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Sustainable insulation materials for E-grocery shipments: A multi-criteria evaluation

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ABSTRACT

Due to the continuous growth of e-groceries, sustainable packaging solutions are needed to reduce the environmental impact of e-grocery shipments. The aim of this paper is to evaluate the operational and economic performance of six different insulation materials. A multi-criteria analysis was conducted to evaluate different aspects of the packaging solutions. Physical properties such as volume utilization and weight were examined, as well as the price attractiveness. Two online surveys with 1,314 respondents in total were performed to evaluate consumer acceptance. Finally, lab tests assessed the thermal insulation performance and the cushioning effect of the insulation materials tested. No single insulation material or solution stands out in all aspects of the multi-criteria analysis. Recycled paper flakes and recycled polyethylene terephthalate (rPET) perform best overall. rPET is lightweight, compact, cost-effective, and offers excellent insulation and cushioning properties. Yet, consumer acceptance is very low. Conversely, recycled paper is well-received by consumers, economically viable, and performs similarly well in insulation and cushioning, but is heavier and less space-efficient. This is one of the first studies comparing several different alternative insulation materials (i.e., recycled paper flakes, rPET, straw, hemp, sheep's wool, recycled cotton) for transport packaging at the same time in a multidisciplinary manner.

1. Introduction

The e-commerce business is characterized by continuous growth, in particular within the grocery sector (Siragusa and Tumino, 2022). The rise of e-commerce has led to significant growth in the packaging industry, which today represents one of the most important economic sectors (Abenghal et al., 2025). E-grocery products are typically shipped using disposable transport packaging, which is disposed of by consumers after delivery. This linear packaging system results in intensive resource consumption and high waste volumes. According to current estimates, transport packaging is causing around 30 % of emissions in online retailing and is therefore, together with last-mile delivery, responsible for the majority of the ecological footprint of online retailing (DHL Research and Innovation, 2022). For temperature-sensitive food products, the environmental impact is even more significant, because the insulation of the products requires substantially more packaging material to guarantee a constant temperature along the distribution chain. The primary function of cold chain packaging is to preserve food quality and safety, which could be compromised by temperature fluctuations, especially in the case of meat, fish and dairy products, with the consequent growth of harmful bacteria. Moreover, transport packaging should absorb impacts, protecting the products, specifically fruit and vegetables, from damage during transportation, thus minimising the risk of quality impairment and unnecessary food loss. Food loss and waste represent a global challenge with high impact on the economy and environment, which account for 8–10 % of global greenhouse gas emissions (Food and Agriculture Organization, 2023; Forbes et al., 2024). Hence, sustainable packaging solutions are essential to address this challenge.

Expanded polystyrene (EPS) is by far the most popular insulation material used for packing temperature-sensitive goods (Vamza et al., 2021). However, conventional EPS is derived from fossil-based raw materials and takes many centuries to decompose if sent to landfill sites (Su et al., 2020). Due to these circumstances, there is an increased focus on developing sustainable alternatives with high-performance characteristics. In this regard, bio-based variants of EPS have become available,

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that enable the material to degrade by 92 % within 4 years in bio-reactive landfills (Markets, 2025). Another possible solution is to recycle EPS. The resulting rEPS maintains most of the desired characteristics of virgin EPS, such as low thermal conductivity, light weight and compressive strength, while reducing the reliance on the virgin material (Acierno et al., 2009). Alongside these strategies, researchers are also exploring novel bio-based insulation materials. For example, Dieckmann et al. (2019) designed non-woven fibre linings made of feathers from the poultry industry and compared their thermal performance with expanded polystyrene (EPS). They found that the feather liners performed similarly or even better than polystyrene under certain conditions, when tested with meat substitutes. However, an increase in the load weight or moisture absorption can significantly reduce their thermal resistance, compromising the overall insulation performance. Other scientists highlighted the possibility of using mycelium-based insulation materials for packaging applications. In addition to their biodegradability, they pointed out the rapidity of growth and versatility of fungi, which can grow on different substrates and can therefore be cultivated worldwide using locally available agricultural by-products (Abhijith et al., 2018; Al-Kamzari et al., 2023; Mojumdar et al., 2021). They underlined the mechanical strength, shock absorption and thermal properties of the resulting foams and composites. Bruscato et al. (2019) determined the compression strength of the mycelium-based foams to be 60 % higher than that of EPS. The thermal conductivity of mycelium bio-composites was found to be in the range from 0.03 to 0.08 W/mK, comparable to or slightly higher than EPS (0.03-0.04 W/mK) (Al-Qahtani et al., 2023).

Cellulose pulp–chitosan foams offer a combination of good mechanical performance and excellent thermal insulation properties, with a thermal conductivity of 0.03–0.04 W/mK. The water resistance and mechanical strength of these foams can be modulated by increasing the chitosan content, making them suitable for applications where water stability is critical (Lujan et al., 2022).

Food by-products and waste are widely used in bioplastic production. Among these, matrices of polylactic acid (PLA) and thermoplastic starch (TPS) have attracted attention as “green” foam products for packaging applications, due to their low thermal conductivities, biodegradability and sustainability. PLA foams have high compressive strength, low water retention (less than 0.19 %) and low density, but are brittle, therefore blending with other polymers or incorporating additives is necessary to improve their mechanical properties (Wang et al., 2020). The thermal conductivity of PLA ranges from 0.0643 to 0.0904 W/mK, depending on the degree of crystallization (Al-Qahtani et al., 2023). Incorporating 40 % polycaprolactone (PCL) into PLA/rice straw (RS) bio-composites has been shown to improve both compression strength and thermal conductivity of the resulting foams, with the latter achieving values of 0.038 – 0.040 W/mK (Xu et al., 2022). Starch-based foams, on the other hand, have poor mechanical properties and high water-susceptibility, which also makes further modifications necessary, such as the incorporation of additives and fillers.

Packaging technologists have recently also rediscovered natural materials and agricultural by-products such as straw, hemp or sheep wool as promising alternatives (Morris, 2019). Similarly, insulation products made from recycled materials, such as wastepaper, cotton and polyester, have been promoted for their insulating properties and their ability to minimize environmental impact. However, a thorough comparison of different sustainable insulation materials for cold chain deliveries is mostly missing in the literature. Vamza et al. (2021) remains the only study that compares different biodegradable insulation materials for transport packaging, specifically mycelium, corn starch, non-woven wool, and non-woven feathers, against polystyrene based on five criteria: density, thermal conductivity, environmental sustainability, ability to hold temperature, and price. However, they did not provide empirical data, such as temperature profiles to evaluate the insulation materials. In contrast, other studies have focused only on conventional, less environmentally friendly insulation solutions and have mainly investigated their effectiveness in maintaining a safe temperature range for perishable food products, providing temperature profiles recorded inside the boxes (Li et al., 2014; Wang et al., 2020; Singh et al., 2008). In addition, sustainability of e-grocery and food delivery services is directly linked to consumer perception and acceptance, an aspect that is often neglected (Janmaimool et al., 2024).

The aim of this research is to provide a comprehensive overview and examination of different insulation solutions commercially available for sustainable e-groceries packaging and assess their potential to be applied to online food retailing. To evaluate the sustainability of packaging innovations, a comprehensive framework considering different aspects is needed, since there might be trade-offs and synergies arising from different evaluation criteria (Santi et al., 2022). Therefore, six criteria for evaluating the operational and economic performance of the insulation materials have been defined. The following research question will be answered: Which alternative insulation material performs best in terms of thermal insulation, consumer acceptance, low weight, volume utilization, price attractiveness and cushioning effect? For this purpose, a multi-criteria evaluation of six different insulation materials was conducted. The insulation materials being studied include recycled paper flakes, recycled polyethylene terephthalate (rPET), straw, hemp, sheep’s wool and recycled cotton. A comprehensive evaluation scheme consisting of different criteria to estimate the potential and feasibility of the insulation solutions was developed. This allows us to derive recommendations on which packaging solutions are best suited to specific requirements and use cases.

2. Materials and methods

This research work was designed to address the previously stated research questions using a two-phase approach, as illustrated in Fig. 1. The first phase involved conducting a comprehensive market study aimed at gathering relevant data on current market trends towards sustainable cold-chain insulation solutions. The second phase employed a multi-criteria approach to evaluate the different insulation solutions identified and selected during the first phase. A detailed description of the applied procedures and methods is provided in this section.

2.1. Market study

To fully capture the variety of technologies and providers existing in the market, desktop research about different insulation solutions was conducted as a first step. We used conventional databases (Google) but also scientific databases (Scopus and Google Scholar) to research the market for innovative and sustainable transport packaging. Thus, we were able to collate a list of 16 insulation solutions from various national and international suppliers that could potentially lead to a reduction of greenhouse gases in e-grocery deliveries (see Table A1 in Annex). We classified the solutions according to the material they are based on, which led to six different insulations materials that were further evaluated in the course of this research: recycled paper flakes, rPET, straw, hemp, sheep’s wool and recycled cotton. We did not apply specific exclusion criteria; instead, we included every insulation solution in this study for which we were able to obtain a sample for physical evaluation. This pragmatic approach ensures a broad and realistic range of insulation solutions that are currently commercially available for temperature-sensitive shipments. For each type of insulation material, we obtained samples from one supplier, for paper flakes and rPET/polyester fibres we obtained two different samples from two suppliers (Fig. 2).

2.2. Multi-criteria approach

A multi-criteria approach was conducted to evaluate the six different insulation materials. Multi-criteria evaluations allow for a holistic and transparent comparative assessment of different alternatives which

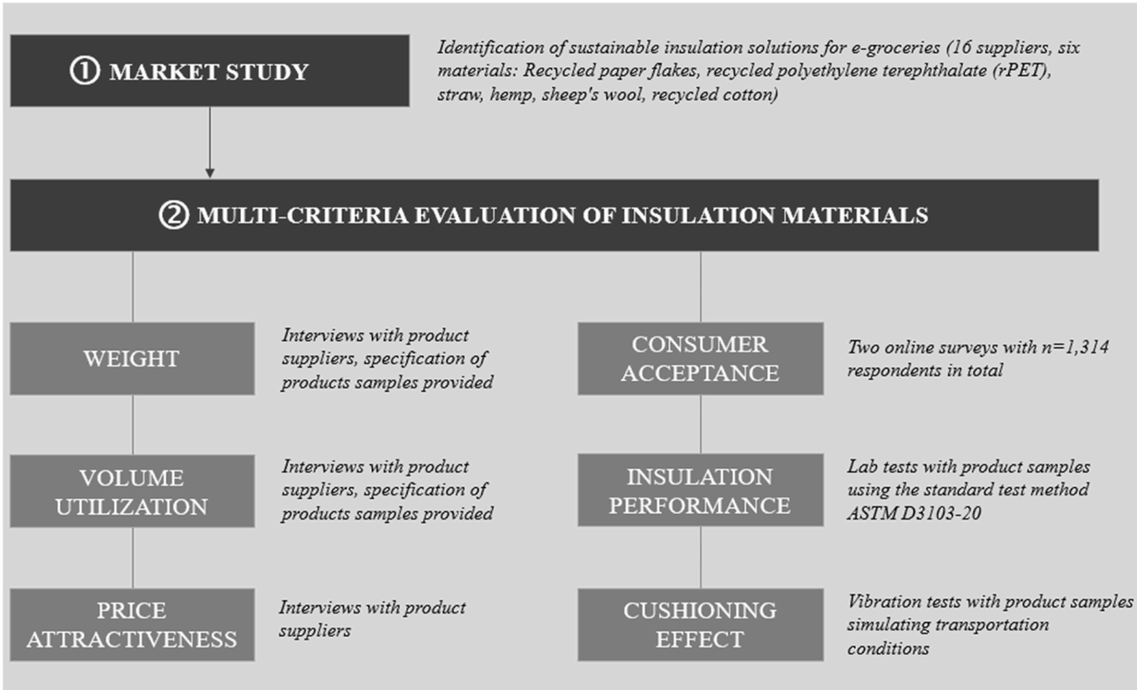

Fig. 1. Research approach to evaluate different sustainable insulation solutions.

Fig. 2. Different sustainable insulation materials in the lab tests (left: rPET, center: recycled paper flakes, right: hemp).

enables a better appraisal of the performance of the available options (Oeuvray et al., 2024). A mixed-method approach was used to analyse different metrics of these packaging solutions and assess their potential for e-grocery deliveries. These metrics included both technical and consumer-oriented criteria.

2.2.1. Physical properties and price attractiveness

Different physical properties of the insulation solutions were determined based on the assessment of the provided product samples. These physical properties included volume utilization, weight and density. To guarantee consistency of these results, a reusable polypropylene-based transport box (45 × 34 × 17 cm) obtained from the company hey circle was used in all these tests. The volume utilization was defined as the percentage of the total internal box volume not occupied by the insulation material and therefore usable for packing the goods. To determine this, the volume of the insulating material was first calculated considering its thickness and geometric configuration, then subtracted from the total box volume. Finally, the remaining available internal volume was divided by the total box volume to obtain the volume utilization percentage. The weight, defined as the total mass (kg) of insulation material required to insulate one standardized hey circle box, was determined by weighing the box fitted with the insulation solutions on a platform scale (KERN DS 20K0.1, Germany). As tara, the weight of the empty hey circle box was used. The density was defined as the ratio between the mass (kg) and the volume (m^3) of a single inlay. In this study, we focused solely on volume utilization and insulation weight, as these two parameters were determined based on the actual amount of material required to fit the examined box. In doing so, we also considered the insulation and box geometries, the number of inlays, and their specific placement in the box. In contrast, density is an intrinsic property of the material and is unrelated to the above-mentioned factors. Finally, the price attractiveness (i.e., purchase costs) of the different insulation solutions was determined based on the pricing information from the providers. Price per unit was calculated for a purchase quantity of 6,000 units. To ensure comparability, we defined one “unit” as the quantity of insulation material required to line one reusable polypropylene-based transport box (hey circle box L; outer dimensions: 45×34×17 cm, volume 26 liters) with insulation panels.

2.2.2. Consumer acceptance

To rate consumer acceptance, two online surveys were conducted. The topic of the first survey was sustainable packaging in general, including topics such as attitude towards different materials, willingness to pay or acceptance of reusable packaging solutions. We employed an online panel to gather responses, enabling us to obtain a sample size of n = 1,017 respondents that is representative of the Austrian population across different age groups and genders. The aim of the second survey was to reveal respondents’ preferences on different sustainable insulation materials. The second survey was conducted to specifically target the topic of e-grocery shipments, in particular temperature-controlled products. The survey was distributed among the customer base of an Austrian e-grocery retailer cooperating as part of this study. The respondents were incentivized with vouchers for the e-grocery retailer. Thus, we were able to reach a sample size of n = 298 respondents with the second survey.

2.2.3. Thermal insulation performance

The thermal insulation performance of the different insulation solutions was determined in terms of maximum temperature holding time according to the standard test method ASTM D3103-20 for thermal insulation performance of distribution packages (D10 Committee, 2020) with minor modifications. The reusable polypropylene-based packaging box from the provider *hey circle* with dimensions 45×34×17 cm (size L) and a wall thickness of 0.5 cm was equipped with the different insulation solutions and placed in a controlled environment reproducing a predefined temperature profile. The insulation materials were arranged inside the box to create an even layer, leaving no uncovered spots. The effect of the pre-conditioning of the insulations on their thermal performance was also studied. In this respect, the materials were pre-cooled in a cold chamber at 4 °C for 48 h before being tested. For the comparison of the thermal insulation quality of the materials, tests were carried out without a product payload. Four 900-g ice packs (CP 1.3) obtained from ECO°COOL GmbH, previously frozen at -25 °C for at least 48 h, were included to cool the inside of the box. The temperatures inside the chamber and the boxes were monitored using climate data loggers (PKDL A1, PARKSIDE) with a temperature measuring range between -30 and 70 °C and humidity range from 0 to 100 % RH. Accuracy according to the manufacturer was ±0.5 °C / ±2.5 % RH with a resolution of ±0.1 °C and ±0.1 % RH. The sensors were placed in different areas of the box: one or two on the side edges and one in the core of the box, in between the ice packs. The measuring interval was set to every 10 min and the test duration to 72 h. A climate chamber from Aralab (Fitoclima S600) was used to simulate the external temperature fluctuations encountered during transport in summer. Specifically, the temperature profile was based on the standard Association française de normalisation (AFNOR) ST-48-b, modified to cover the entire duration of the test. The temperature range analysed varied from 20 °C to 32 °C, with a one-hour ramp transition from one temperature to the next, providing a realistic scenario of the typical summer temperatures in Austria. The complete temperature profile is given in Table B1 in the annex. To guarantee homogeneity in the conditions, the chamber was ventilated (60 %). Relative humidity in the controlled environment was 50 %. After acclimatisation of the chamber to the starting conditions (22 °C and 50 % RH), the box containing the insulating materials, the sensors and coolant, was sealed and immediately placed in the controlled environment, where the summer profile was started. The monitoring of the temperature inside the box allowed us to determine how long the temperature could be kept below the reference temperatures of 4 °Celsius and 8°Celsius. The measurements of the maximum insulation time were repeated three times, and the average values were calculated. Control tests were run on the *hey circle* box containing no insulation.

2.2.4. Cushioning effect

The cushioning performance of the different insulation solutions was evaluated through vibration tests. Apples (*Malus domestica* Borkh. cv. ‘Red Delicious’ and cv. ‘Gala’), purchased from a local store, were used as test specimens, as they are very susceptible to mechanical damage, which can occur during transportation. The apples were visually inspected for superficial defects and only those that did not show mechanical damage due to post-harvesting treatment and handling were used for testing. Each insulating material was tested in triplicate, using a single apple per trial, to ensure that the results were not influenced by the interactions between apples, such as collisions, but were only attributable to the material’s ability to absorb the shock energy caused by the vibrations. The boxes containing the insulation solutions and the apples were subjected to defined mechanical stress (300 rpm for 240 min) on an orbital shaker (Edmund Bühler SM-30) to simulate the vibrations caused by transport. Control experiments were conducted without any insulation material to quantify the cushioning effectiveness of each insulation material, comparing the severity of mechanical damage sustained by the apples in the absence of any protection. Multispectral images of the entire apples were captured with a VideometerLab instrument (Videometer A/S, Herlev, Denmark) before and after shaking, on four sides of the apples (top, bottom, and two sides). Since the images also included a blue background and the stems of the apples, a mask was first created to eliminate these surrounding effects, which could interfere with the bruise detection. Normalized canonical discriminant analysis (nCDA) was then used for discriminating between bruised and non-bruised areas of the apple. Finally, the area fraction of bruises was calculated. The bruises were mostly visible in the NIR (band 19, 970 nm) and Cyan (band 6, 505 nm) spectral bands. The implemented procedure is outlined in Fig. 3.

3. Results and discussion

3.1. Market study

Based on the desktop research, six types of insulation materials were identified for further examination regarding their suitability for e-grocery deliveries (see Table A1 in annex for an overview). Most of the solutions identified in course of the market study utilize cardboard or paper materials. The further evaluation in this study includes two paper flakes solutions from the suppliers SUPASO and easy2cool. They are made from recycled wastepaper and can be conveniently disposed of in the paper bin for further recycling. There are also several solutions made of rPET on the market, for example the Smartliner of EcoCool. The Smartliner is composed of 80 percent recycled PET bottles. The polyester fibres from rPET are processed into a lightweight insulation fleece that helps maintain cool temperatures for food items. Another solution made of recycled material is the Greenin insulation inlay provided by Tempack. It is made of 100 % recycled cotton originating from fashion retailers. Cotton, as the most extensively used textile fibre worldwide, generates large amounts of waste at all production stages, representing a valuable recycling opportunity (Sezgin et al., 2021).

The company Landpack provides two plant-based insulation solutions, one made of straw and the other made of hemp. The straw is supplied by local farmers. Straw is a by-product of grain harvesting, currently underutilized and not competing with food production. To ensure hygiene standards, samples undergo microbiological testing before being processed into packaging. Using straw for insulation purposes is considered to be a mature technology; straw bundles were utilized in building structures as far back as 1800 due to their benefits,

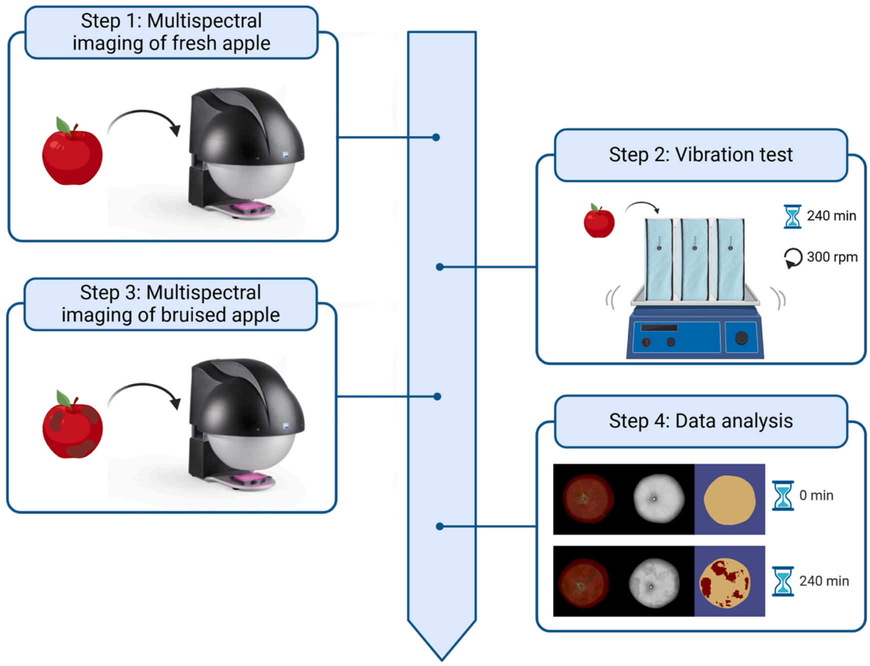

Fig. 3. Overview of the procedure used for studying the cushioning effect of the insulation solution tested in the hey circle box.

including renewability and excellent thermal insulation properties (Li et al., 2023). However, it is currently still a niche technology (Platt et al., 2020). Hemp has a remarkable ecological balance (Zampori et al., 2013). The hemp plant grows up to four cm every day, disproportionately uptaking CO_2 and simultaneously enhancing soil fertility. The hemp fibre possesses exceptional strength due to its composition of pectin, hemicellulose, and lignin (Promhuad et al., 2022).

Three suppliers were identified providing insulation solutions made from sheep's wool, one of them being Lehner Wolle. Sheep's wool is a fully biodegradable material which is often considered to be a useless by-product of sheep farming for dairy and meat purposes (Szatkowski et al., 2022; Bhavsar et al., 2021). Reusing and recycling this "waste wool" is a circular approach to minimize resource consumption. Sheep's wool is said to have hygroscopic characteristics (Hegyi et al., 2020), thus the suppliers promote sheep's wool by highlighting its ability to absorb condensation from chilled food items during transportation, thereby regulating moisture within the package more effectively than other insulation materials.

We found a number of further insulation solutions based on other materials as well, e.g., feathers (Pluumo, see Dieckmann et al., 2019) or cardboard ("Foodmailer" by PackIt). Since we were unable to obtain product samples of these solutions, they are not further considered in this study. While this may not represent the entire market, it reflects a realistic cross-section of currently accessible and operationally relevant solutions.

3.2. Physical properties and price attractiveness

Volume utilization is an important performance indicator in logistics to ensure maximum use of capacities and increase sustainability (Wong et al., 2018; Khan et al., 2017). We therefore determined the degree to which the six insulation materials utilize the volume in a shipping box (Table 1). The wall thickness of the individual insulation solutions is the key figure to determine volume utilization (Table A2, in annex). It has been found that the wool product has the lowest wall thickness (around 15–20 mm) and thus performs best in terms of volume utilization. This is followed by rPET. The paper flakes, cotton and straw products scored worst in this evaluation category since they have around 25–30 mm wall thickness which leads to a poor volume utilization rate.

Table 1
Volume utilization, total insulation weight required per hey circle shipping box (size L) and corresponding density for each insulation material.

Insulation type	Volume utilization (%)	Total weight of the insulation / hey circle box (kg)	Density (kg/m^3)
Straw	53.52	1.475	112.82
Hemp	47.42	1.360	75.56
PAPER 1	55.06	1.355	93.90
PAPER 2	46.18	1.235	83.97
Sheep's wool	64.30	0.415	37.56
rPET 1	52.02	0.420	16.91
rPET 2	58.22	0.600	52.70
Cotton	46.18	0.885	55.13

Another important logistics indicator is weight (Table 1). In view of weight limits and tariffs tied to a shipment's weight, it is relevant how heavy the insulation is (García-Arca et al., 2020; Zuo et al., 2022). The weight of the packaging also exerts a significant influence on the overall environmental performance of the shipment (Meng et al., 2023). In terms of weight, again the sheep wool insulation solution scored best. The total weight of the sheep wool needed to insulate a hey circle shipping box size L only accounts for 0.42 kg. Polyester fibres made from recycled PET are almost as light as sheep's wool, followed by cotton. All other insulation materials are substantially heavier. Paper flakes, hemp and straw scored worst in the weight category: for these materials, the total weight needed to insulate a hey circle shipping box amounts to roughly 1.2 – 1.4 kg each, which is considerably more than the weight of the sheep wool or rPET insulation.

Price attractiveness is one of the main preconditions for the acceptance of sustainable logistics innovations (Pfoser, 2022). Hence, the purchase price of the six insulation materials is juxtaposed per unit (= the quantity of insulation material required to line one reusable hey circle box L with a volume of 26 liters). The information on purchase prices is either based on quotations we received from the suppliers or online retail prices. It turned out that the insulation made of recycled paper flakes has the lowest purchase price and thus the best price attractiveness (depending on the purchase quantity the purchase price of the paper flakes insulation from SUPASO is between €3.44 per unit (minimum order quantity 300 pieces) and €3.14 per unit (minimum order quantity 3,000 pieces). The insulation made from hemp has the highest purchase price (around €11 per unit). The price of the other products lies in between (see Table A3 in annex).

3.3. Consumer acceptance

Two online surveys with 1,314 respondents in total were carried out to understand consumer preferences for different packaging materials. Details on demographics, representativeness, and biases are provided in the following Table 2. The first survey is representative of the Austrian population in terms of age and gender, as ensured through the use of an online panel. It should be noted that the sample of the second survey was not fully gender-balanced, with a majority of female respondents (70 %). This reflects the demographic composition of the cooperating e-grocery retailer's customer base. Since women traditionally play a leading role in grocery shopping decisions in many households (Storz et al., 2022; Munro et al., 2023), the sample still provides relevant insights into the preferences of a key consumer group. In the second survey, 55 respondents (18 %) did not provide demographic information. This is due to the fact that indicating age and gender was voluntary. Such partial non-response is common in online surveys (Ziegenfuss et al., 2021) and was accepted in order to increase overall participation and data quality.

In the initial survey with a representative sample of 1,017 end consumers we found that when it comes to online shopping, consumers place considerable emphasis on sustainable packaging: 72 % of the respondents stated that sustainable packaging has a high significance or at least a rather high significance to them. It has been observed that consumers frequently feel guilty about the creation of packaging waste when shopping online. This confirms that it is important for e-grocery retailers to engage with sustainable packaging alternatives. The survey results also reveal that end-consumers show a willingness to pay for the packaging in case it is perceived as a sustainable alternative to conventional materials. 60 % of the respondents stated to be willing to pay for sustainable packaging. Regarding packaging materials for the external packaging (transport packaging), natural materials such as grass cardboard (i.e., cardboard where wood fibres are partially replaced by grass fibres) or packaging made from fungal mycelium (i.e., the roots of fungi) were estimated to be very sustainable. 91 % of the respondents rated grass cardboard to be very sustainable or rather sustainable, 80 % of the respondents rated fugal packaging to be very or rather sustainable. This is followed by traditional cardboard (74 %) and bioplastic (68 %). Plastic ranks lowest, as the vast majority of respondents do not consider it to be sustainable: 91 % of the respondents

Table 2
Demographics of respondents.

	Study 1		Study 2	
Gender	n	%	n	%
Female	509	50,05 %	210	70,71 %
Male	508	49,95 %	30	10,10 %
Diverse	0	0,00 %	1	0,34 %
Other	0	0,00 %	1	0,34 %
n.a.	0	0,00 %	55	18,52 %
Age Group				
18-29	220	21,63 %	55	18,52 %
30-39	205	20,16 %	61	20,54 %
40-49	196	19,27 %	49	16,50 %
50-59	231	22,71 %	49	16,50 %
above 60	165	16,22 %	29	9,76 %
n.a.	0	0,00 %	54	18,18 %
Municipality Size				
Up to 5,000 inhabitants	339	33,33 %	93	31,31 %
5,001 - 15,000 inhabitants	194	19,08 %	41	13,80 %
15,001 - 50,000 inhabitants	95	9,34 %	29	9,76 %
50,001 - 100,000 inhabitants	49	4,82 %	9	3,03 %
over 100,000 inhabitants	340	33,43 %	71	23,91 %
n.a.	0	0,00 %	54	18,18 %

stated that they do not estimate plastic packaging to be sustainable. We also asked respondents what surface texture they most associate with sustainable packaging. We found that a "textured/rugged" packaging surface was rated most sustainable, followed by "grainy" and "rough". The properties "soft" or "smooth" were most frequently rated as "not sustainable". This supports the perception that nature-based materials like grass cardboard are particularly seen as sustainable.

The second survey with n = 297 respondents had a particular focus on insulation materials. We first asked respondents to evaluate which type of insulation material they would prefer for their e-grocery shipments. Then we asked them to estimate how sustainable they consider different insulation materials for e-grocery packaging (Fig. 4). The results of the second survey again confirm that especially the plant-based materials are believed to be environmentally friendly. The respondents rated straw and hemp as the most environmentally friendly insulation material, followed by recycled paper flakes. Also sheep's wool and recycled cotton are considered to be rather sustainable. In contrast, rPET is estimated to be less sustainable and polystyrene even to be unsustainable. As can be seen from Fig. 4, there is an interrelation between the estimation of sustainability and the preferences for using the respective insulation materials. The three materials considered to be most sustainable constitute the three materials which are most preferred by consumers to be used for their e-grocery deliveries, although the order is different. Recycled paper flakes are most preferred, followed by hemp and then straw. Polyester fibres, though originating from recycled PET bottles, are estimated to be least sustainable by end-consumers and they are also the least preferred sustainable insulation material. This corroborates consumers' general dislike of plastic as a material (Zwicker et al., 2021; Marchi et al., 2020).

As part of an open-ended question, the respondents were able to provide additional comments regarding the various insulation materials. This allows us to get some deeper insights into consumers' attitude towards the materials. In grocery deliveries, cleanliness is an important issue. Notably, some consumers show hygiene concerns regarding particular materials. Hygiene concerns are especially related to straw, hemp, and sheep wool. Here, respondents have expressed anxieties regarding moisture and mould formation. On the other hand, plastic and polystyrene are mainly considered to be clean and uncontaminated materials, which confirms the findings from the first survey.

Materials perceived as natural, particularly straw, hemp and recycled paper, were favoured for their eco-friendly and renewable properties, while sheep wool received mixed responses due to concerns over animal welfare and unwanted smell. Although cotton's recyclability and sustainability were recognized, respondents also expressed concerns about its disposal and energy consumption during recycling. This shows that consumers are critically reflecting the environmental effects which goes along with an increased awareness on sustainable consumption that customers have developed over the previous years (Yang et al., 2021; Yamane and Kaneko, 2021). Respondents also showed to be interested and eager to learn more about the sustainable insulation alternatives as we received a number of questions in the comment section of the survey. The concept of the circular economy has also resonated with consumers. Some comments refer to the materials needing to follow the principles of circularity, for example: "Recycling is generally desirable, but only if the recycled product continues to circulate within the system, rather than being incinerated."

Recycled paper was rated highly in the survey. One reason for this is that consumers are very familiar with it, they see it as a cost-effective option and know how to handle it: "For materials like sheep's wool, straw, hemp, and cotton, as an end consumer, I wouldn't immediately know how to sensibly dispose of them. I want to avoid plastic and styrofoam. I can easily recycle paper or, if in doubt, even burn it". However, there were occasional concerns expressed about paper as well, since it requires the clearing of forests for wood.

Consumers correctly anticipated during the survey that sheep's wool is quite an expensive alternative material. They therefore suggest that it

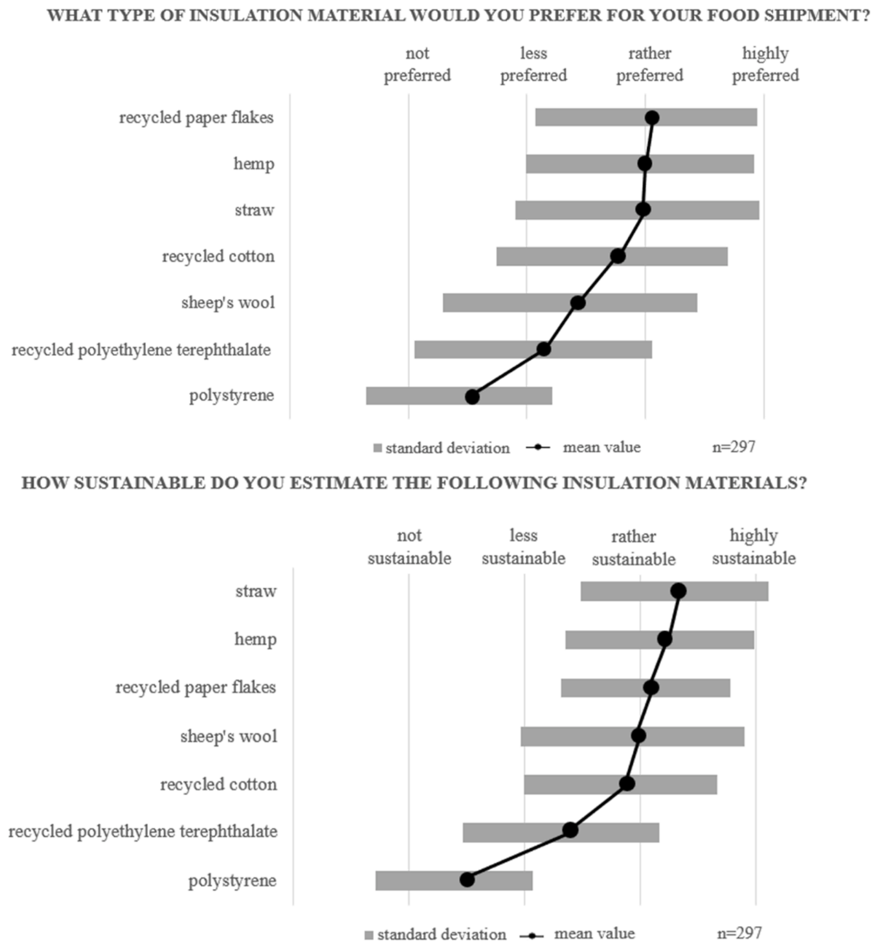

Fig. 4. Consumers' evaluation of insulation materials.

should be rather used for other purposes than insulation: "I imagine sheep's wool to be quite expensive for 'just' insulation" or "Straw is easily compostable, whereas sheep's wool should be used for other purposes, not as insulation material for shipping".

The survey findings indicate that consumers are open to reusing insulation materials as they recognize environmental benefits and potential cost savings. However, concerns exist about how to return these materials and worries about hygiene and waste. When it comes to online shopping, customers stress the importance of both sustainability and product quality. Most participants preferred a personal pickup of empty packaging, with an average desired return duration of 12 days, indicating a preference for a practical and timely return process. Additional feedback showed a general positivity toward reusable packaging and a preference for package-free options, but there were also concerns about

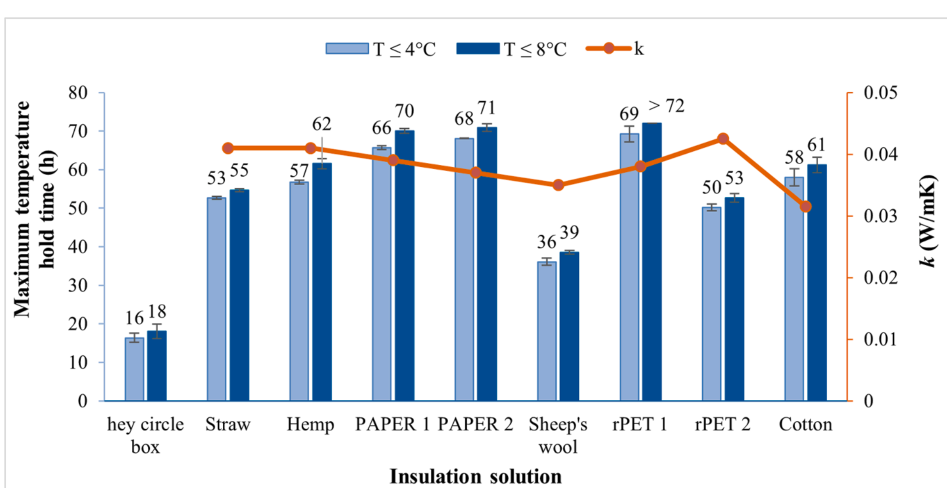

Fig. 5. Thermal insulation performance, expressed as maximum temperature holding time, for the insulation products tested and the hey circle box without insulation. Results are expressed as mean ± SD (n = 3). The orange line represents the thermal conductivities of the insulation solutions as provided by the manufacturer, except for rPET 2, whose value is based on literature (Patnaik et al., 2015; Drochytka et al., 2017).

cost implications and practical challenges.

3.4. Thermal insulation performance

Fig. 5 shows the thermal insulation performance, expressed as maximum temperature holding time (mTHT) in hours, of the *hey circle* box and the insulating solutions tested with 4 cold packs and subjected to the summer temperature profile. The thermal conductivity (*k)* of the different insulation materials is also displayed.

The mTHT is highly dependent on several factors, such as the number of cooling elements, the temperature profile used, the thickness and density of the insulation materials and the box configuration. Since the amount of cooling inside the package is the main temperature regulator in the passive insulated boxes, an increase in the number of the cold packs will increase the temperature holding time. By maintaining the same basic parameters throughout the experiments, a relative comparison of the insulation products was possible. A representative temperature profile of a single test run using the cotton-based insulation product is depicted in Fig. 6A. Fig. 6B, on the other hand, shows the moisture profiles recorded inside the climate chamber and the box for the same insulation product over a 72-hour period. Temperature and humidity profiles for the other insulation products tested and the *hey circle* box with no insulation are included in the annex (Appendix B: Fig. B1, B2, B3, B4, B5, B6, B7 and B8).

Under the tested conditions, the recycled polyethylene terephthalate rPET 1 showed the best insulation performance, as the temperature inside the box was kept below 4°Celsius for about 69 h and below 8°Celsius for at least 72 h. This result was to be expected considering the fibrous nature and low-density of the material, in which air is enclosed in a capillary structure, resulting in a low thermal conductivity of 0.038 W/mK (according to the product manufacturer). Furthermore, PET fibres are moisture-resistant since they do not degrade in the presence of high humidity and dry out once the water source has been removed, with no impairment of their thermal performance, making it possible to reuse the insulation (Drochytka et al., 2017). In contrast, rPET2's performance was not equally excellent, with a mTHT of only 53 h below 8°Celsius. This is probably due to the different geometric configuration, which provides a single layer of insulation all around, whereas rPET 1 provides, the way it was designed, a double layer of fibres at the bottom and top, resulting in a better performance. Another reason can be ascribed to the higher density of rPET 2, which results in a more effective energy transfer between the atoms, since they are closer to each other, leading to an increase in thermal conductivity.

The insulation performance of the recycled paper flakes was similarly high, with a THT of 66 and 68 h below 4°Celsius and 70–71 h below 8°Celsius for PAPER 1 and PAPER 2, respectively. Cellulose fibres are excellent thermal insulators, but in themselves very hygroscopic; therefore, if they come into direct contact with moisture, their insulation performance can be adversely affected. It is hence necessary that the recycled paper flakes are sealed to prevent this. The paper-based insulations tested here were wrapped in a thin layer of polyethylene that protected the paper flakes from coming into contact with water, so performance would not be affected.

Sheep's wool on the other hand showed the weakest insulation performance with only 36 h THT below 4°Celsius, and 39 h below 8 °C. By itself, sheep wool is also a very good insulator, with thermal conductivity comparable to the two above-mentioned materials (see Fig. 5). However, the thickness of the sheep wool insulation was significantly lower, being only 1.5 cm on the sides and 2 cm at the top and bottom, thus resulting in reduced cooling performance. Furthermore, wool is very easily affected by a higher moisture content, which leads to a performance drop. In order to preserve the insulation properties of the mats, the wool components should ideally be covered with water-repellent layers.

Hemp and cotton have very comparable insulation quality, despite the different thicknesses (1.8 cm for hemp and 3 cm for cotton) and the different geometric configurations, with 57–58 h THT below 4 °Celsius, and 61–62 h below 8 °C, followed by straw with a reduced temperature holding time of 53 h below 4 °C and 55 h below 8 °C. As with sheep's wool, also hemp, straw and cotton, being natural fibres, tend to easily absorb moisture when exposed to the environment, especially in high humidity conditions. This can significantly affect their ability to provide thermal insulation. In this study, hemp and straw were wrapped in a polylactic acid-based non-woven fleece cover, which does not protect them adequately from the humidity, while the cotton inlay was wrapped in a low-density polyethylene film, which allows the cotton to stay dry preserving its good insulation properties. However, it has been observed, that if the products are given sufficient time to completely dry, they can be used several times.

Control tests conducted on the *hey circle* box without insulation showed that the temperature limits of 4 °C and 8 °C were reached after 16 and 18 h respectively, proving that the use of insulation products can extend the insulating properties of the box up to approximately four times in the best cases.

Pre-cooling the insulation products has only a slight impact on the temperature hold time. In particular, an increase of 1–2 h could be observed for all tested solutions, except for the recycled paper flakes, for which no difference in the thermal performance could be noted with or without pre-conditioning at 4 °C, whereas a worsening could be observed for sheeps wool (see Table B2 in annex).

3.5. Cushioning effect

The results obtained by comparing the multispectral images of the apples before and after shaking for 240 min at 300 rpm, in the *hey circle* box and in the tested insulation solutions, are presented in Fig. 7, as a percentage of the apple's bruised area. Normalized canonical discrimination analysis (nCDA) allowed to distinguish between bruised and non-

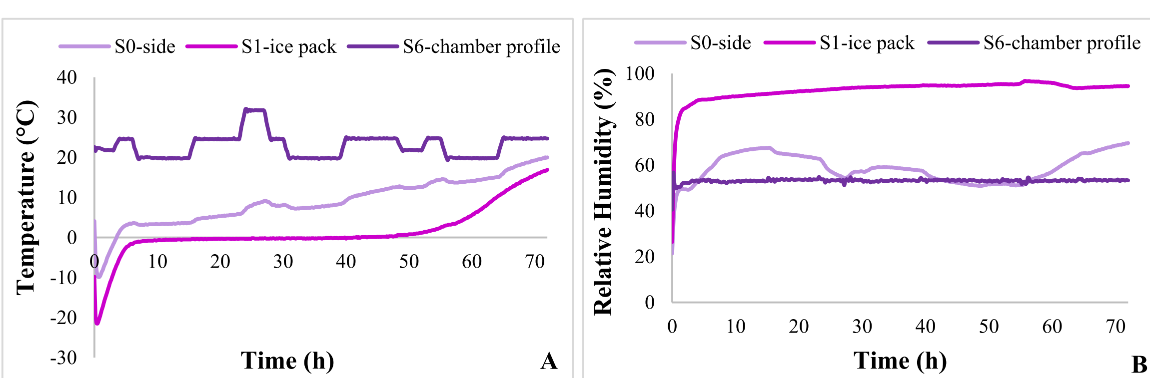

Fig. 6. A) Temperature and B) humidity profiles recorded in the climate chamber and the hey circle box equipped with the cotton insulation under the modified standard summer profile (AFNOR), with four cooling elements.

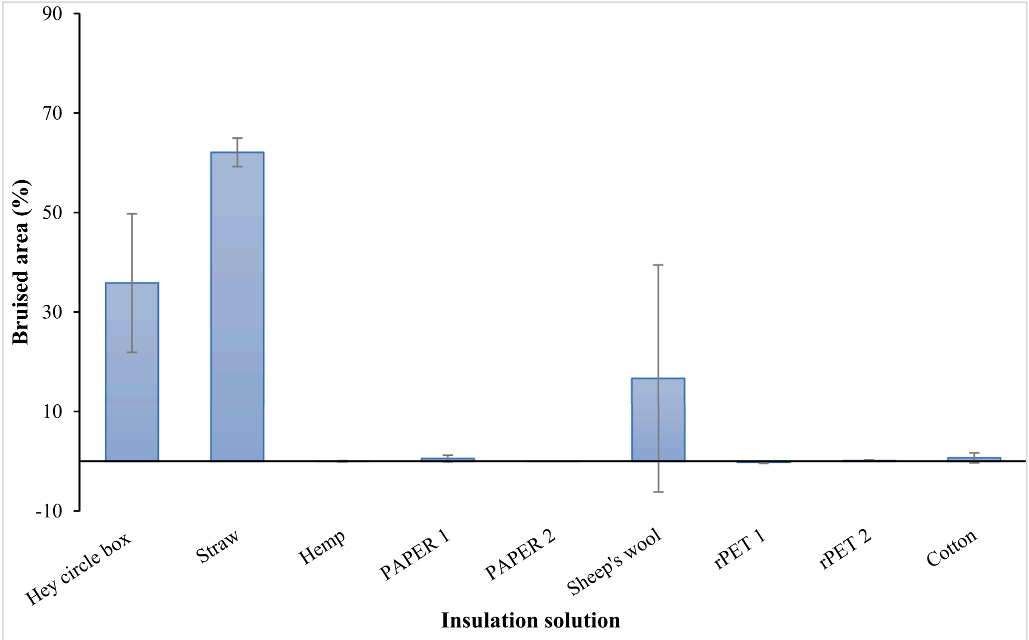

Fig. 7. Bruised area on the apples after vibration tests for the different insulation solutions studied. Results are expressed as mean ± SD (n = 3).

bruised areas on the surface of the apples. Under the tested conditions, all materials showed very strong cushioning performance when exposed to high mechanical vibrations. The only exception was straw, which performed the worst, exhibiting a bruised area of 62 %, even higher than that observed on the apples tested in the hey circle box without any insulation (36 %). The high level of damage was attributed to the rupture of the cover in certain spots, causing the apple to rub directly and continuously against the straw fibres. The performance of sheep's wool insulation followed, with a bruised area of 16 %, which is considerably lower compared to that of the uninsulated hey circle box. Similar to the straw insulation, this result may also be related to the vulnerability of the paper-based cover, which was damaged after several uses, resulting in a reduction of the cushioning effectiveness of the insulation solution. Among the materials, which resulted in low bruising, rPET 1 exhibited exceptional cushioning performance, as no bruising was observed on the apples after the vibration tests. The same can be stated for PAPER 2 and hemp, followed by rPET 2 with only 0.16 % bruising, PAPER 1 with 0.58 % and finally cotton with 0.70 % bruised area. Although these tests do not fully represent real shipping conditions, they do show plausible worst-case scenarios and can be used to better identify crucial properties of the insulation solutions.

4. Conclusion, implications and outlook

This study estimates the potential of six sustainable insulation materials for e-grocery shipments. Fig. 8 summarises the findings based on the six different evaluation criteria explored in Chapter 3. In cases where multiple solutions based on the same material were tested, the properties of the best-performing product are displayed. The results show that there is no 'one size fits all' solution which scores best in every dimension of the multi-criteria evaluation. Considering the different dimensions altogether, recycled paper flakes and rPET are the best

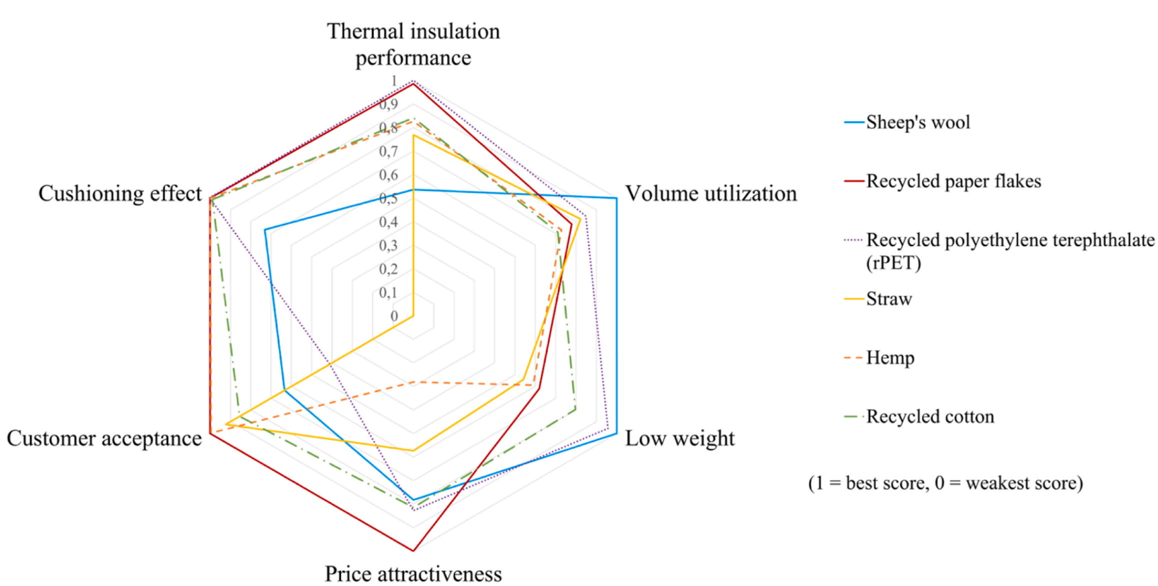

Fig. 8. Multi-criteria evaluation of different insulation materials (1 = best score, 0 = weakest score).

performing insulation materials. rPET is light and takes up little volume, it is cost efficient and performs best in terms of insulation and cushioning. However, plastic/polyester fibres show very low consumer acceptance compared to the other materials, even though it is recycled. In contrast, recycled paper flakes show the highest consumer acceptance and are very well received by consumers. Recycled paper flakes are the most economic insulation material with the lowest purchase price and their thermal insulation and cushioning performances are similarly good to rPET. However, high weight and poor volume utilization pose disadvantages for the recycled paper flakes solution.

4.1. Managerial implications

The findings provide valuable insights for retailers, helping them make informed decisions that align with their operational goals and sustainability commitments. The future of e-grocery shipments lies in innovative solutions that can efficiently meet diverse requirements while minimizing environmental impact, paving the way for more sustainable and consumer-friendly solutions in the rapidly growing online grocery market. The results of the online surveys highly encourage e-grocery retailers to consider sustainable packaging for temperature-controlled food deliveries, as it shows the importance consumers pose on sustainable packaging. By using environmentally friendly packaging, retailers can address one of the most serious barriers to online grocery shopping: The occurrence of additional packaging waste due to food shipping (Pfoser et al., 2020). The results of this study guide help retailers in choosing a sustainable insulation solution which meets their requirements best. There is no insulation material which outperforms all other materials in every dimension of the multi-criteria analysis. Depending on the particular requirements of the e-grocery retailer, different insulation solutions may be preferred. For example, if the retailer aims for a low purchase price, the recycled paper insulation scores best. However, recycled paper has a rather high weight and poor volume utilization. If the retailer is looking for maximum temperature hold time, rPET scores best. However, plastic (even though recycled) shows the lowest customer acceptance.

4.2. Theoretical implications, limitations and further research

This is one of the first studies comparing several different alternative insulation materials for transport packaging at the same time. Most existing studies either elaborate on individual alternative packaging materials only (e.g., Dieckmann et al., 2019 on feathers, Abhijith et al., 2018 on mycelium) or are related to the construction industry and not packaging (e.g., Corscadden et al., 2014). Vamza et al. (2021) is the only study which compares different insulation materials to be used for transport packaging, but they do not provide empirical evidence such as temperature profiles to evaluate the insulation materials. In this study, sustainable insulation solutions already on the market were evaluated and compared. All insulation materials tested were selected based on market availability and the feasibility of obtaining physical samples for testing. This approach may introduce a sample bias, as some promising solutions, such as feather- or mycelium-based materials, were excluded due to lack of access. Another limitation is that the insulation solutions are characterised by different thicknesses and different configurations. In order to be able to compare the base materials in an unambiguous way, it would be necessary to use materials with the same geometric characteristics. In addition, the trials conducted in the climate chamber did not take into account the stacking effect of multiple boxes, which would better represent how packages are practically shipped. Thus, the temperature holding time might be longer under real conditions. Finally, to test the reproducibility of the results, the same insulation solutions were used several times, which represents a limitation, as this would not account for a drop in performance after several uses. However, it can be stated that the overall ranking of the insulation products was not affected by this, since after multiple uses, no significant changes in the mTHT of the products could be observed. Another limitation is that we were not able to get reliable and comparable data to contrast the environmental performance of the sustainable insulation materials. We aimed to assess the environmental performance of the insulation materials based on different ecological KPIs, e.g., primary energy consumption, water consumption, origin of raw material or use of certified materials. The expert interviews with sales managers from the insulation providers showed however, that it is very difficult to compare the different materials with each other. Each supplier provides different KPIs which are not directly equivalent. Further research is needed to obtain reliable data to compare the environmental footprint of the materials. Lastly, a limitation of this study is the lack of analysis regarding the scalability and large-scale availability of the tested insulation materials. While materials such as sheep wool or hemp may offer ecological and functional benefits, their global availability and supply chain stability can vary significantly. Long-term costs associated with scaling production and ensuring supply chain resilience were also not assessed. These factors may influence the commercial viability of these materials beyond the operational and economic criteria considered in this research. Future studies should incorporate comprehensive market analyses and supply chain assessments to provide a more holistic evaluation of sustainable insulation solutions.

CRediT authorship contribution statement

Cecilia Nicoletti: Writing – original draft, Methodology, Investigation, Data curation. **Sarah Pfoser:** Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Manuela Brandner:** Writing – review & editing, Project administration, Investigation, Data curation. **Bernhard Blank-Landeshammer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Marion Dornmayr:** Project administration, Investigation, Funding acquisition, Conceptualization. **Julian Weghuber:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Specification of insulation materials

Table A1
Sustainable insulation solutions identified in the desk research (solutions printed in bold letters are part of the multi-criteria evaluation. We included all solutions in the evaluation of which we were able to gather product samples).

Material base	Supplier / packaging solution	Supplier origin	Insulation material
Paper / cardboard	DS Smith: ClimaCell	United Kingdom	Paper, biobased materials
	easy2cool [PAPER 1]	**Germany**	**Recycled paperflakes**
	EcoCool: Innobox	Germany	Paper
	Packit: Foodmailer	Austria	Cardboard
	RanPak	United States	Paper thermal liner
	SUPASO [PAPER 2]	**Austria**	**Recycled paperflakes**
Recycled polyethylene terephthalate (rPET)	**EcoCool: Smartliner [PET 1]**	**Germany**	**Polyester, recycled polyethylene terephthalate (rPET)**
	Isopack	Germany	Plastic (50% recycled)
	Storopack	Germany	Recycled polystyrene
	Tempack: PET Thermpack [PET 2]	**Spain**	**Recycled PET**
Straw	**Landpack: Landbox Straw**	**Germany**	**Straw**
Hemp	**Landpack: LandboxHemp**	**Germany**	**Hemp**
Animal-based	**Lehner Wolle: Isolena 400**	**Austria**	**Natural woolfibres**
	Pluumo	United Kingdom	Surplus feathers
	Puffin Packaging	United Kingdom	Natural woolfibres
	WoolCool	United Kingdom	Natural woolfibres
Cotton	**Tempack**	**Spain**	**Recycled cotton (old clothes of fashion retailers)**

Table A2
Specification of the insulation solutions under evaluation.

Insulation type	Supplier / packagingsolution	Dimensions (mm)	Wall tickness (mm)[a]	Weight single piece (kg)[b]	Pieces/box
Recycled paperflakes	SUPASO: Ecoliner	I: 300 × 380	30	0.288	6
	Easy2Cool: Paperfloc	II: 350 × 180		0.153	
		III: 180 × 380		0.178	
		A: 400 × 1070	15	0.635	2
		B: 1350 × 400		0.720	
Recycled polyethylene terephthalate (rPET)	Eco Cool: Smartliner L	A: 1500 × 380	20	0.210	2
	Tempack: PET Thermpack	B: 1070 × 510	25		
		A: 820 × 460	22	0.430	2
		B: 1030 × 140		0.170	
Straw	Landpack: Landbox-Straw	1 Panel: 300 × 260	25	0.220	10 cuts
Hemp	Landpack: Landbox-Hemp	1250×400	18	0.680	2
Sheepwool	Lehner: Isolena 400	S: 200 × 1150	15	0.145	2
		L: 400 × 1020	20	0.270	
Recycled cotton	Tempack: Greenin	A:825 × 465	30	0.665	2
		B: 1035 × 135		0.220	

I = top/bottom
II = short side
III = long side
[a] According to samples provided by the suppliers
[b] According to samples provided by the suppliers

Table A3
Indicated prices of insulation solutions under evaluation (based on an order quantity of 6,000 pieces).

Insulation type	Supplier / packaging solution	Indicated price per unit	Source
Recycled paper flakes [PAPER 2]	SUPASO	3.14 €	Supplier quotation
Recycled polyethylene terephthalate [rPET 1]	Eco Cool: Smartliner L	5.00 €	Supplier quotation
Straw	Landbox-Straw	7.80 €	Ratioform[b]
Hemp	Landbox-Hemp	11.02 €	Ratioform[a]
Sheep wool	Lehner: Isolena 400	5.50 €	Supplier quotation
Recycled cotton	Greenin Cold Chain Inlays	5.15 €	Supplier quotation

[a] https://www.ratioform.at/p/thermobox-hanf-standard-terra-landbox-p153196
[b] https://www.ratioform.at/p/thermobox-stroh-terra-landbox-p145367/ldp1/

Appendix B. Thermal insulation performance

Table B1
Summer temperature profile based on the AFNOR standard modified to cover 72 h test duration.

Segment	T (°C)	RH (%)	Ventilation (%)	Time (min)
0	22	50	60	180
1	25	50	60	60
2	25	50	60	120
3	20	50	60	60
4	20	50	60	480
5	25	50	60	60
6	25	50	60	420
7	32	50	60	60
8	32	50	60	180
9	25	50	60	60
10	25	50	60	120
11	20	50	60	60
12	20	50	60	480
13	25	50	60	60
14	25	50	60	480
15	22	50	60	60
16	22	50	60	180
17	25	50	60	60
18	25	50	60	120
19	20	50	60	60
20	20	50	60	480
21	25	50	60	60
22	25	50	60	420

Table B2
Comparison of the thermal insulation performance of the different insulation products with and without pre-cooling at 4 °C for 48 h, with 4 cold packs (900g each). Results in the table refer to single test runs and are expressed in terms of temperature holding time (THT).

Product	With pre-cooling		No pre-cooling	
	THT ($T \leq 4$ °C) [h]	THT ($T \leq 8$ °C) [h]	THT ($T \leq 4$ °C) [h]	THT ($T \leq 8$ °C) [h]
Straw	56	57	53	54
Hemp	57	61	57	61
rPET 1	70	> 72	69	> 72
rPET 2	53	55	51	54
Cotton	60	63	58	62
PAPER 1	66	70	66	70
PAPER 2	68	70	68	70
Sheep's wool	35	37	37	39
Hey circle box	18	19	17	18

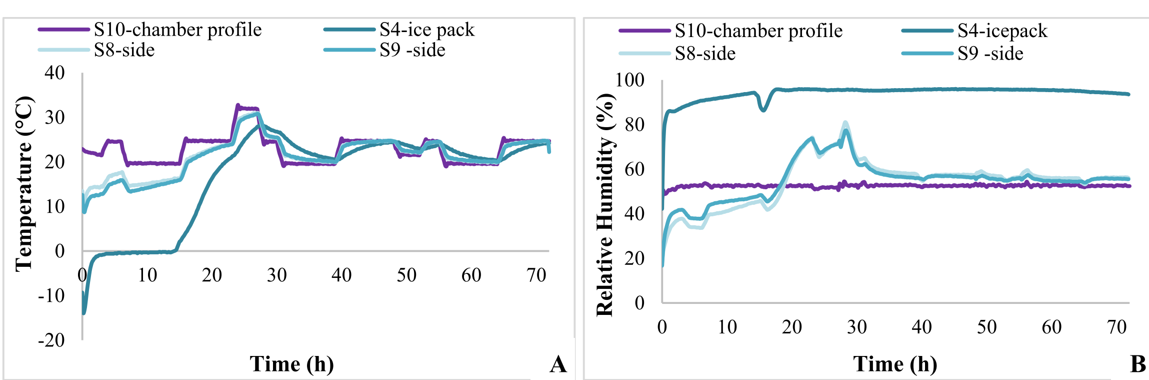

Fig. B1. A) Temperature and B) humidity profiles recorded inside the hey circle box with no insulation and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements.

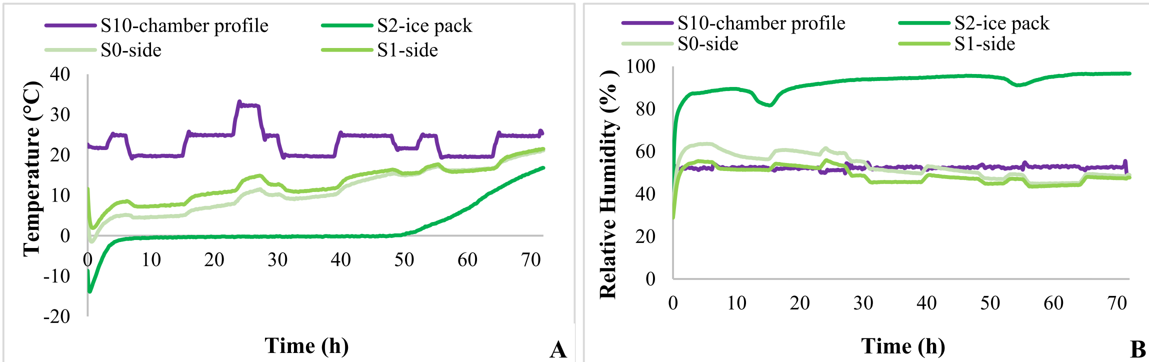

Fig. B2. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the hemp insulation product.

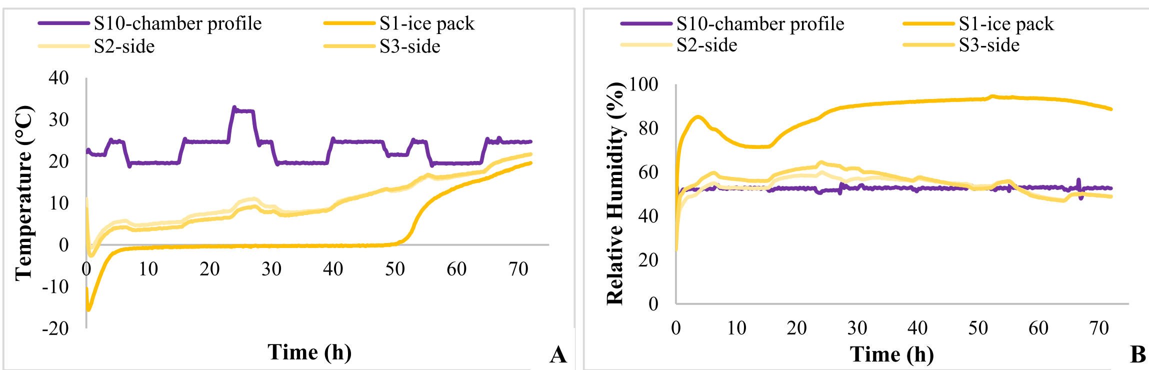

Fig. B3. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the straw insulation product.

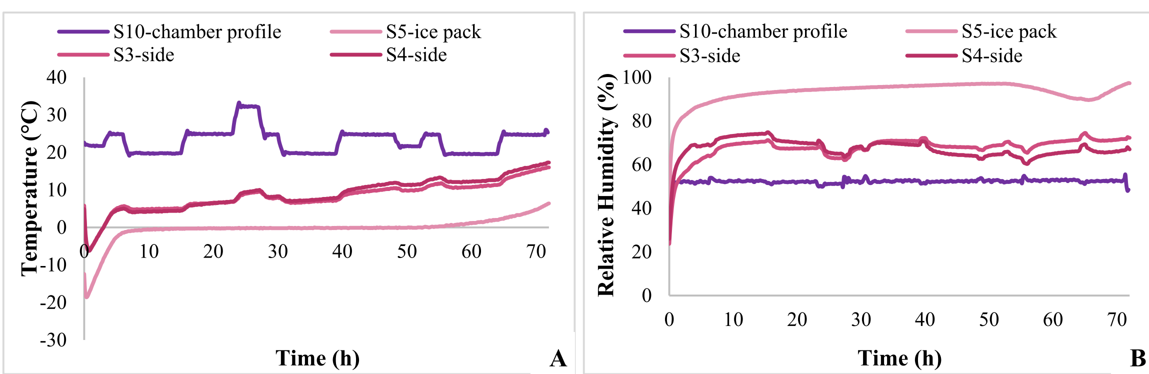

Fig. B4. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the recycled polyester fibres insulation product (rPET 1).

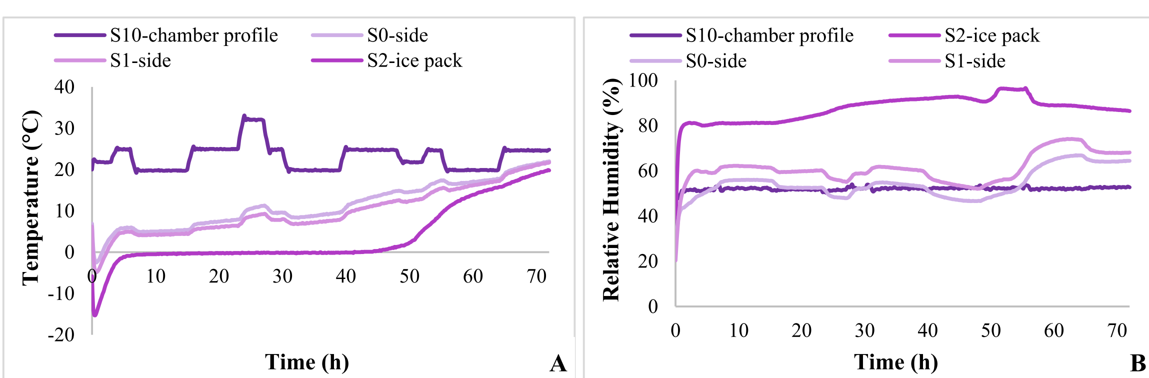

Fig. B5. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the recycled polyester fibres insulation product (rPET 2).

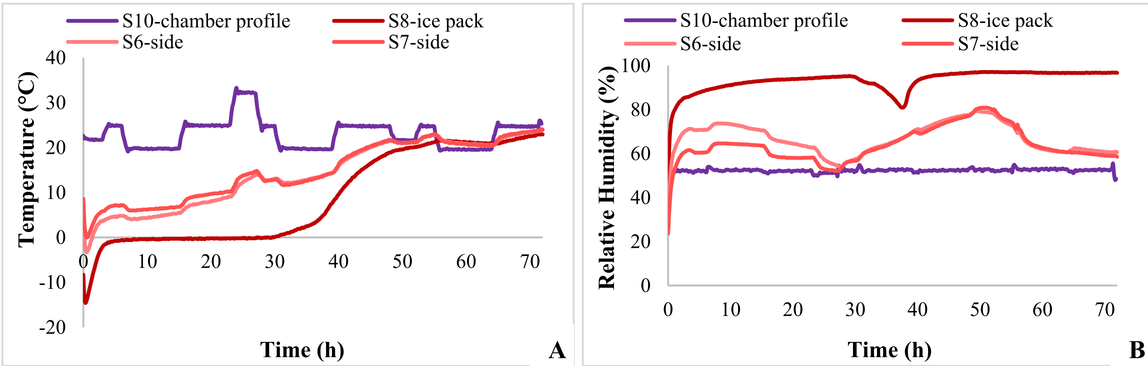

Fig. B6. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the sheep's wool insulation product.

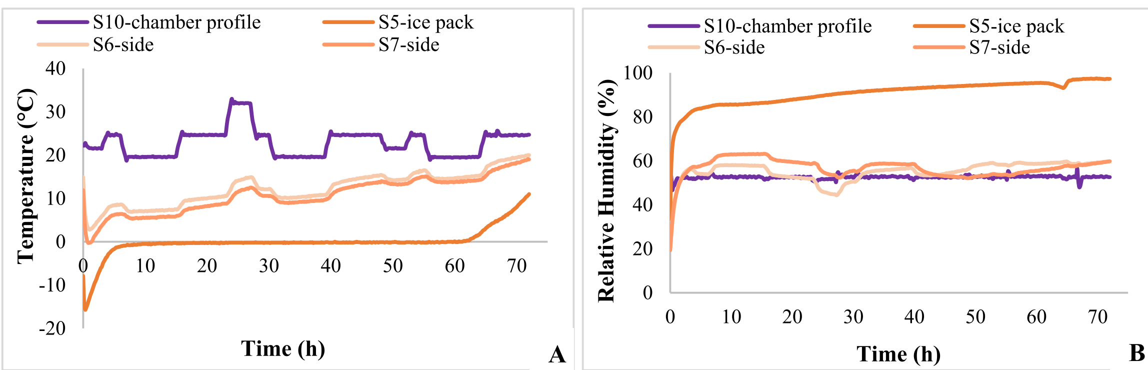

Fig. B7. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the recycled paper-based insulation product (PAPER 1).

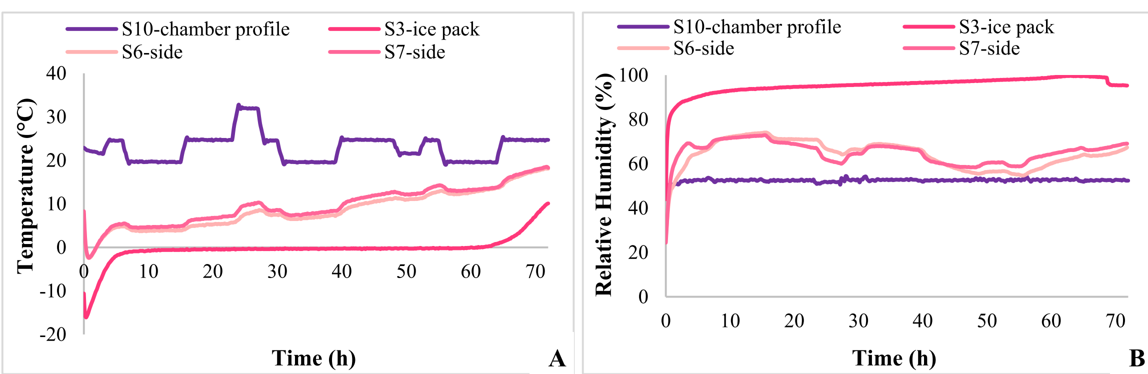

Fig. B8. A) Temperature and B) humidity profiles recorded inside the hey circle box and the climate chamber under the modified standard summer profile (AFNOR), with four cooling elements for the recycled paper-based insulation product (PAPER 2).

Data availability

Data will be made available on request.

References

Abenghal, L., Bley, J., Tolnai, B., Njamen, G., Chabot, B., 2025. Development of a new sustainable packaging paper based on cellulose filaments and refined kraft pulp. Future Foods 11, 100540.

Abhijith, R., Ashok, A., Rejeesh, C.R., 2018. Sustainable packaging applications from mycelium to substitute polystyrene: a review. Mater. Today: Proc. 5 (1), 2139–2145. Part 2.

Acierno, S., Carotenuto, C., Pecce, M., 2009. Compressive and thermal properties of recycled EPS foams. Polym. Plast. Technol. Eng. 49 (1), 13–19.

Al-Kamzari, S.M.A., Nageswara-Rao, L., Lakavat, M., Gandi, S., Reddy, P.S., Kavitha Sri, G., 2023. Extraction and characterization of cellulose from agricultural waste materials. Mater. Today: Proc. 80, 2740–2743.

Al-Qahtani, S., Koç, M., Isaifan, R.J., 2023. Mycelium-based thermal insulation for domestic cooling footprint reduction: A review. Sustainability 15 (17), 13217.

Bhavsar, P., Balan, T., Dalla Fontana, G., Zoccola, M., Patrucco, A., Tonin, C., 2021. Sustainably processed waste wool fiber-reinforced biocomposites for agriculture and packaging applications. Fibers 9 (9), 55.

Bruscato, C., Malvessi, E., Brandalise, R.N., Camassola, M., 2019. High performance of macrofungi in the production of mycelium-based biofoams using sawdust. Sustainable technology for waste reduction. J. Clean. Prod. 234, 225–232.

Corscadden, K.W., Biggs, J.N., Stiles, D.K., 2014. Sheep's wool insulation: A sustainable alternative use for a renewable resource? Resour. Conserv. Recycl. 86, 9–15.

D10 Committee, 2020. Test method for thermal insulation performance of distribution packages. ASTM International, West Conshohocken, PA, pp. 1– 7. No. ASTM D3103-20.

DHL Research and Innovation, 2022. Delivering on Circularity: Pathways for fashion and consumer electronics. Bonn, pp. 1–40 available online at https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/DHL_Delivering_on_Circularity_White_Paper_2022.pdf.

Dieckmann, E., Nagy, B., Yiakoumetti, K., Sheldrick, L., Cheeseman, C., 2019. Thermal insulation packaging for cold-chain deliveries made from feathers. Food Packag. Shelf Life 21, 100360.

Drochytka, R., Dvorakova, M., Hodna, J., 2017. Performance evaluation and research of alternative thermal insulation based on waste polyester fibers. Procedia Eng. 195, 236–243.

Forbes, H., Peacock, E., Abbot, N., Jones, M., 2024. Food Waste Index Report 2024: Think Eat Save: Tracking Progress to Halve Global Food Waste, pp. 1–193. https://wedocs.unep.org/20.500.11822/45230.

García-Arca, J., Comesaña-Benavides, J.A., González-Portela Garrido, A.T., Prado-Prado, J.C., 2020. Rethinking the box for sustainable logistics. Sustainability 12 (5), 1870.

Hegyi, A., Dico, C., Szilagyi, H., 2020. Sheep wool thermal insulating mattresses behaviour in the water vapours presence. Procedia Manuf. 46, 410–417.

Janmaimool, P., Chudech, S., Khajohnmanee, S., Chontanawat, J., 2024. Communicating norms to increase food delivery customers' sustainable waste management behaviors. Future Foods 9, 100288.

Khan, S.A.R., Qianli, D., SongBo, W., Zaman, K., Zhang, Y., 2017. Environmental logistics performance indicators affecting per capita income and sectoral growth: evidence from a panel of selected global ranked logistics countries. Environ. Sci. Pollut. Res. 24 (2), 1518–1531.

Li, Y., Schrade, J.P., Su, H., Specchio, J.J., 2014. Transportation of perishable and refrigerated foods in mylar foil bags and insulated containers: a time-temperature study. J. Food Prot. 77 (8), 1317–1324.

Li, Y., Zhu, N., Chen, J., 2023. Straw characteristics and mechanical straw building materials: a review. J. Mater. Sci. 58 (6), 2361–2380.

Lujan, L., Goñi, M.L., Martini, R.E., 2022. Cellulose–chitosan biodegradable materials for insulating applications. ACS Sustain. Chem. Eng. 10 (36), 12000–12008.

Marchi, E.de, Pigliafreddo, S., Banterle, A., Parolini, M., Cavaliere, A., 2020. Plastic packaging goes sustainable: an analysis of consumer preferences for plastic water bottles. Environ. Sci. Policy 114, 305–311.

Informa Markets Engineering (2025), Bio-based EPS offers new packaging alternative, PlasticsToday, January 2025, pp. 1-3. available at: https://www.plasticstoday.com/packaging/bio-based-eps-offers-new-packaging-alternative.

Meng, T., Wang, Y., Fu, L., Wang, Y., Zhang, N., Wang, Z., Yang, Q., 2023. Comparison of the environmental impact of typical packaging systems for food cold chain express based on life cycle assessment. J. Clean. Prod. 430, 139756.

Mojumdar, A., Behera, H.T., Ray, L., 2021. Mushroom mycelia-based material: an environmental friendly alternative to synthetic packaging. In: Vaishnav, A., Choudhary, D.K. (Eds.), Microbial Polymers. Springer Singapore, Singapore, pp. 131–141.

Morris, A., 2019. Rediscovering natural materials in packaging. In: Ormondroyd, G.A., Morris, A. (Eds.), Designing with natural materials. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 181– 198.

Munro, P., Kapitan, S., Wooliscroft, B., 2023. The sustainable attitude-behavior gap dynamic when shopping at the supermarket: A systematic literature review and framework for future research. J. Clean. Prod. 426, 138740.

Oeuvray, P., Burger, J., Roussanaly, S., Mazzotti, M., Becattini, V., 2024. Multi-criteria assessment of inland and offshore carbon dioxide transport options. J. Clean. Prod. 443, 140781.

Food and Agriculture Organization, 2023. Tracking progress on food and agriculture-related SDG indicators 2023. FAO, pp. 1–215. https://doi.org/10.4060/cc7088en.

Patnaik, A., Mvubu, M., Muniyasamy, S., Botha, A., Anandjiwala, R.D., 2015. Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. Energy Build. 92, 161–169.

Pfoser, S., Mosor, T., Brandtner, P., Schauer, O., Kubicek, A., 2020. Marktanforderungen und akzeptanz von online-lebensmittelzustellungen in Österreich. In: Jahrbuch der Logistikforschung, 3. Trauner Verlag Universitat, Linz, Austria, pp. 245–254.

Pfoser, S., 2022. Decarbonizing freight transport: Acceptance and policy implications. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 1– 142.

Platt, S., Maskell, D., Walker, P., Laborel-Préneron, A., 2020. Manufacture and characterisation of prototype straw bale insulation products. Constr. Build. Mater. 262, 120035.

Promhuad, K., Srisa, A., San, H., Laorenza, Y., Wongphan, P., Sodsai, J., Tansin, K., Phromphen, P., Chartvivatpornchai, N., Ngoenchai, P., 2022. Applications of hemp polymers and extracts in food, textile and packaging: A review. Polymers 14 (20), 4274.

Santi, R., Garrone, P., Iannantuoni, M., Del Curto, B., 2022. Sustainable food packaging: an integrative framework. Sustainability 14 (13), 8045.

Sezgin, H., Kucukali-Ozturk, M., Berkalp, O.B., Yalcin-Enis, I., 2021. Design of composite insulation panels containing 100% recycled cotton fibers and polyethylene/polypropylene packaging wastes. J. Clean. Prod. 304, 127132.

Singh, S.P., Burgess, G., Singh, J., 2008. Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. Packag. Technol. Sci. 21 (1), 25–35.

Siragusa, C., Tumino, A., 2022. E-grocery: comparing the environmental impacts of the online and offline purchasing processes. Int. J. Logist. Res. Appl. 25 (8), 1164–1190.

Storz, M.A., Beckschulte, K., Brommer, M., Lombardo, M., 2022. Current sex distribution of cooking and food shopping responsibilities in the United States: a cross-sectional study. Foods 11 (18), 2840.

Su, Y., Duan, H., Wang, Z., Song, G., Kang, P., Chen, D., 2020. Characterizing the environmental impact of packaging materials for express delivery via life cycle assessment. J. Clean. Prod. 274, 122961.

Szatkowski, P., Tadla, A., Flis, Z., Szatkowska, M., Suchorowiec, K., Molik, E., 2022. Production of biodegradable packaging with sheep wool fibres for medical applications and assessment of the biodegradation process. Anim. Sci. Genet. 18 (3), 57–67.

Vamza, I., Valters, K., Dzalbs, A., Kudurs, E., Blumberga, D., 2021. Criteria for choosing thermal packaging for temperature sensitive goods transportation. Environ. Clim. Technol. 25 (1), 382–391.

Wang, K., Yang, L., Kucharek, M., 2020. Investigation of the effect of thermal insulation materials on packaging performance. Packag. Technol. Sci. 33 (6), 227–236.

Wong, E.Y.C., Tai, A.H., Zhou, E., 2018. Optimising truckload operations in third-party logistics: A carbon footprint perspective in volatile supply chain. Transp. Res. D: Transp. Environ. 63, 649–661.

Xu, C., Sun, C., Wan, H., Tan, H., Zhao, J., Zhang, Y., 2022. Microstructure and physical properties of poly(lactic acid)/polycaprolactone/rice straw lightweight bio-composite foams for wall insulation. Constr. Build. Mater. 354, 129216.

Yamane, T., Kaneko, S., 2021. Is the younger generation a driving force toward achieving the sustainable development goals? Survey experiments. J. Clean. Prod. 292, 125932.

Yang, M.X., Tang, X., Cheung, M.L., Zhang, Y., 2021. An institutional perspective on consumers' environmental awareness and pro-environmental behavioral intention: evidence from 39 countries. Bus. Strategy Environ. 30 (1), 566–575.

Zampori, L., Dotelli, G., Vernelli, V., 2013. Life cycle assessment of hemp cultivation and use of hemp-based thermal insulator materials in buildings. Environ. Sci. Technol. 47 (13), 7413–7420.

Ziegenfuss, J.Y., Easterday, C.A., Dinh, J.M., JaKa, M.M., Kottke, T.E., Canterbury, M., 2021. Impact of demographic survey questions on response rate and measurement: a randomized experiment. Surv. Pract. 14 (1), 1– 11.

Zuo, J., Feng, J., Gameiro, M.G., Tian, Y., Liang, J., Wang, Y., Ding, J., He, Q., 2022. RFID-based sensing in smart packaging for food applications: A review. Future Foods 6, 100198.

Zwicker, M.V., Brick, C., Gruter, G.-J.M., van Harreveld, F., 2021. (Not) doing the right things for the wrong reasons: an investigation of consumer attitudes, perceptions, and willingness to pay for bio-based plastics. Sustainability 13 (12), 6819.