture transfer during storage. If the packaging provides this protection, the final kept value is YES
No	Yes	No	If the food is not sensitive to humidity and the packaging is a high-barrier film against humidity, this property of the packaging is not required (oversizing) and the final value is NO
Yes	No	No	If the packaging does not provide the required protection against humidity, it is under sized and the final value is NO
No	No	Yes	If protection against humidity is not required and the packaging does not provide a humidity barrier, it is considered well-dimensioned packaging and the final score is YES

product: 'Is the product packed under MAP or vacuum?' and 'If the product is air packed, is it susceptible to oxidation?'. Then, there is only one mirror question for the packaging: 'Does the packaging provide a good gas barrier?'. MAP-, vacuum-, and air-packed oxygen-sensitive products all required packaging with good barrier properties. These two questions and their mirror question cover all the cases currently relevant in the food industry. These two questions are not relevant for all food products and in that case, the 'Does not apply' answer must be given.

One last question related to packaging was asked in the 'Food waste/food preservation' section: 'Is the packaging solution designed at the necessary/optimal level?' The purpose of this question is to assign a bonus (an additional 'Yes' value) to packaging that has been optimised. For instance, the user could have identified the range of gas- and water-vapour barrier properties required by the product to use as targeted packaging specifications. This permits the user to select optimised packaging material, that is, packaging that matches the barrier properties required by the food.

Once the user has answered all questions listed in Table 3, the final score for the pillar is computed using Equation (4) considering the 'Yes' answers as positive and 'No' answers as negative. No weighting of criteria was applied, as it is assumed that they all have the same impact.

4.3.3 | Post-Usage

The term 'Post-Usage' was used for this pillar although stakeholders often mentioned 'end-of-life (EOL)' instead. This term was chosen to highlight the difference between post-usage treatment, which differs from the end-of-life fate of the material. Indeed, post-usage fate (e.g., recycling) is not related to the long-term fate (e.g., long-term persistence of the recycled item).[48] The results of the interviews clearly showed that recyclability is one of the main criteria quoted by the experts. This is consistent with the packaging waste treatment that is currently being promoted by European and national governments (SUP directive, French AGEC law). Other alternative post-treatments were also quoted as important (e.g., composting and anaerobic digestion). However, such treatments are unequally applied in Europe, although the revised EU Waste Framework Directive[49] allows biodegradable and compostable packaging to be collected together with bio-waste[50] and recycled in industrial composting and anaerobic-digestion systems. Recycling is also not equally applied in Europe. In 2018, recycling accounted for 38.5% of plastic post-consumer waste treatment in Europe, but only 24.2% in France compared to 50% in Germany.[51] In addition, some recyclable packaging is not recycled because treatment facilities are not available (e.g., polypropylene and low-density polyethylene). Therefore, to make the most impartial evaluation of the post-usage impact of the packaging material, it was decided to first evaluate the 'capability' of a packaging material to fit currently available post-treatments (e.g., able to be recycled or composted), followed by evaluating the feasibility of these treatments in the selected region (i.e., if a material is recyclable, is it effectively recycled in the considered country/region?).

Multimaterial packaging has to be considered as a whole in the Post-Usage pillar since it is often not possible to separate the different constituents (e.g., tray and lid film) in practise. The first question asked is thus 'Does the packaging present any risk of losing parts?'. A 'Yes' answer provided to the former question is considered negative (equivalent to a 'No' answer in the final count in Equation 4).

For each question related to the 'capability' to be recovered, recycled or composted, there is a mirror question that asks if the material is recovered and processed in the country of interest. The

TABLE 5 List of questions for the Post-usage pillar.

1. Questions (whole packaging)		**Example answer**
1.1 General aspects of the packaging		
1.1.1.	Does the packaging present any risk of losing parts (such as caps, straws, lids)? *(For on-the-go products).*	Does not apply
1.2.1.	Does the packaging allow for separation and optimal treatment of its different parts (if different treatments are required for different parts)? *For small pieces such as caps, sorting may prove difficult for optimal treatment*.	Yes
1.2. Sorting instructions		
1.2.1.	Does the packaging provide complete and understandable information about end-of-life instructions *(e.g., sorting of all components)*? Relevant to the country/location considered.	Yes
2. Questions (parts of packaging)		
Parts of the packaging (core of the packaging, caps, lids, etc.)		*e.g., Injection-moulded PP cup*
% of the final packaging		*0.63*
2.1. Re-use, recovery, recycling …		
2.1.1.	Is the packaging part monolayer?	Yes
2.1.2.	In the case of multilayers, can all the constituents with different end-of-life treatments be separated?	Does not apply
2.1.3.	Is the packaging reusable? *(e.g., glass)*	Does not apply
2.1.4.	Can the packaging be recycled? (Packaging can be sorted and treated at the industrial scale somewhere).	Yes
2.1.5.	Can the packaging be composted industrially?	No
2.1.6.	Can the packaging be composted in home-compost systems?	No
2.1.7.	Can the packaging be treated in anaerobic digestion *(e.g., bio-methanisation)*?	No
2.1.8.	Is the packaging suitable for energy recovery (incineration)?	Yes
	According to the available treatments in the market country, is the material actually treated?	
2.1.9.	Answer only if YES at Q 2.1.3: Reused **(if different from YES put Does not apply)**	Does not apply
2.1.10.	Answer only if YES at Q2.1.4: Recycled **(if different from YES put Does not apply)**	I do not know
2.1.11.	Answer only if YES at Q 2.1.5: Industrially composted **(if different from YES put Does not apply)**	Does not apply
2.1.12.	Answer only if YES at Q 2.1.6: Treated by AD **(if different from YES put Does not apply)**	Does not apply
2.1.13.	Answer only if YES at Q 2.1.8: Incinerated with energy recovery **(if different from YES put Does not apply)**	Yes
2.2. Risks associated to post-usage treatment		-
2.2.2.	Is there any risk of disturbing the sorting and/or post-treatment of other materials if the target material is not properly sorted? *(e.g., dark plastic trays mixed with white PET)*	No
2.3. Risks associated with long-term fate		-
2.2.1.	Is there any risk of generating persistent plastic particles?	Yes

user answers the question related to the feasibility only if they answered 'Yes' to the corresponding capability question. If not, it does not apply. This procedure avoids penalising the material twice; if a material is not recyclable ('No' answer to the first question) there is no chance that it will be recycled.

For questions related to biodegradation in industrial, home-compost, or anaerobic-digestion facilities, it is evident that 'does not apply' is relevant for glass and aluminium, while for paper, cardboard and plastic, these questions must be considered as some types of these materials are compatible with these treatment processes. This ensures that all materials are evaluated using the same rules.

Additional questions were added for the Post-Usage pillar related to the risk associated to waste treatments. 'Is there any risk of disturbing the sorting and/or post-treatment of other materials if it is not properly sorted?' considers whether the material might affect the post-treatment of other materials (e.g., dark plastic trays mixed with white PET). 'Is there any risk of generating persistent plastic particles?' is asked to determine the risk of persistent plastic pollution if the material is not properly discarded and treated in the post-usage stage. This risk is usually not considered in quantitative environmental assessments because there is currently no quantitative model to predict it.[48] The advantage of a qualitative approach is that this risk can be included with other more easily observable aspects (e.g., 'Is the packaging part monolayer?').

All questions regarding the post-usage treatments must be answered for every element of the packaging that can be separated and has a different post-treatment method (Table 5). Once the user has answered all questions listed in Table 5, the final score for the pillar is calculated by counting all 'Yes' and 'No' answers (Equation 4). To develop a user-friendly tool, no weighting of criteria was applied. No weighting between components means that a bottle cap counts the same as a bottle in the calculation of the final score, even if the mass of the cap is 10 times lower. Similarly, the post-treatment impact is weighted the same as the weight/size of the material.

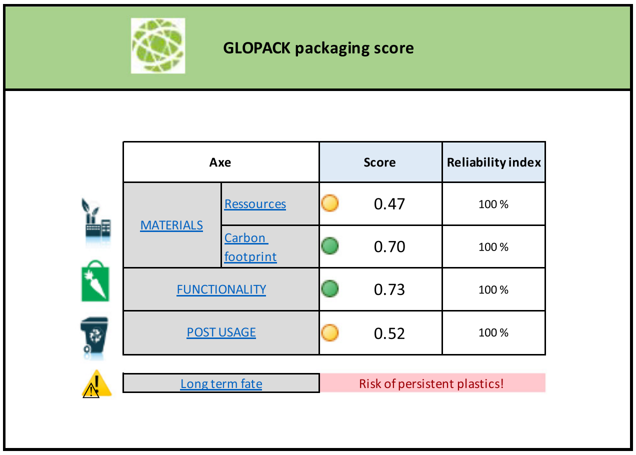


FIGURE 2 Example of a possible output layout of the GLOPACK packaging score calculator for strawberry no. 1 (see Table 9).

4.4 | GLOPACK packaging score outputs

The pillar approach presented above provides four different scores between 0 (*worst option*) and 1 (*best option*): two scores for Materials (resource footprint and carbon footprint scores), one for Functionality, and one for Post-Usage (Figure 2). These scores can be used to analyse which aspect of the packaging life cycle has the greatest impact and identify the hot spots and potential for improvement. Each score has a related reliability index (Equation 5) that indicates the percentage of known values used to calculate the scores. Even when the data for the packaging material is incomplete, a score can be calculated, considering the worst case as the missing value by default. The reliability index decreases with an increasing number of missing data. For the Functionality and Post-Usage pillars, the 'I do not know' answers decrease the reliability index but are not considered in the

TABLE 6 Description of the food packaging case studies.

Packaging short name	Opaque PET bottle + HDPE cap	HDPE bottle + HDPE cap+ lid film in aluminium	Multilayer cartons with cap (without al)	Multilayer CARTON + cap	Multilayer CARTON without cap
					
Material used	Pigmented monolayer PET (with TiO_2)	Pigmented monolayer ($HDPE + 2\% TiO_2$)	75% cardboard 25% plastic with a given percentage coming from biomass	20% polyethylene 75% cardboard (non-recycled) 5% Al (origin not specified) cap: PEHD	20% Polyethylene 75% cardboard (non-recycled) 5% Al (origin not specified)
Transport of raw material	NA	NA	NA	NA	NA
Processing	Blow moulding of PET bottles from bottle preforms by the food company	Blow moulding of the HDPE bottles at the milk packaging site	Cartons are formed and sealed at the bottom by the end-user company, filled with milk, and capped	No specific information about process optimisation Classical processing assumed	No specific information about process optimisation Classical processing assumed for PE, cardboard, and aluminium.
Shelf life	Same shelf-life for all – material optimised for the shelf-life				
End of life	Recyclable bottle but rarely recycled; Cap recyclable, not recycled; Disturbs transparent PET recycling	Recyclable and recycled bottle; Cap recyclable, not recycled	Recyclable and recycled pack Cap recyclable, not recycled	Recyclable and recycled pack; Cap recyclable, not recycled	Recyclable and recycled pack

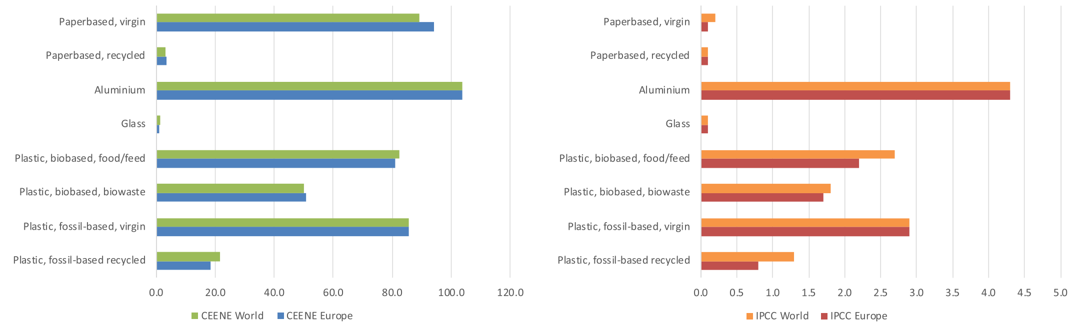


FIGURE 3 Comparison of (left) CEENE values in MJex/kg of material and (right) IPCC values in kg CO_2 eq/kg for raw materials originating from Europe or world regions (source: Ecoinvent database v3.5).

score calculation as they would punish the results too much. In addition to the individual scores, a warning is provided to the user about the long-term fate of the material as an additional criterion in the Post-Usage score. For example, if the material contains plastics that are non-biodegradable in natural environmental conditions, there is a risk of persistent plastic particles. Other warnings could be added in future versions to highlight hotspots of sustainability improvement.

4.5 | Assessment of the GLOPACK packaging score

4.5.1 | First case study

The tool was first used on commercial UHT milk containers (Table 6). This food product is particularly relevant because several types of packaging are available on the market. Five different containers were selected, which are all suitable for 1 L of UHT milk: (1) opaque PET bottle with HDPE cap; (2) HDPE bottle with an aluminium lid film and an HDPE cap; (3) multilayer carton (no aluminium) with an HDPE cap; (4) multilayer carton with an HDPE cap; and (5) multilayer carton without a cap. The scores were calculated for each pillar for each container. The original files can be downloaded at https://doi.org/10.57745/JRQESS.

For the Materials pillar for each container, we do not know the origin of the raw material. Therefore, we chose 'World' for all cases. The final packaging was also assumed to travel a long distance to the food company by cargo (water, transoceanic). However, regardless of the type of transport (even intercontinental air transport), the contribution of the transport to the overall score is very low (less than 0.5% of the resource and carbon footprints) compared to resources and manufacturing (second transformation), with contributions of approximately 63% and 35%, respectively. The origin of the resources 'Europe' and 'Rest of the World' also does not have a large impact on the resource and carbon footprints in the extraction step (Figure 3). Therefore, in this case, the distinction between Europe and the Rest of the World is not relevant, and some simplifications could have been implemented at this stage. However, in the near future, some new materials may be added to the database (e.g., new bioplastics) which have a greater dependence on their origin. Therefore, we chose to keep this option open to let the user choose the specific origin of the material. In the case of a multilayer carton system, to consider the paper, plastic layer, and/or aluminium layer, the constituents were considered separately, for example, 75% cardboard and 25% plastic, and answers are provided for each constituent separately.

For the Functionality pillar, it was considered that the packaging is optimised for retail and distribution and that the answer to the question 'Can the product dry out or lose crispiness during storage?' is 'Does not apply'. Answers to all other questions related to the food product are 'Yes'. The answer to the question 'Is the packaging solution designed at the necessary/optimal level?' is 'I don't know' as we do not know if such an approach was applied by the providers concerned. Therefore, the only point of difference between the packaging options for this pillar is if the packaging is easy to reseal/reclose ('Yes' for a reclosure system like a cap, otherwise ''No'). The milk packaging was globally optimised for milk preservation for the 9 months of shelf-life, so the score for this pillar is expected to be high for all cases shown in Table 6.

For the Post-Usage pillar, it was assumed in all cases that the HDPE cap is recyclable and recycled. In the case of a multilayer carton system, all layers were considered together, as for post-consumer treatment. Therefore, questions were answered only once for the carton and once for the cap. In France, 47% of opaque PET bottles, 53% of HDPE bottles, and 57% of cartons are recycled.[52] Opaque PET is considered a contaminant in the sorting and post-treatment of PET, while this is not the case for the other materials.[53] Therefore, minimum and maximum values were calculated considering 0% and 100% of recycling, respectively. An average value between these two was calculated and used as the final score for the Post-Usage pillar. A fifth criterion was added in the form of a warning regarding the long-term fate of the material in the environment, that is, a value of 0 corresponding to a 'red' point (risk of persistent plastic in the environment) or 1 corresponding to a 'green' point (no risk). The corresponding results are shown in Table 7.

The Resource footprint score was low in all cases, ranging between 0.18 (Milk 4; carton with Al) to 0.24 for a multilayer carton (Milk 3 and 5). Even for the container with a high content of cardboard (Milk 3), the Resource footprint score is low because the

TABLE 7 Results of the GLOPACK packaging score (reliability index, %) calculations for the five milk packaging types.

	Packaging short name	Resource footprint score	Carbon footprint score	Functionality score	Post-usage score[a]	Long-term fate warning[b]	Malus French eco-score
Milk 1	Opaque PET bottle + HDPE cap	0.19 (100%)	0.40 (100%)	1 (90%)	0.57–0.62 = 0.595 (100%)		−4
Milk 2	HDPE bottle + PP cap + Al film lid	0.19 (100%)	0.42 (100%)	1 (90%)	0.57–0.63 = 0.60 (100%)		−6
Milk 3	Multilayer cartons with cap (without Al)	0.22 (100%)	0.69 (100%)	1 (90%)	0.59–0.68 = 0.64 (100%)		−5
Milk 4	Multilayer cartons + cap (with Al)	0.18 (100%)	0.48 (100%)	1 (90%)	0.59–0.68 = 0.64 (100%)		−5
Milk 5	Multilayer cartons without Cap (with Al)	0.24 (100%)	0.57 (100%)	0.78 (90%)	0.62–0.69 = 0.66 (100%)		−4

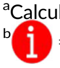
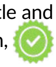
[a]Calculated considering that the bottle and the cap are recycled by 50%, min value is for 0% recycling and max value for 100%.
[b]  = risk of microplastic pollution,  = no persistent plastic.

TABLE 8 Aggregation results obtained from the Borda voting method and final ranking (number of Borda points) for the milk case study.

Milk food case	
Resource footprint score	Milk 5 > Milk 3 > Milk 1 = Milk 2 > Milk 4
Carbon footprint score	Milk 3 > Milk 4 > Milk 2 = Milk 5 > Milk 1
Material total score	**Milk 3 > Milk 5 > Milk 4 > Milk 2 > Milk 1**
Functionality score	**Milk 1 = Milk 2 = Milk 3 = Milk 4 > Milk 5**
Post-usage score	Milk 5 > Milk 4 = Milk 3 > Milk 2 = Milk 1
Long-term fate warning	Milk 1 = Milk 2 = Milk 3 = Milk 4 = Milk 5 (all yes)
Post-Usage total score	**Milk 5 > Milk 4 = Milk 3 > Milk 1 = Milk 1**
Final ranking	**Milk 3 (7) = Milk 5 (7) > Milk 4 (5) > Milk 2 (2) > Milk 1 (1)**

resource depletion of cardboard made with virgin fibres is high. The Carbon footprint score ranges from 0.40 (Milk 1) to 0.69 (Milk 3). The score is higher when paper-based instead of plastic-based containers are used, which is the case for Milk 3, which contains 75% cardboard and no Al foil. The use of an Al film in multilayer cartons tends to decrease the Carbon footprint score. Indeed, Milk 5 is disadvantaged compared to Milk 3 with respect to its Carbon footprint score due to the presence of an Al foil, although Milk 5 is the simplest material with little plastic resource use (only a carton with no cap). Small differences between cartons could arise from the difference in total weight and weight of each layer.

The Functionality score was high in all cases because the packaging was optimised for milk preservation and is commercially available. The reliability index is only 90% because of the 'I don't know' answer to the question 'Is the packaging solution designed at the necessary/optimal level?' In the case that this answer was 'Yes', the reliability index would be 100%. The score is 1 for all packs with a cap; the cap enables easy pouring of the milk (avoiding wastage) and easy reclosing of the pack (improved storage conditions). In contrast, the pack without a cap (Milk 5) obtained a Functionality score of 0.78 because 'No' was answered for the two following questions 'Is the packaging easy to reseal/reclose?' and 'Does the packaging facilitate use and consumption? Easy to grip, open, and dose' because the pack is less easy to reclose and does not facilitate consumption.

The average Post-Usage score was between 0.59 for the opaque PET bottle (Milk 1) and 0.66 for the multilayer carton without a cap (Milk 5). The other scores were 0.60 for the HDPE bottle and 0.64 for the multilayer cartons with a cap (Milk 3 and 4). The multilayer carton without a cap (Milk 5) has a higher score (0.66) because the material is less complex (fewer components) for post-usage treatment, while Milk 3 has a plastic cap that must be treated in addition to the carton itself. The reliability index is 90% for all Post-Usage scores because 'I don't know' was answered for the question 'Does the packaging provide complete and understandable information about end-of-life instructions'. Milk 1 Post-Usage score (0.59) was the worst compared to all other containers, especially the other plastic bottle (Milk 2). This Post-Usage score was lowered by the fact that opaque PET is considered a contaminant in the recycling chain of transparent PET. For all milk containers considered here, the long-term fate warning is a red point because of the presence of durable plastic in all formulations.

To aggregate the scores and compare the five milk containers, the Borda voting methodology was used. The first step was to aggregate scores for the Materials pillar (Resource footprint and carbon footprint scores) to obtain the Material total score. Then, the Post-Usage

TABLE 9 Results of the GLOPACK packaging score (reliability index, %) calculations for the three strawberry packaging case studies.

	Packaging short name	Resource footprint score	Carbon footprint score	Functionality score	Post usage score	Long-term fate warning	Malus French eco score
Strawberry 1	PET tray + PET flowpack film 	0.47 (100%)	0.70 (100%)	0.73 (100%)	0.52 (100%)		−9
Strawberry 2	Cardboard tray + cellulose-based film (equilibrium modified atmosphere packaging) 	0.34 (100%)	0.85 (100%)	0.82 (100%)	0.67 (100%)		−1
Strawberry 3	Cardboard tray + PET flowpack film 	0.36 (100%)	0.82 (100%)	0.73 (100%)	0.55 (100%)		−2

TABLE 10 Aggregation results obtained with the Borda vote methodology and final ranking (number of Borda points) for the strawberry case study.

Strawberry case study	
Resource footprint score	Strawberry 2 > strawberry 1 > strawberry 3
Carbon footprint score	Strawberry 2 > Strawberry 3 > Strawberry 1
Material total score	**Strawberry 2 > Strawberry 1 = Strawberry 3**
Functionality score	**Strawberry 2 = Strawberry 3 = Strawberry 1**
Post-usage	Strawberry 2 > Strawberry 3 > Strawberry 1
Long-term fate warning	Strawberry 2 > Strawberry 1 = Strawberry 3
Post-usage total score	**Strawberry 2 > Strawberry 3 > Strawberry 1**
Final ranking	**Strawberry 2 (4) > Strawberry 3 (1) > Strawberry 1 (0)**

total score was obtained considering the Post-Usage score and the long-term fate warning. The final ranking was obtained by applying the Borda vote methodology again to the three pillar scores. This approach ensures that each pillar is considered with the same weight in the aggregation. Table 8 summarises the intermediate and final rankings obtained for the milk case study.

Table 8 shows that decision-making regarding the best packaging option for UHT milk based on the three individual rankings per pillar is not straightforward: Milk 3 performs the best with respect to Materials, Milk 5 has the highest Post-Usage score, and four of the five milk containers are equivalent in terms of Functionality. The Borda methodology aggregated the three rankings per pillar into a single ranking: Milk 3 (multilayer carton without Al) and Milk 5 (carton without a cap) are the best alternatives, followed by Milk 4 (carton with Al layer and a cap), and finally, the plastic bottles are the worst options, with the PET bottle (Milk 1) being worse than an HDPE bottle (Milk 2) from an environmental point of view. Overall, cartons perform better than fully plastic bottles because they obtained higher rankings for Material and Post-Usage pillars. Milk 3 and Milk 5 obtained the same aggregated packaging score and it is not possible to differentiate them using our tool. Note that the ranking obtained in this example could be further refined based on new data for each pillar. In addition, some weighting of the pillars could be applied to consider priorities for minimising the total environmental impact of the product.

4.5.2 | Second case study

The tool was then applied to three packaging solutions for fresh strawberries (Table 9): Strawberries 1 (PET tray + PET flowpack film) and Strawberries 3 (non-coated cardboard tray + PET flowpack film) are commercial solutions that do not enable an internal atmosphere favourable to the preservation of strawberries (equilibrium-modified atmosphere). In contrast, Strawberries 2 (non-coated cardboard tray + cellulose-based film) is a packing solution currently in the research-and-development phase, where the lid film is directly sealed on the tray and the gas permeabilities of the materials were optimised to achieve an equilibrium-modified atmosphere. Such equilibrium-modified atmosphere has proven efficient in minimising fresh fruits and vegetable losses.[1,54,55]

The Strawberry 2 packaging clearly provides functionality by decreasing food loss and obtained a higher Functionality score (0.82) than the other cases (0.73), as expected. The Functionality score for Strawberry 2 was limited because the packaging does not include the conditions of preservation before and after opening, as for Strawberry 1 and 3, and because the pack is not resealable (answer 'No' to the question 'Is the packaging easy to reseal/reclose?'). This case study highlights that the method proposed here can score the functionality of the packaging, that is, longer shelf-life and reduced food losses, which is important for a packaging environmental assessment.[11,19,39,56]

In the case of the Materials score, packaging with cardboard performs better because of lower Carbon footprint score. For the Post-Usage pillar, Strawberry 2 has a higher score because it is fully biodegradable under various conditions (domestic and industrial compost). In addition, it scored a 'green point' for the long-term fate as it contains no persistent plastic. The final ranking obtained with the Borda methodology is given in Table 10. As expected, Strawberry 2 performs better than Strawberry 1 and 3 as it obtained a higher score in each pillar.

This case study highlights the importance of packaging functionality, which can offset the direct impacts of the material itself. Indeed, focusing only on resources, the ranking of the strawberry packaging would have been completely different and favour plastic material, which is not suitable to preserve strawberries from deterioration (poor usage benefit) and has high risks related to post-usage fate. This case study also highlights that the tool could be used in the packaging development step when the first design of the packaging has been set but the choice of the final packaging components has not yet been decided. For instance, the tool can be used to compare the impact of different source of material (e.g., virgin vs. recycled cardboard), the food protection provided by the packaging concept, and the

TABLE 11 Results of the GLOPACK packaging score calculations (reliability index, %) for the three sugar packaging case studies.

	Packaging short name	Resource footprint score	Carbon footprint score	Functionality score	Post usage score	Long-term fate warning	Malus French eco score
Sugar 1	Paper sachet 	0.52 (100%)	0.93 (100%)	0.82 (100%)	0.83 (100%)		−**1**
Sugar 2	Cardboard box with a cardboard-based dispenser nozzle 	0.18 (100%)	0.72 (100%)	0.91 (100%)	0.83 (100%)		−**1**
Sugar 3	Multilayer plastic sachet with a cap 	0.39 (100%)	0.64 (100%)	0.64 (100%)	0.65 (100%)		**- 10**

post-usage treatment. Therefore, the tool is very useful for optimising the packaging design with respect to its environmental impact and enables the user to objectively and transparently select the most suitable packaging material for a given application.

4.5.3 | Third case study

As a commercial case study, we analysed packaging for caster sugar: a paper sachet; a cardboard box with a dispenser nozzle (re-closable); and a multilayer plastic sachet with a cap ('doypack'). The first two packages contain 1 kg of sugar, while the doypack contains only 750 g of sugar (it does not exist on the French market in a 1-kg size). All individual score results are summarised in Table 11 and the final Borda rankings are given in Table 12.

As expected, paper and cardboard-based packaging (Sugar 1 and Sugar 2) obtained higher scores for the carbon footprint, functionality and post-usage aspects. In addition, they obtained a 'green' point for the long-term fate warning. The paper sachet also obtained the highest score for the resource footprint because of its low weight compared to the two other options. The Functionality score of the multilayer plastic sachet was the lowest because it was considered as 'over dimensioned' for sugar; the performance exceeds the requirements of the food as a good oxygen-barrier performance is not necessary for sugar. Over-dimensioning is highly detrimental to the environment because it often leads to the selection of materials that are usually not recyclable (multilayers), not biodegradable (plastic), and generally more expensive. The Borda methodology (Table 12) confirms the previous discussion based on individual scores; the paper-based sachet (Sugar 1) is the best option, followed by the cardboard box (Sugar 2) and plastic sachet (Sugar 3).

4.5.4 | Comparison with other methods

To compare the GLOPACK packaging score method with other initiatives in the field of sustainability scoring, the three case studies were also evaluated using the French Eco-Score method (Table 1). This approach differs from the GLOPACK one in that the impact of the food product itself is considered through LCA data. The LCA output gives a score out of 100. Positive or negative impacts of other criteria not considered in the LCA constitute some bonus or malus that influence the final score. Hence, the packaging is considered a malus, accounting for a maximum of 15 points. In this malus, two indicators are considered. First, an upstream indicator that represents the origin of the resources: (1) use of recycled materials in the packaging formulation (1 point), (2) use of renewable and durable raw resources (0.75 points), (3) renewable resource (0.5 points), or (4) non-renewable (0 points), and second, a downstream indicator that focuses on the end-of-life treatment: (1) recyclable (1 point), (2) biodegradable (0.5 points), and (3) incineration and landfilling (0 points). The upstream and downstream indicators are then calculated based on the percentage of each type of resource or end-of-life treatment for the final packaging formulation. Note that in this approach, recycling is considered better than biodegradability, and the incorporation of recycled resources is considered better than the use of renewable and durable resources, which could be debatable. These assumptions are based on the current situation in France and may not be suitable for other countries.

TABLE 12 Aggregation results obtained from the Borda vote methodology and final ranking (number of Borda points) for the sugar case study.

Sugar case study	
Resource footprint score	Sugar 1 > Sugar 3 > Sugar 2
Carbon footprint score	Sugar 1 > Sugar 2 > Sugar 3
Material score	**Sugar 1 > Sugar 2 = Sugar 3**
Functionality score	**Sugar 2 > Sugar 1 > Sugar 3**
Post-usage	Sugar 1 = Sugar 2 > Sugar 3
Long term fate warning	Sugar 1 = Sugar 2 > Sugar 3
Post-usage total score	**Sugar 1 = Sugar 2 > Sugar 3**
Final ranking	**Sugar 1 (4) > Sugar 2 (3) > Sugar 3 (0)**

We compared the packaging malus from the French Eco-score method to the ranking of materials obtained from the GLOPACK packaging evaluation method. The packaging malus (Table 7) obtained for the milk containers gives the following classification: Milk 1 (PET bottle) = Milk 5 (multilayer carton without a cap) > Milk 4 (multilayer carton with Al, with a cap) = Milk 3 (multilayer carton without Al, with a cap) > Milk 2 (PEHD bottle with a lid and cap). The GLOPACK method gave: Milk 3 = Milk 5 > Milk 4 > Milk 2 > Milk 1.

The ranking based on the packaging malus is not the same than the one obtained with the GLOPACK method. The opaque PET bottle (Milk 1) is considered recyclable and does not disrupt recycling, so it was given a higher score by the French Eco-Score method than by the GLOPACK method, where opaque PET is considered recyclable but also a recycling disruptor in transparent PET recycling (stakeholder testimony). Cartons with or without Al are also not differentiated by the French method (malus of −5 in both cases). The HDPE bottle + lid + cap (Milk 2) is more strongly penalised than Milk 1, with a malus of −6 compared to −5, respectively, while with the GLOPACK method, Milk 2 performs better than Milk 1. The functionality of the packaging is not considered at all in the French method. Therefore, the multilayer carton without a cap (Milk 5) has a similar performance to that of the opaque PET bottle (Milk 1), based solely on the fact that opaque PET and multilayer carton are both recyclable. Different rankings were obtained using the GLOPACK and French Eco-score methods because they do not consider the same number and type of criteria.

The packaging malus for the three strawberry packages gave the following ranking: Strawberry 2 > Strawberry 3 > Strawberry 1, which is the same as that obtained using the GLOPACK packaging score method.

For the third case study, the French Eco-score malus gave: Sugar 1 = Sugar 2 > Sugar 3 (i.e., no difference between Sugar 1 and Sugar 2 alternatives), whereas the GLOPACK method differentiated between these options.

The ranking obtained using the French Eco-score packaging malus and the GLOPACK method are difficult to compare because the considered criteria are different. The comparison of the sugar and strawberry case studies shows that for very different types of material (paper/cardboard versus plastic) both approaches provide similar rankings. This is not the case for plastic packaging where information on the recyclability and use of recycled resources prevailed in the French Eco-score method, which distorted the final score. Overall, the GLOPACK method is considered more complete and provides a better overview of the sustainability of a packaging solution considering both its direct and indirect impacts (including functionality).

5 | CONCLUSIONS AND RECOMMENDATIONS

In a context where sustainability and environmental consciousness are becoming increasingly important for both consumers and producers of food and beverages, the development of a tool that can easily calculate the environmental impact of food packaging is crucial. In this study, we presented a method that scores food packaging considering three key pillars of its lifecycle, (1) Materials, (2) Functionality, and (3) Post-Usage fate, and does not require the collection of extensive lifecycle inventory data.

The developed tool fulfilled all the initial specifications defined by the working group. The Materials pillar does not focus only on climate change, but considers both the carbon and resources footprints, which is novel compared to existing methods, such as the EEFP tool.[19] Our tool considers the functionality of the packaging material, which is still lacking in many scoring and eco-design tools (apart from EEFP), and the long-term fate in the environment and risk of micro/nanoparticle generation that is especially relevant for plastic-based materials. The post-usage options are regionally dependent, and our tool provides different scores depending on the country. This tool is accessible to non-LCA experts and does not require the input of data and knowledge that is generally lacking in many food companies. The intended user is a packaging or food company that needs to select suitable packaging for a given food. Our tool can help the user improve the score of existing packaging by identifying the pillars that require further improvements. Although our tool cannot be used to directly design a new packaging format, it could be useful in the packaging-development step by providing insights into reducing the environmental impact of a packaging solution, by, for instance, testing different materials or judging a panel of existing packaging. When use in the development phase, some criteria must be answered based on assumptions that, for instance, people really understand the new packaging concept, the way of emptying, disposing, etc. These assumptions need to be validated once the final design is set up together with the economic and technical feasibility of the solutions suggested by the tool.

The GLOPACK packaging score is evolutive because it is scalable and can be easily upgraded with new criteria to consider new regulations and scientific breakthroughs in the domain of packaging science. The database used for the background calculations of carbon and resource footprint scores could also be extended with new materials. Other possible improvements of the tool could include the addition of weighting among the pillars/criteria to consider the most important features in the final ranking calculation. Some criteria may be more important than the others, for example, the urgency of overcoming plastic pollution, and including importance weightings is the most important direction for improving the tool in the future. Another direction for improvement could be extending the assessment to societal impacts to better evaluate the overall sustainability of the packaging.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in GLOPACK project dataverse at https://entrepot.recherche.data.gouv.fr/dataverse/glopack, reference number https://doi.org/10.57745/JRQESS, https://doi.org/10.57745/JR.

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