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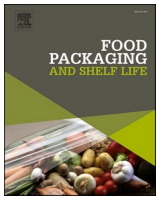

Current usage of paperboard packaging: A case study of the European landscape on tomato packaging

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ABSTRACT

Current pressures to decrease plastic packaging for food have resulted in increased demand for paperboard packaging of fruits and vegetables. Additionally, the new European Regulation on packaging waste calls for recyclable and for incorporation of recycled fibre in packages which challenges safety. Resistance in humid conditions is critical for paper-based packaging for fresh fruits and vegetables and cellulosic materials are typically chemically treated for improving these parameters. The content in recycled fibre also affects the resistance to moisture and as consequence the composition in additives required for sizing. It is recognised that several factors contribute to the behaviour of the paperboard, including the fibre origin, physic-mechanical treatments, bulk composition and material surface treatments. This work aimed at addressing the relationship between these factors, by conducting a deep physic-chemical characterisation of packages of cherry tomato collected in 4 European countries, in both high and low-cost supermarkets. Samples varied in terms of fibre origin, treatments (bleaching, printing), functional additives (surface or bulk agents). Statistical analysis demonstrated that it is possible to group samples according to different properties that are inter-related, such as the type of fibre and typical formulations (i.e. plasticizers and functional additives used). Materials varied significantly in their performance regarding the hydrophobicity character. Repulpability was also tested as step needed for recyclability. A number of chemicals of concern with Cramer class III toxicity such as mineral oil hydrocarbon, biocide, DiPN isomers and BPA replacers were observed across the samples. This work represents a concept study for larger inter-European studies and clearly points to the need for harmonization of practices and regulations for the utilization of paperboard as food contact material.

1. Introduction

Currently, there is a strong drive to decrease single-use plastic packaging, due to mismanaged plastic waste that may lead to adverse environmental impact (Saavedra et al., 2023). Furthermore, end of life of plastics has shown to cause the widespread presence of micro- and nano- plastic accumulating in the environment, landfills and oceans, eventually entering the human body, terrestrial, and marine animals (Stubbins et al., 2021). A high demand and consumption of plastics is observed in the food packaging industry (Jadhav et al., 2021) with substantial portion being used to pack fresh and convenience fruits and vegetables (F&V) (Dilucia et al., 2020). These concerns with excessive use of plastic packaging have led to an increased application of cellulose-based packaging for foods including F&V, aligning with the EU Circular Economy Action Plan (EU European Union, 2020; Pira, 2022). As a result, a shift from plastic to cellulose-based materials has been observed.

F&V are appreciated by consumers for the freshness and are important components in healthy and nutritious diets, but highly perishable. Ensuring the freshness, quality, and safety of these products

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while extending their shelf life is crucial for improving affordability and reducing waste. However, this remains a significant challenge for the food industry (Robertson, 2013). F&V are high in water activity, they release moisture and require storage under refrigeration at high levels of humidity, therefore the replacement of plastic films with cellulose-based materials such as paper or paperboard present a challenge. Cellulose-based packaging is inherently hydrophilic, hence, the resistance to moisture of paper and paperboard packaging must be improved. Low wettability and moisture sorption are important properties for paper-based food contact materials intended for high water content foods such as tomatoes and for use under refrigerated storage where high relative humidity levels are observed. To make the paperboard resistant under these conditions, functional additives maybe added as surface coating or to the bulk pulp (bulk sizing). Resins, which enhance the mechanical strength of paper when wet, for example polymers based on formaldehyde, melamine-formaldehyde or polyamide resins cross-linked with epichlorohydrin may also be added, as well as dry strength resins, like synthetic polymers (Ottenio et al., 2004). Laminating directly a polymer layer, e.g. polyethylene, or coating with polymeric dispersions, ionomeric or styrene-based, are common approaches (Basak et al., 2024).

Recently, Per- and Polyfluoroalkyl substances (PFAS), a group of chemical compounds used since the 1960s to provide functional properties to paper, have been in focus due to health and environmental concerns (Phelps et al., 2024). Therefore, alternatives to these processing aids are being explored, to provide paper with the necessary hydrophobicity, and amongst the novel practices are lamination/coating with biopolymers (Rhim et al., 2013) or cellulose surface treatments (Cunha et al., 2010a; Cunha et al., 2010b; Farhat et al., 2017; Hubbe et al., 2017; Samyn, 2013).

Surface treatment techniques entail both chemical and physical modifications. Chemical modification methods include esterification (Missoum et al., 2013), etherification (Zhang et al., 2023), and grafting (Carlmark et al., 2012). Physical modification techniques include treatments using plasma (Vesel & Mozetic, 2012), supercritical CO_2 (Kazarian, 2000) and ion-beam treatment (Bangar et al., 2022). Some of the most common chemical modifications involve silane-type treatments such as alkoxysilanes (Szlek et al., 2022), styrene-acrylic based treatments (Li et al., 2022; Stroganov et al., 2021), and ester modification with alkenyl succinic anhydride (ASA) or alkyl ketene dimer (AKD) (Garnier et al., 1998; Hubbe, 2006).

It is important to note that the safety of these alternative substances must be guaranteed for application as food contact materials (FCMs). In Europe all materials are regulated through the Regulation (EC) No 1935/2004 (EU European Union, 2021). The safety of plastics is regulated by the specific Regulation (EU) No 10/ 2011 (EU European Union, 2025a), a harmonised regulation and therefore applicable in all Member-States. On the other hand, cellulosic-based products lack such harmonized and internationally accepted legislation. Thus, several regional and national standards and/or recommendations are used for safety evaluation of paper-based packaging materials. One of the most relevant is the German Federal Institute for Risk Assessment recommendations on Food Contact Materials. These provide a framework of specifications and restrictions applicable to raw materials, production aids, additives and refining agents used in the production of paper and paperboard intended to contact with foodstuffs (BfR, 2024). These recommendations include, characteristics of the substances listed, limits of concentration in the final material, and migration or extraction limits under specific conditions.

Within the context of circular economy, recycling is promoted and recognized as an approach for packaging waste management. However, this practice is also a challenge from the safety perspective, as recycled fibres are considered as a major source of contaminants (Poças & Hogg, 2007). Recently introduced the regulation on packaging waste management Regulation (EU) No 2025/40 sets targets for materials recycling and for minimum requirements for recycled material incorporation, which challenges safety. Additionally, this regulation also sets stricter limits on the concentration of PFAS from all food contact materials (EU European Union, 2025b), particularly of interest for recycled paper-based materials.

To address the relevance, trends and research gaps in the field of paper and paperboards, a bibliographic search was recently conducted and was analysed using the VOSviewer software (Bukar et al., 2023). The outcome is shown in Fig. 1. It focused on 1 000 journal articles retrieved from *Web of Science*, with the search addressing "food" using the keywords "paper", "board", "packaging" and "surface treatment", covering the timeframe 2010 onwards (data retrieved on October 2024).

Fig. 1 highlights that the most recent research trends (indicated in yellow) focus on recycled paperboards, cardboards, corrugated boards and surface modification. The blue and dark green colour of the hits correspond to publication years from 2010 and around 2014, which were directed mainly to migration studies and safety concerns related to packaging materials. Contaminants which are typically found in recycled fibres, such as benzophenone, were recorded. These chemicals are often linked with printing ink components (Biedermann & Grob, 2010; Fengler & Gruber, 2022; Liu & Mabury, 2021). From 2016 onwards (shown in light green to yellow), there has been a noticeable increase in research on different contaminants and type of contamination, namely mineral oil and bisphenol A, along with use of paperboard for dry foods and more effort in modelling studies. The major fields of research are currently the evaluation on one hand of surface treatments to modify the physical properties of the material, and on the other, the safety aspects related to paperboard packaging, including recycled paperboards. It is important to note that while substantial research has been performed on assessing the safety of cellulosic packaging materials containing recycled fibres, there is limited data on the transfer of additives, production aids and other substances applied in virgin cellulose-based materials.

An example of substances that need to be considered in the safety analysis of paper and paperboard is dialkylketones (DAK) resulting from the degradation of alkyl ketene dimer (AKD). Commercial AKD are mixtures of varying chain lengths, producing DAK with long aliphatic lateral chains, such as palmitone and stearone. The specific limit for DAK transfer into food is 5 mg kg^{-1} (BfR, 2024). These chemicals belong to the toxicity Cramer Class II, and being hydrophobic they migrate to a large extent in organic solvent and high lipid food simulants (Lestido-Cardama et al., 2020). Likewise, the use of styrene-based coatings in cellulose-based packages may also contribute to consumer exposure to styrene for which a specific migration limit of 0.04 mg kg^{-1} is foreseen to be applied as precautionary measure (EC European Commission, 2023).

More recently, new paper-based packaging products entering the market often involve various treatments (Szlek et al., 2022) and additives that are not conventional fossil-based but originating from bio-based sources (Dal et al., 2020). To date, compositional and migration studies for these newly introduced substances are scarce, while bio-based alternative are growing in the market. The aim of this work was addressing the relationship between sustainability and circular requirements and safety implications. The first is a driver for the use of more recycled fibre and PFAS free cellulosic materials, while the second implies the incorporation of additives to improve resistance to moisture and the recycling-derived contaminants. The research focused on packages for fresh cherry tomatoes collected from European market represented by Denmark, France, Portugal and Slovenia to evaluate variation in material properties and identify potential migrants, as a proof of concept to determine the extent of variation in paper-based packages across Europe.

2. Materials and methods

2.1. Sample collection

Samples of packages of fresh cherry tomatoes were collected in

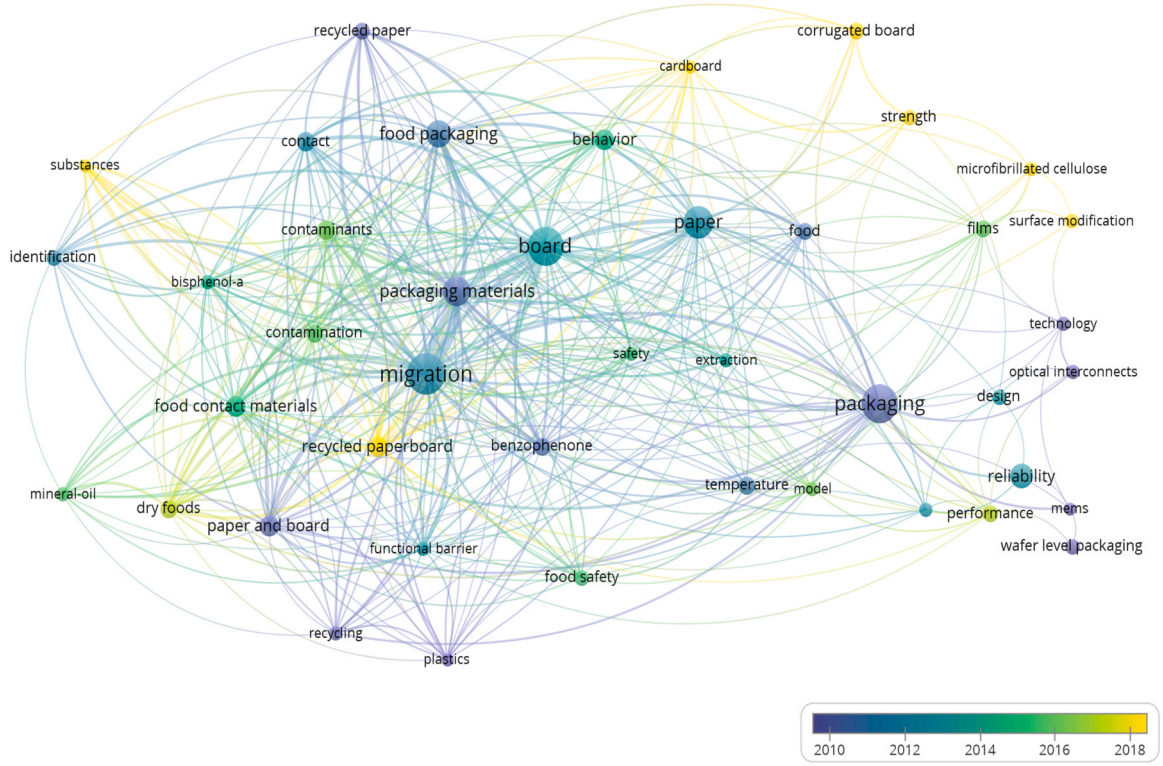

Fig. 1. Bibliometric analysis on "food" using the keywords "paper", "board", "packaging" and "surface treatment", covering the timeframe 2010 onwards.

different supermarkets in four European Union countries, namely Portugal (6), Denmark (3), Slovenia (3), and France (6), in a total of 18. Cherry tomato was selected as model food because it is a common product with relevant consumption volume in the four countries considered for market sampling. Preliminary market observations also showed that a wide variety of packages is used for this product providing for the intended overview of the samples' compositional analysis. A key criterion in the selection process was the exclusion of packages that were coated with plastic layers, to focus on the examination of chemical treatments for paperboard packaging, instead of continuous-layer plastic liners. The samples included packages ranging from 150 to 500 g and were collected during the Spring of 2023. Physical characteristics such as thickness, grammage, target weight of packed tomatoes and in-store conditions were analysed by each partner.

2.2. Microscopic images

The morphological images of the contact side of paper packages were obtained using a Olympus BX51 fluorescence optical microscope (Olympus, Japan) with a 10x objective lens, slide filter position 1 and a Olympus EP50 camera (Olympus, Japan) camera. Artificial LED light was projected via a LED Driver LSVC3A UNI (HEP group, Taiwan) to adjust the luminosity of the images. A total magnification was set at x100 on all the contact side of the samples captured without staining. Software ImageJ (version 1.51 m9) was used to process and annotate the obtained images.

2.3. Infrared spectroscopy

Infrared spectra of the contact side of tomato packages were recorded using an Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR). The spectra were obtained between 4000 and 400 cm^{-1} on a Bruker VERTEX 70 instrument. The spectra were recorded with 32 scans at 4 cm^{-1} resolution. A DLaTGS MIR, equipped with a Pike GladiATR plate (diamond crystal) for attenuated total reflectance (ATR) at room temperature was used.

The spectra data were processed with an in-house unsupervised model and used to perform a principal component analysis (PCA) on Python™ version 3.8. The spectra were pre-processed using the standard-scaler function from the scikit-learn library. The same library was called to implement the PCA function, where the spectral data was reduced into 2-D space and k-means clustering grouped the reduced data.

2.4. Material interaction with water

Low wettability and moisture sorption are important properties for paper-based food contact materials for fresh fruits and vegetables. Wettability refers to the interaction with liquid water while moisture sorption with water in gas phase. Cellulosic materials are typically chemically treated for improving these parameters. The content in recycled fibre also affects the resistance to moisture and as consequence the composition in additives required for sizing may also change. Therefore, analysing both properties is essential for the objective of our work, that aims at addressing the relationship between these factors.

2.4.1. Water contact angle

The contact angles of the contact side of the tomato packages were determined using the sessile drop method on a surface analyser system (Lauda Surface Analyzer LSA 100, Lauda Scientific GmbH, Lauda-Königshofen, Germany) according to the ISO 15989:2004. After the adjustment of resolution, the dynamic contact angle values were measured for 300 s by 2 s intervals. A drop of water with a fixed volume of 15 μL placed onto the surface of samples. Ten measurements for each sample were taken and the average of them were reported.

2.4.2. Dynamic water sorption behaviour

The water sorption properties of the samples were determined using a thermogravimetric sorption analyzer system (TGA-sorption) (Mettler Toledo TGA 2 Stare System, Greifensee, Switzerland) equipped with a

controlled modular humidity generator (MHG32, ProUmid, GmbH & Co. KG, Ulm, Germany) maintaining the humidified air flow at 23 °C with an interface attachment and a cooling system (Huber® CC-K6 with controller Pilot One, Offenburg, Germany). This is a common method to determine materials sorption isotherms (Parker et al., 2006). Paper samples were cut into 6 mm disks and placed into the aluminium oxide (Al_2O_3) crucibles with the coated sides up (70 μL, Alox, Mettler Toledo, Greifensee, Switzerland). A preliminary study was performed to verify the time required for samples to reach the equilibrium at pre-defined relative humidity (RH). Isothermal equilibrium condition of each cycle was 0.01 % w/w and the RH was maintained at 5 % for 6 h, and then increased successively to 10, 20, 30, 40, 50, 60, 70, 75 and 80 % maintaining the RH level for 2–3 h before changing the setpoint to the next target value. The change in paper weight, the actual RH, and the target RH based on the running time were recorded with a 30 s of time interval during the sorption test at 23 °C.

The GAB model (Guggenheim-Anderson-de Boer) was employed to describe the moisture sorption isotherms. It is expressed by the equation:

$$WC = \frac{CKa_wX_m}{(1 - Ka_w)(1 - Ka_w + CKa_w)}$$

where, WC is the moisture content, a_w is the water activity, and X_m, K, and C are the three free sorption parameters characterising sorption properties of the material. X_m denotes the moisture content corresponding to the monomolecular layer on the whole free surface of the material and the parameters K and C depend on temperature by Arrhenius-type equations.

2.5. Repulpability

The repulpability tests were performed according to Confederation of European Paper Industries (CEPI) guidelines. The protocols described in those documents consist of a simulation of the steps of a recycling plan and evaluate the ease at which the fibres can be separated using equipment of a recycling mill with conventional process. The complete test includes the potential to form sheets out of the recovered fibres without significant disruption and the sheets visual appearance. The evaluation and quantification of different fractions separated (coarse, fine rejects), the level of fragmentation of disrupting materials (adhesives, metals, plastic film) and colloidal substances below 12 microns resulting from non-paper components are also part of the full protocol. In this work, a disintegration procedure based on ISO 5263–1:2004 was applied. Thirty-two (32) g of air-dried packages were diluted with 1 L of tap water at 40 ± 1 °C to achieve a stock consistency of 3.25 % (approximately 2.86 g oven dried at 105 ± 2 °C for 3 h). A standard pulp disintegrator PD-10 (Techlab System, Spain) was employed for 10 min at 3000 rpm in the sample preparation process. Fibre analysis was conducted on disintegrated pulp using the Valmet fibre image analyser FS5 (Valmet, Finland) and Lc(w) (weight-weighted average fibre length) and fibre width, were determined, along with fines and fibrillation. The self-diluting method was utilized during this phase, where the machine autonomously determined the optimal dilution for accurate analysis. The fibres of selected samples were also observed without staining under Dialux 20 EB (Leitz, Germany) microscope using brightfield light for analysis of fibre origin (Supplementary Information S2).

2.6. Gas chromatography–mass spectrometry

Gas chromatography coupled with a mass spectrometer (GC-MS) was used to analyse the chemical composition of the samples, highlighting potential migrants necessary to assess safety. Extraction of paper and board was carried out for a total representation of volatiles and semi-volatiles using two different approaches: headspace and liquid. For headspace analysis, the sample was cut in 0.6 dm^2 placed in a 20 mL vial with 100 μL of water followed by incubation for 1 h at 80 °C. This small volume of water provided wettability to facilitate extraction. For liquid extraction to capture heavier and semi-volatile substances, pure ethanol and isooctane was used. 0.5 g of sample in small pieces was extracted with 5 mL of each solvent at 23 °C for 2 weeks through total immersion method.

After incubation the samples were injected into a chromatograph system (GC) GC456 incorporating a triple quadrupole SCION TQ (MS) mass spectrometer (Bremen, Germany) coupled with an automatic injector Combi-pal, with a separation column Zebron 5MS plus (30 m x 0.25 mm ID, 0.25 μm BR5ms phase). MS was operated in EI at 70 eV, scan mode from 33 to 700 *m/z*.

For headspace examination, the injector temperature was maintained at 250 °C, with an injection volume of 1 mL (split 1:10). The oven temperature commenced at 40 °C and was held for 5 min, subsequently programmed to increase to 320 °C and held for 2 min, featuring a ramp rate of 10 °C min^{-1}. For the liquid extraction using ethanol and isooctane solvents, the injector temperature was 280 °C and an injection volume of 1 μL (splitless for 0.75 min). The oven temperature initiated at 50 °C, held for 3 min, and was then programmed to rise to 320 °C, maintained for 15 min, with a ramp rate of 10 °C min^{-1}. Identification of the peaks relied on the comparison of spectra with NIST library 2.3.2017 and calculated linear retention index of an alkane mixture. Peaks in both the analyses were semi-quantified based on deuterated dodecane at 2.5 mg mL^{-1} for headspace analysis and 0.006 mg mL^{-1} for liquid analysis.

Toxicity data was analysed using an open software application Toxtree® developed by the Decision Tree Approach of the Joint Research Centre of European Union to classify the identified substances on the basis of Cramer Class principle. The migration limits were tallied using Decernis® software and correspondent legislation.

3. Results

3.1. Inspection of packaging samples for physical and surface characteristics

Table 1 presents physical characteristics of the collected tomato packages. Samples were categorised based on their most prominent feature, which is referred throughout the text as “characteristic feature”. The physical characteristics were compared with data from microscopic images, FTIR and GC-MS analyses.

Most of the samples (14/18) included recycled fibres and were unbleached. Two samples were bleached and two samples did not declare fibre recycled information in the label. Four samples were printed on the outer surface, one from Denmark was fully printed in black, one from Slovenia in green, one from Portugal in white and one from France in purple and white. Microscopic views of the food contact side are presented in Fig. 2. The general view of the samples is presented in the supplementary information (S1).

Visual observations already suggested a wide variability of type of paperboard packaging across the sampling locations. PT1 was discoloured, confirming bleaching on the contact side. However, a few dark spots were observed, suggesting contamination from printing of the outer side, as sample was fully printed, as previously suggested in the literature (Wagner, 2012). Additionally, microscopic image on the fibre-level presented coating agglomeration as shown in the Supplementary Information (Figure S2 i).

Similar discolouration was observed on the contact side of PT2, although in this case, almost no dark spots were seen. Sample PT3 was homogeneous, and the contact side had fewer dark spots compared to the other samples. PT4 and PT5, on the other hand, had several darker and smaller spots. As these packages were not visibly printed, the spots are probably due to the incorporation of recycled fibre (CEPI, 2020). PT4 has a darker fibre colouration as compared to PT5, which corresponds to the incorporation of a higher proportion of recycled fibre. FR1, FR2, FR3, FR4 and FR5 samples were alike, all containing several colour

Table 1
Origin and physical characteristics of the selected samples.

Sample Label	Origin	Outer surface	Thickness (mm)	Grammage ($mgcm^{-2}$)	Food contact surface	Fibres	Characteristic feature
DN1	Denmark	Unbleached; Open from one side, wrapped in plastic	0.83 ± 0.57	32.0 ± 0.3	Unbleached	Recycled	Recycled
DN2	Denmark	Unbleached; Open from one side, wrapped in plastic	0.61 ± 0.06	37.4 ± 0.3	Unbleached	Mixture	MIX
DN3	Denmark	Black printed surface	0.70 ± 0.13	45.6 ± 0.4	Unbleached	Not labelled	Black printed
FR1	France	Unbleached; vents for atmosphere	1.61 ± 0.06	34.9 ± 2.4	Unbleached	Recycled	Recycled
FR2	France	Unbleached; Open from one side, wrapped in plastic	1.47 ± 0.01	27.6 ± 1.4	Unbleached	Recycled	Recycled
FR3	France	Unbleached; packed with paper from all sides	1.52 ± 0.04	34.6 ± 2.9	Unbleached	Recycled	Recycled
FR4	France	Unbleached; Open from one side, wrapped in plastic	0.91 ± 0.03	37.6 ± 1.5	Unbleached	Recycled	Recycled
FR5	France	Unbleached; Open from one side, wrapped in plastic	1.39 ± 0.01	25.4 ± 3.6	Unbleached	Recycled	Recycled
FR6	France	Unbleached and purple ink; packed from all sides	1.54 ± 0.04	35.2 ± 0.4	Unbleached	Not labelled	Printed
PT1	Portugal	Printed (cups)	0.42 ± 0.02	27.8 ± 1.8	Bleached	Mixture	Bleached
PT2	Portugal	Printed, unbleached (cups)	0.44 ± 0.04	27.7 ± 0.4	Bleached	Mixture	Bleached
PT3	Portugal	Printed with white ink on the outside	0.57 ± 0.01	33.8 ± 0.6	Unbleached	Mixture	Printed
PT4	Portugal	Unbleached with recycled stamp	1.80 ± 0.09	37.1 ± 2.8	Unbleached	Recycled	Recycled
PT5	Portugal	Unbleached; Open from one side, wrapped in plastic	1.56 ± 0.03	32.6 ± 0.7	Unbleached	Mixture	MIX
PT6	Portugal	Printed in patterns, mostly brown (cups)	0.49 ± 0.01	33.0 ± 0.4	Unbleached and glossy	Mixture	MIX
SL1	Slovenia	Entirely printed with green ink	0.70 ± 0.01	51.4 ± 0.9	Unbleached	Recycled	Printed
SL2	Slovenia	Unbleached; Open from one side, wrapped in plastic	1.53 ± 0.03	31.3 ± 2.3	Unbleached	Recycled	Recycled
SL3	Slovenia	Unbleached; Open from one side, wrapped in plastic	1.75 ± 0.04	38.2 ± 0.4	Unbleached	Recycled	Recycled
Average ± StDev	-	-	1.10 ± 0.49	34.6 ± 6.2	-	-	-

spots and having a profile similar to PT4, DN1, SL2 and SL3 (all listed as containing recycled fibres). DN2 containing mixed fibres showed no dark spots but a slight lighter coloration than other samples. FR6 is a heavily printed package though the pigmentation did not severely migrate on the contact side. Samples PT6 and DN3 could not be observed by microscopy due to, respectively, sample shortage and surface black colour. SL1 sample showed a variety of impurities, most of them were lighter colour and formed agglomerates. This sample was printed with different colours and various pigments could be the reason behind these coloured impurities.

3.2. Infrared spectroscopy

The infrared spectra collected for the various paperboard samples are presented in Fig. 3a. The spectra were grouped according to their general profile, allowing easier comparison. The principal component analysis (PCA) plot presented in Fig. 3b confirmed the clustering of the samples. The four groups were group 1: PT1 and PT2 with bleached fibres, group 2: FR1-FR5, PT4-PT6 with recycled or mixed fibres (recycled and virgin), group 3: DN1, DN2, PT3 and SL1-SL3 with both recycled and mixed fibres including printed boards, group 4: DN3 with black printed surface.

3.2.1. Effect of sizing and surface treatment

Group 1 (PT1 and PT2) showed an intense band attributed to C-H stretching at 2916 and 2850 cm^{-1} indicating the presence of alkyl groups. These C-H stretching band were the most intense in the case of group 1, followed by group 3 and majority of group 2. This can result from the introduction of alkyl group due to printing process, such as for PT1 and PT2 samples (both printed), as mentioned in literature (Fengler & Gruber, 2022; Queen's University, 2024). Hydrophobic treatment like AKD can introduce additional aliphatic chains, enhancing these C–H stretching bands. However, in the GC-MS analysis AKD were not detected. Therefore, these samples should have other surface treatment and in fact a coating agglomerate was observed in PT1 using microscopy (Figure S2i).

Group 3 showed prominent band at 1500 cm^{-1} region, attributed to C═C stretching denoting the presence of alkenes (Pavia et al., 2001). Notably, sample SL1 (which was printed) had the highest peak intensity. This was clearly noted during GC-MS analysis of SL1 (Section 3.5) which identified the presence of DiPN isomers. Sample SL1 also showed another characteristic band for 2,6-diisopropylnaphthalene at 869 cm^{-1} further establishing this relation (Franke et al., 2007). DiPN isomers contain aromatic alkenes, which are typical and are found in printing ink and in recycled paperboards (Poças et al., 2011; Zhang et al., 2008).

3.2.2. Effect of bleaching

Bleaching process was responsible for the presence of more intense peak at 1700 cm^{-1} observed due to the C═O stretching vibration (PT1 and PT2 samples). It has been reported that bleaching processes, for example using ozone, could increase carbonyl groups (Perrin et al., 2014). Carbonyl groups can also be associated with sites for cationic retention additives (Barbosa et al., 2013). These additives are employed to better retain fines and fillers during paper sheet formation. Group 1 also did not show an intense band in the spectral region between 3700 and 3100 cm^{-1}. This band, attributed to the O-H stretching (hydroxyl group) originates from the presence of carbohydrates, due to the vibration caused by hydrogen bonding in cellulose, hemicellulose and lignin, the major biomass present in paper (Zhuang et al., 2020; Morán et al., 2007). As bleaching process reduces residual lignin, the two bleached surfaces showed the characteristic behaviour (Bajpai, 2021). Similarly, a quite low band at the 1010 cm^{-1}, indicating C-O stretching and O-H deformation, was observed. This band is characteristic of the presence of major biomass and hindered by bleaching. This peak is dominant for group 2 and 3, which were not bleached. Group 1 samples showed the highest water contact angles and low moisture sorption (see Section 3.3) in line with these FTIR findings.

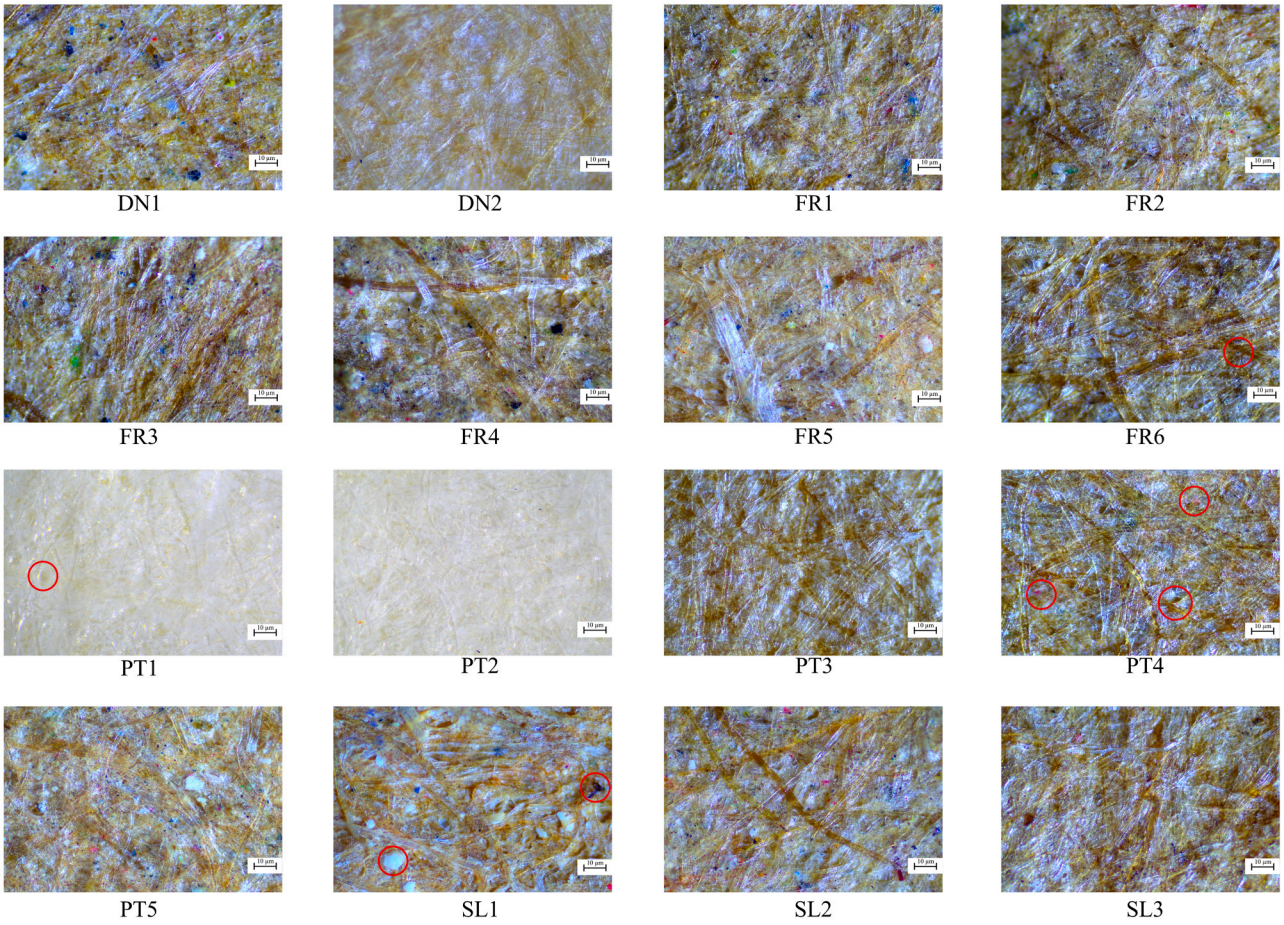

Fig. 2. Microscopic images of the samples (DN3 and PT6 are not included).

3.2.3. *Effect of recycled fibres*

Groups 2 and 3 showed similar spectra profiles, with differences attributable to different percentages of recycled fibres used. Group 3 containing printed, recycled and mixed fibres showed more intense bands as compared to group 2, with the exception of PT6, which was slightly printed. Higher water interaction for samples in these groups due to the presence of more recycled fibres, *i.e.*, more accessible hydroxyl groups is expected. This was reflected in the more intense band around 3000 cm^{-1} for group 3 as compared to group 2. All the samples in the group 2 showed a low sorption gain (see below, Section 3.3) except for PT4 and PT5, suggesting the presence of internal sizing. Both group 2 and group 3 presented intense bands at the 1000 cm^{-1} region.

Overall, the FTIR PCA results show an alignment of spectra by country for France and Slovenia, possibly due to the type of pulp used, typical formulations or processing techniques e.g., sizing, coatings. Samples from Portugal had varying spectra that clustered them into 3 different groups, respectively together with French samples, or Slovenia and Denmark, or constituting a separated Group (PT1 and PT2). The bands that most contribute to the variance along PC1 (89 %), were the wavenumbers 2916 cm^{-1} and 2850 cm^{-1} (C-H stretching) highlighting the role of chemical treatments and biomass in clustering (Fig. 3c). Scores on PC2, on the other than, only explained 6.0 % of the total variance, but still were relevant for the samples clustering. The variance was due to the regions at 3500 cm^{-1} and 1000 cm^{-1} bands, relating with biomass differences.

3.3. *Material interaction with water*

3.3.1. *Water contact-angle measurements*

Water contact angle (WCA) measurements were conducted to evaluate the surface wettability and hydrophobicity of the samples. Typically, during contact angle measurements, the drop spreads to a certain degree after which the contact angle remains approximately constant as the water is absorbed into the sheet. To highlight the different sample behaviour, the contact angles are reported for different times of contact (10, 100, 200 and 300 s) and the data are plotted in Fig. 4. Additional data are presented in the Supplementary Information (S3).

The contact angle measurements at 10 s are of relevance to understand the initial wettability of the samples (Krainer & Hirn, 2021). Among the samples, DN1, PT4 and FR1 exhibited remarkably low WCAs indicating strong hydrophilic behaviour.

WCA measurements overtime are important to evaluate the moisture absorption of porous materials (Krainer & Hirn, 2021). Samples DN1, FR1–3,5, PT4 and SL2 were classified as hydrophilic samples, and all contained recycled fibres (Fig. 4). This agrees with the fact that recycled fibres have reduced hydrophobicity due to mechanical and chemical stress caused during the recycling process, increase porosity and fibrillation (Liukkonen, 1997).

In contrast, samples DN2–3, FR4 and FR6, PT1–3, PT5–6 and SL1 and SL3 ranging from bleached fibres, printed outer surface, mixed or recycled fibres were more hydrophobic. The initial contact angle was in the range of 80.4° to 95.9° and decreased only to the range of 74.2° - 93.8° over the testing time. This could be directly linked to several sizing agents or additives that can help repelling moisture from the surface, for example, presence of fatty acid esters, long-chain alcohols, plasticizers, hydrophobic ketones and silicon-based compounds as detected by GC-MS. This has been previously mentioned, as wetting of paper can relate to various components (Liukkonen, 1997). Therefore, the variety of treatments are expected to have a significant impact on their

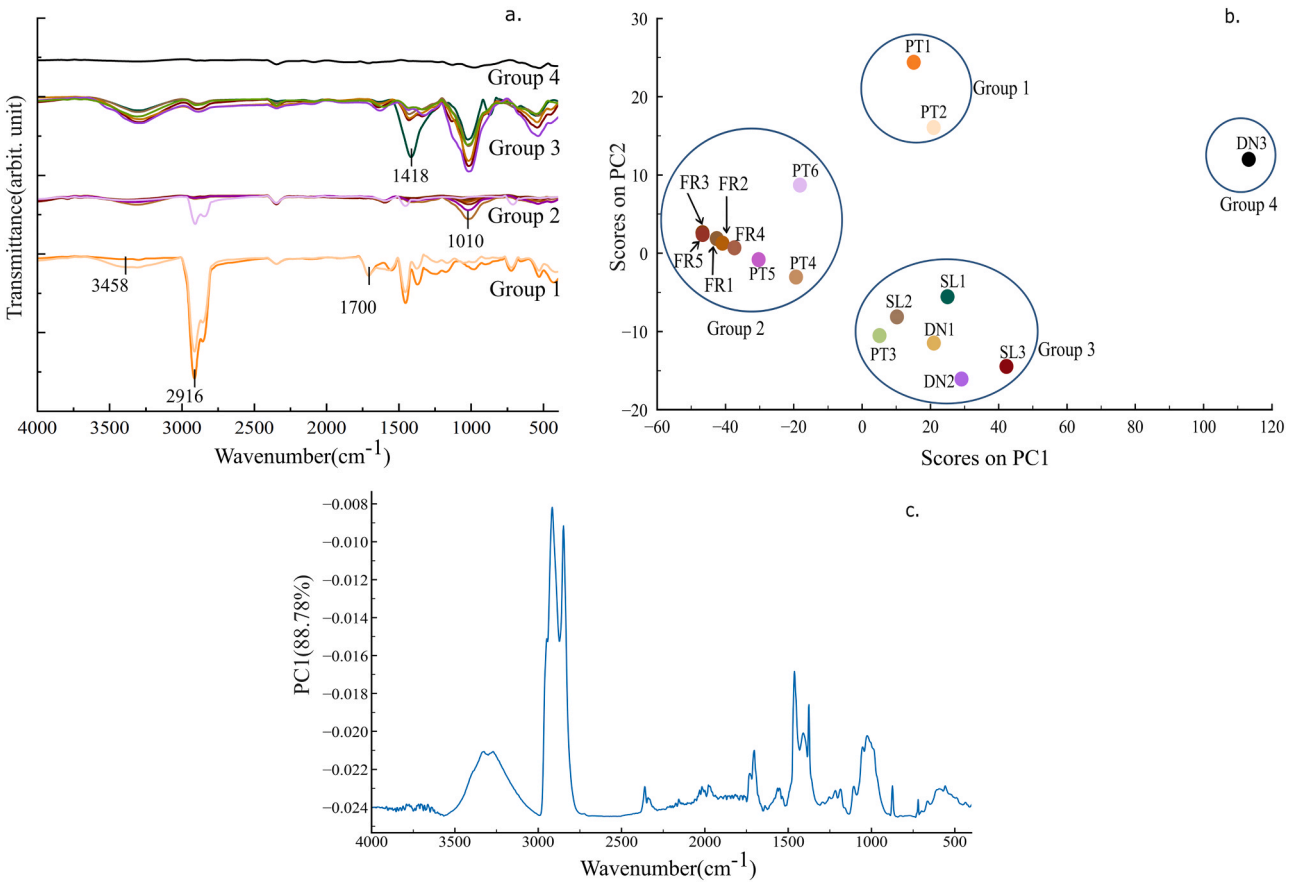

Fig. 3. a - Infrared spectra, b - PCA plot and c - loadings on PC1. Group 1: PT1( ), PT2( ); Group 2: FR1( ), FR2( ), FR3( ), FR4( ), FR5( ), PT4( ), PT5 ( ), PT6( ); Group 3: SL1( ), SL2( ), SL3( ), DN1( ), DN2( ), PT3( ) and Group 4: DN3( ). FR6 and DN3 are not included.

performances (Mathew et al., 2018).

3.3.2. *Dynamic water sorption behaviour*

Sorption analysis and moisture uptake measurements are of particular interest to understand bulk properties at different humidity conditions. Fig. 5 presents the moisture sorption isotherm of the samples carried out at 23 °C. As expected, the moisture content increases with water activity in an exponential curve typical for sorption isotherms (Parker et al., 2006). Results indicate that the samples are distinguished at the higher water activities (> 0.75), while in the middle and lower ranges of water activity the differences between samples are less pronounced. The moisture content increases across the different recycled fibres (brown) and mix fibres (purple), showing the difference in the recycled content.

The samples that are printed (green), showed one of the lowest moisture uptakes along the increase of water activity. This could be due to the presence of printing inks or coatings that acts as a surface barrier as seen with the contact angle measurements. The black surface of DN3 showed an intermediate moisture uptake, which showcases that while the unique black printing can reduce hydrophilicity, it is not as effective as other processes.

Bleached surfaces (orange) showed one of the least moisture uptakes, which showed both bulk hydrophobicity by infrared analysis and surface hydrophobicity by contact angle measurements.

The GAB model fits very well with the experimental data of each sample (results presented in the Supplementary Information – S4). The X_m values recorded were between 4.0 and 6.7, except for sample FR4, values in line with previously reported in the literature (Parker et al., 2006).

The relationship between the moisture uptake (bulk properties) and the surface of the sample (water contact angle) is depicted in Fig. 6.

Four main behaviours can be identified, corresponding to (1) high moisture adsorption and low contact angle, (2) low moisture adsorption and low contact angle, (3) high moisture adsorption and high contact angle, and (4) low moisture sorption and high contact angle.

All packages with only recycled fibres (brown) except for FR4 and SL3, presented properties in the low contact angle range (lower than 50°), showing, however, a wide range of bulk moisture uptake. These characteristics suggest internal sizing and not surface treatment particularly, as the bulk moisture barrier was more effective than the surface barrier. It is important to note that this group of samples showed the presence, as detected by GC-MS (see below, Section 3.5) of several additives such as glycerol-based and fatty acid-based, which improve bulk properties or surface properties depending on the process of application. The GC-MS results also showed the presence of styrene, a common component in surface sizing agents, in the case of both FR4 and SL3, which showed higher WCA. FR4 and FR5 have quite high moisture gain despite very similar composition as compared to the other French recycled packages. This could be due to any additional mechanical treatments such as beating and refining during paper production (Lindner, 2018). Samples PT4, SL2 and FR5 instead, may have a higher degree of recycled fibres and low functional additives, conducing to relative high values of moisture sorption (Fig. 6).

The third group of samples was a mix containing recycled boards, boards containing mix fibres and printed boards (top right side of Fig. 6). This group did not show any similarity based on the GC-MS results except for natural or cellulose degradation compounds. However, presence of styrene which is used as a surface sizing (detailed in 3.5) was

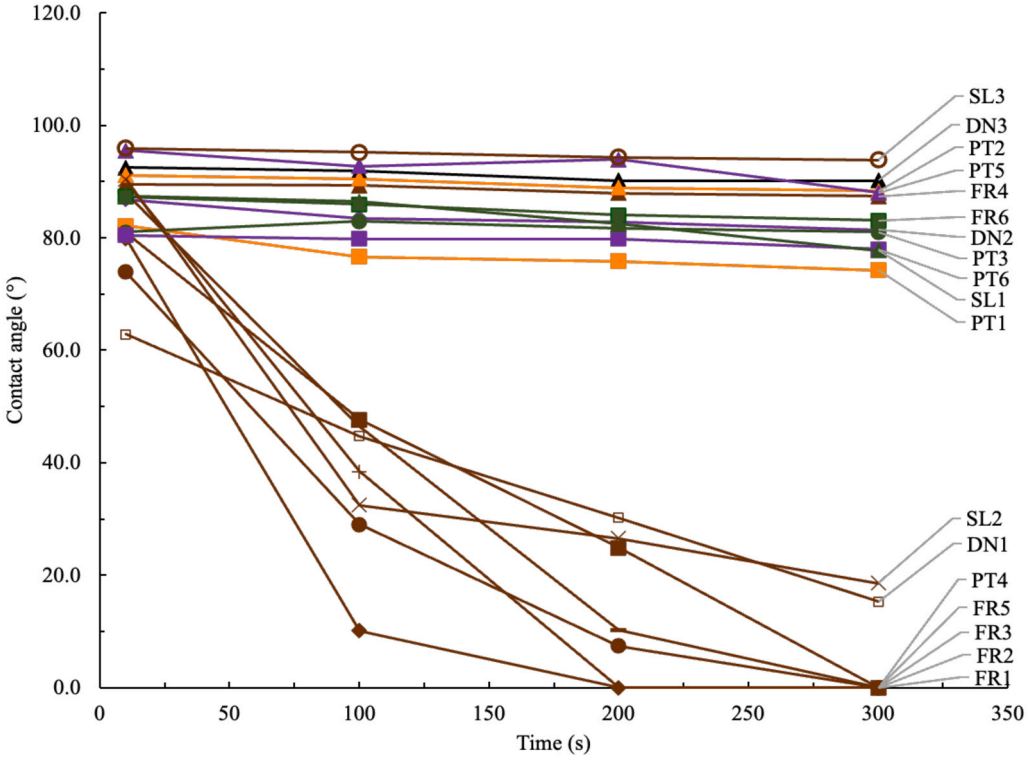

Fig. 4. Water contact angles over time. DN1(□), DN2 (◆), DN3(▲), FR1(●), FR2(-), FR3(+), FR4(▲), FR5(■), FR6(■), PT1(■), PT2(▲), PT3(●), PT4(◆), PT5(▲), PT6(■), SL1(▲), SL2(x), SL3(○).

noted in sample DN2. The possibility of having a higher contact angle is also related to the surface roughness or type of fibre and not exclusively due to the additive application (Rejeb et al., 2021). Although, surface roughness was not measured in the current work, the differences can be noted by the microscopic images presented earlier.

The fourth group (bottom right side of Fig. 6) of paperboard samples showed better bulk and surface hydrophobicity (low moisture absorption and high contact). PT1 and PT2 were already concluded to have lowest moisture influence by infrared analysis and it is potentially related to their bleaching process. PT6 was also seen to have good barrier but it was not bleached. It is important to note that PT1, PT2 and PT6 sample were all cups and not trays like the other samples. All these 3 samples have FTIR 2916 cm^{-1} bands indicating chemical similarity. They contained more hardwood fibres as compared to the other samples as observed in the microscopic analysis (Supplementary Information S2). The 3 samples were printed and additionally, the content in virgin fibre was probably higher than those samples with mix fibre. The samples SL1 and SL3 showed presence of styrene suggesting surface hydrophobicity and several additives that could contribute to its good functional properties.

It is recognised that many factors contribute to the behaviour of the paperboard and its interaction with water and moisture. These include the fibre characteristics, pulp physic-mechanical treatments, bulk composition and final surface treatments. Beating and refining affect fibre fibrillation and crystallinity. The density and porosity of the fibre matrix are affected by calendering and pressing treatments. Pulp bulk composition in natural cellulose components, and specially in hydrophobic additives is critical to the resistance of the material under humid conditions. Surface chemical nature and structure determine the access of water and moisture to the fibres and are controlled through coating and printing. The final performance is a result of these different factors, making the overall assessment complex.

It should be noted that in most of the samples studied, the trays are additionally protected with a perforated plastic bag. Only samples PT1, 2 and 6, FR 1,3 and 6 have designs avoiding the plastic bag (Figure S1). These samples all showed high WCA and/or low moisture absorption and are produced with bleached fibre (PT1 and PT 2).

3.4. Repulpability

The packaging waste Regulation No 2025/40 (EU, 2025b) sets targets for the recycling of paper-based packaging: 75 % by 2025 and 85 % by 2030. Recyclability of the material is largely affected by the fibre characteristics (length and strength), material structure (coatings and layered structures) and content in additives, fillers, binding agents, etc. These can prevent recycling, reduce the yield and/or lower the pulp quality. In this work, the selection of samples considered only packages without plastic liners. However, some additives aiming to increase hydrophobicity negatively affect recyclability, depending on their chemical nature and how they are applied in bulk or surface sizing. Therefore, the samples were analysed for repulpability to complement the physic and chemical characterization made.

According to the CEPI guideline, a material to be recyclable must show fibres to disintegrate efficiently without forming agglomerates or retaining adhesives that can cause poor separation. Neither the guidelines nor any legislation indicate criteria for the repulpability parameters. Coarse and fines are to two main fractions of fibrous material after pulping and screening and they are related to fibre quality, recyclability, and paper strength. The protocol recommends that the coarse fraction should freely pass through a sieve of 5 mm and the fines fraction through a 150 μm pore size plate. All fibres obtained during the repulping testing were tested for length and width to check their suitability to be filtered through two sieves. All samples had fibre length Lc(w) and fibre width (μm) below the coarse and fine sieve openings (Table 2) and showed no

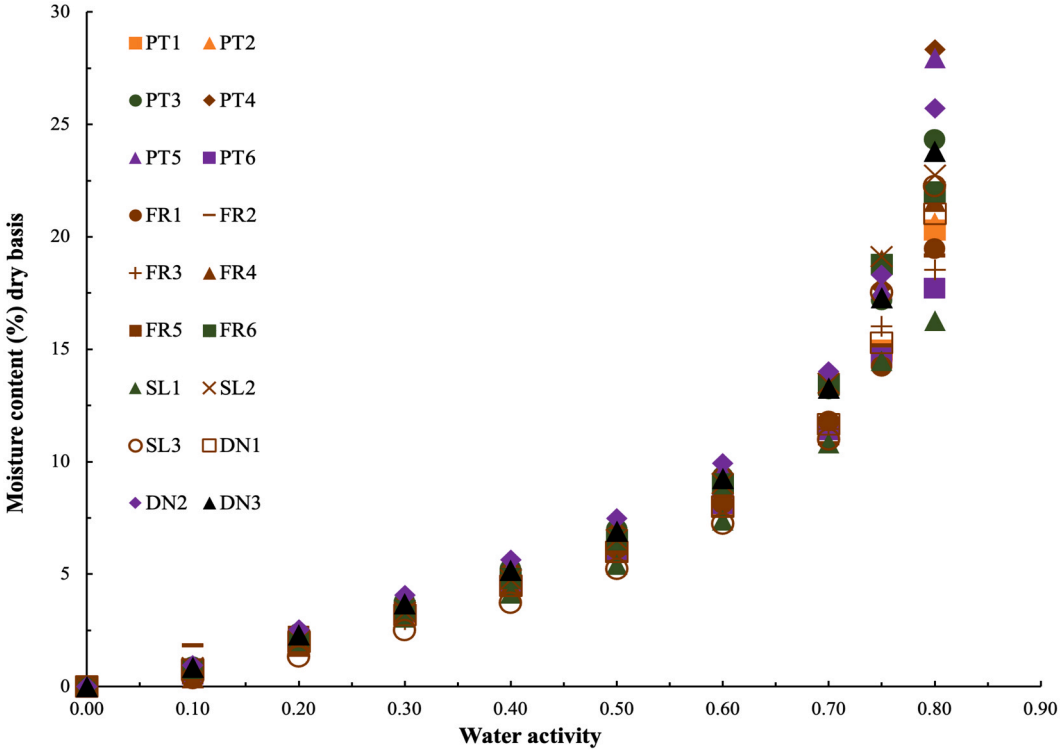

Fig. 5. Moisture sorption isotherms. DN1(□), DN2 (◆), DN3(▲), FR1(●), FR2(-), FR3(+), FR4(▲), FR5(■), FR6(■), PT1(■), PT2(▲), PT3(●), PT4(◆), PT5(▲), PT6(■), SL1(▲), SL2(x), SL3(○).

visible retention on either of the two sieves, therefore successfully met the CEPI criteria. No retention of dissolved fibres in the sieves will result in high fibre yield at the end of the recycling process.

The maximum width was observed for PT6 sample with the value of 36.58 μm. Samples PT1 and PT2 showed shortest fibre length, 1.12 and 1.14 mm, respectively, while the other samples had lengths above 1.50 mm. Along with this, PT1 and PT2 also had thinnest fibre width of 17.95 and 18.41 μm, respectively. Microscopic view of the fibres (See Supplementary Information - Figure S2 ii) showed a higher quantity of birch (PT1) and eucalyptus (PT2) – hardwood fibres for these samples. This result is coherent with the length and width fibre values (Simões et al., 2023). Sample DN2 showed fibre length of 2.05 mm and width of 29.30 μm. These values, among the highest, were consistent with softwood fibres which was confirmed by microscopy (Figure S2 iii).

Fines content (Table 2) influence the dewatering process because of higher surface area-to-volume ratio and water bounding. This water is harder to remove from the matrix than free water between longer fibres, resulting in slower drainage during papermaking. On the other hand, fines content can yield an increase in paper strength due to better bonding of long cellulose fibres and lower matrix porosity. Most of the samples had a fines range of 70–85 %. Two samples PT1 and PT2 had the lowest values (lower than 60 %) together with shortest fibre lengths of respectively 1.12 and 1.14 mm.

Higher content of recycled fibre can be related to higher fine content, indicating low subsequent recyclability. For example, sample DN2, has softwood fibres but showcases higher fines content which could negatively impact its recyclability. Sample SL1 shows not only high percentage of fines but also includes impurities (Fig. 2 and Figure S2 iv). The combination of low fines content and long fibre fraction (e.g. PT6) is expected to allow a reduced purification effort and a lower chemical demand in the subsequent processes of dissolving pulp, therefore can be considered with higher recyclability (Hempfer & Bauer, 2024). Similarly, a pulp with a combination of low fines content and high fibrillation which is related to bonding potential is likely to be more recyclable (e.g. DN3 and SL1). In general, low fines fraction in the recovering process improves the recycling process efficiency and the pulp quality (Hempfer & Bauer, 2024).

The samples showed remarkable difference in the pulp colour on repulping test according to the fibre category. It was evident that the recycled fibres showed the darkest colour, and bleached fibres were the opposite, with no colouration, as expected. De-inking was recommended for samples SL1, DN2, DN3, FR6, PT1–3, and PT6 in line with the samples that were printed.

3.5. *Identification of volatiles and semi-volatiles by GC-MS*

3.5.1. *Overall sample analysis*

An overall analysis was conducted with focus on potential toxic compounds. A total 128 chemicals were detected with relevant intensity across all the samples. The full list of these compounds is presented in the Supplementary Information (S5). The substances tentatively identified were classified according to chemical category (function chemical group) and according to the origin or potential reason for being present in the paperboard. Compounds naturally occurring and from degradation of cellulose and lignin were detected, as well as additives, sizing agents and substances derived from printings inks. The substances were semi-quantified and were classified according to their Cramer Class of toxicity. A graphical representation of this analysis is presented in Fig. 7 and showcases the groups of chemicals with respect to their Cramer class of toxicity.

Table 3 presents the number of compounds detected per type and toxicity class. The count column in the table indicates the total number (the same compound or compounds of the same family according to the probable use).

Fig. 7 shows that simpler and linear structures that are, aliphatic compounds, formed the great majority of the toxicity class I substances.

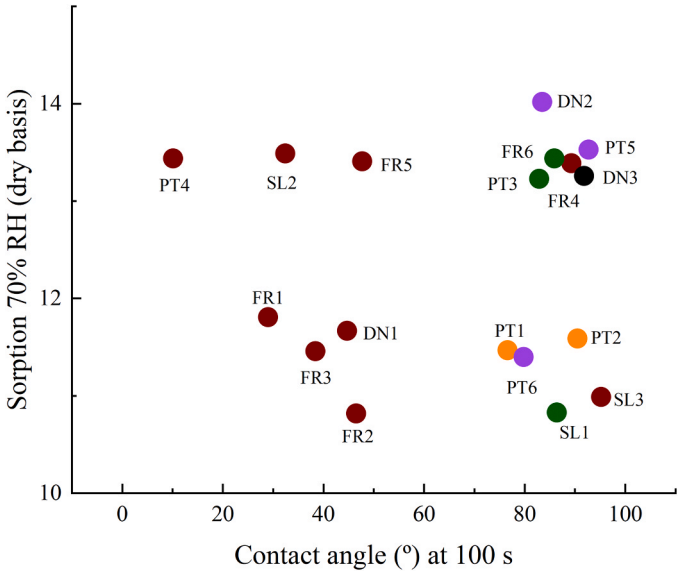

Fig. 6. Relation between moisture sorption and water contact angle. Recycled (), mix fibres (), black printed (), bleached () and printed ().

Table 2
Parameters of repulpability test according to CEPI guidelines.

Sample Labels	Lc(w) (mm)	Fibre width (μm)	Fines (%)	Fibrillation (%)
DN1	1.65	20.93	84.64	1.86
DN2	2.05	29.30	87.06	1.91
DN3	2.29	32.87	81.68	1.97
FR1	1.69	21.02	79.72	1.72
FR3	1.62	20.30	78.56	1.67
FR4	1.73	22.01	78.05	1.73
FR5	1.57	20.90	76.92	1.62
FR6	1.86	20.81	68.40	1.38
PT1	1.12	17.95	57.76	1.42
PT2	1.14	18.41	57.10	1.43
PT3	2.16	27.89	83.35	1.81
PT4	1.54	20.12	81.21	1.69
PT5	1.56	19.76	79.85	1.70
PT6	2.88	36.58	77.15	1.44
SL1	1.66	24.45	80.06	1.90
SL2	1.60	20.24	77.63	1.65
SL3	1.68	20.95	80.83	1.72
Average ± StDev	1.75 ± 0.42	23.21 ± 5.30	77.06 ± 8.38	1.68 ± 0.18

Most of these substances are due to the natural degradation of cellulose or degradation of additives, coatings or treatments (Table 3), such as hexanal, nonanal and decanal. These decomposition organic compounds were already reported in food contact materials including paper and boards (Castle et al., 1997; Vera et al., 2020). Some complex structures such as aromatic aldehyde and terpene were also observed such as α-Pinene, β-Pinene, L-Limonene which are pulp natural components or released from degradation (Bengtström, 2014). Styrene that could be due to the application of styrene-based surface sizing was detected in DN1, DN2, FR2, PT4, SL1–3 samples.

The toxicity class II compounds found were all aliphatic ketones, due to either a natural cellulose compound or related to the presence of printing ink compounds or sizing agent. Sizing agents were particularly abundant in the French samples.

Amongst the class III chemicals, there was a high dominance of heterocyclic or aromatic compounds. Based on the Table 4, these compounds consisted of residues from photoinitiators, plasticizers, bisphenol A precursors degradation, non-intentionally added substances (NIAS) and mostly printing inks components – all linking towards recycled fibres. 2-Isobutylthiazole, which is a biocide, was detected in only one sample. This is not considered endocrine disruptor (ECHA et al., 2018). Another important printing ink component detected was mineral oil hydrocarbons in one of the samples. Fig. 8 compares the relative abundance of components detected in the samples with their condition regarding being printed or coloured and the type of fibre (recycled or mix).

3.5.2. Specific compounds determination

In this section, specific compounds detected at highest concentrations are discussed based on relevance for moisture resistance and food safety. Data can be found in supplementary information (S5).

DINCH (1,2-Cyclohexane dicarboxylic acid diisononyl ester) a non-phthalate plasticiser was detected in sample SL1 only, at a very high level (490 mg kg^{-1}). As this sample was printed, the origin of the plasticiser must be the ink components. DINCH is commonly used as a "safer" alternative to phthalate plasticizers in food contact applications. DINCH is not regulated for paper-based materials, but the plastic Regulation No 10/2011 (EU, 2025a) sets a migration limit of 60 mg kg^{-1} (sum of isomers), highlighting the far exceeded estimated value in SL1.

Trans-13-Octadecenoic acid, a trans-fatty acid, can possibly have been incorporated into a sizing emulsion or in a coating. It was detected at 870 mg kg^{-1} in sample SL2. In plastics, fatty acids are often stabilizers or slip agents, with the range of migration limit between 20 and 50 mg kg^{-1}.

Different alkyl ketones were also detected, but the most prominent were 16-Hentriacontanone and Tritriacontan-16-one detected in sample FR1, at levels respectively of 110 and 140 mg kg^{-1}. These dialkyl ketones are product of hydrolysis of commonly used surface and more recently as internal sizing agent's alkyl ketone dimers (Lestido-Cardama et al., 2020). Alkyl ketones were detected mainly in French samples (average concentration of 50 mg kg^{-1}) and in PT4 at 12 mg kg^{-1}. As stated earlier, BfR has established a migration limit of 5 mg kg^{-1} for DAK transfer into food which is largely exceeded in the samples. Therefore, migration studies into food are relevant to understand the overestimation of organic simulants.

Bis(2-ethylhexyl) maleate was detected at 110 mg kg^{-1} in sample PT3, and in 6/18 samples at lower levels. This compound finds application in papermaking as a plasticizer and a hydrophobic agent when incorporated as a sizing agent. As this sample was printed, it should have been added as ink component.

Besides the plasticizers already referred detected at high levels, other substances with plasticizing effect were also detected at medium levels: Bis(2-ethylhexyl) phthalate, Bis(2-ethylhexyl) fumarate, Phthalic acid, butyl octyl ester, Bis(2-ethylhexyl) terephthalate, Di-2-ethylhexyl isophthalate, at average level of 17 mg kg^{-1}. Di-isobutyl phthalate was detected at much lower level. Plasticizers, like phthalates, structurally similar substances and replacement substances, are presently being re-evaluated by EFSA (Calvano et al., 2023). Therefore, occurrence data of plasticizers in FCMs is of interest.

DIPN (Diisopropylnaphthalenes) is typically found in recycled fibres (Nerín et al., 2007; Poças et al., 2011) and it was detected in 12/18 samples at levels not exceeding 1 mg kg^{-1}. Substances related to replacers of bisphenol-A as sensitisers in thermal inks, like Diphenyl sulfone (from degradation of bisphenol S) and Benzyl 2-naphthyl ether, were detected in some of the French samples at levels from 3 to 7 mg kg^{-1}

Styrene was detected in 7/18 samples at levels not exceeding 0.3 mg kg^{-1} and is related with the styrene-containing additives (Li et al., 2022; Stroganov et al., 2021). After styrene was classified as probably carcinogenic to humans by the International Agency for Research on Cancer (IARC), the European Commission asked the EFSA to re-evaluate its safety for use in plastic food contact materials (EFSA

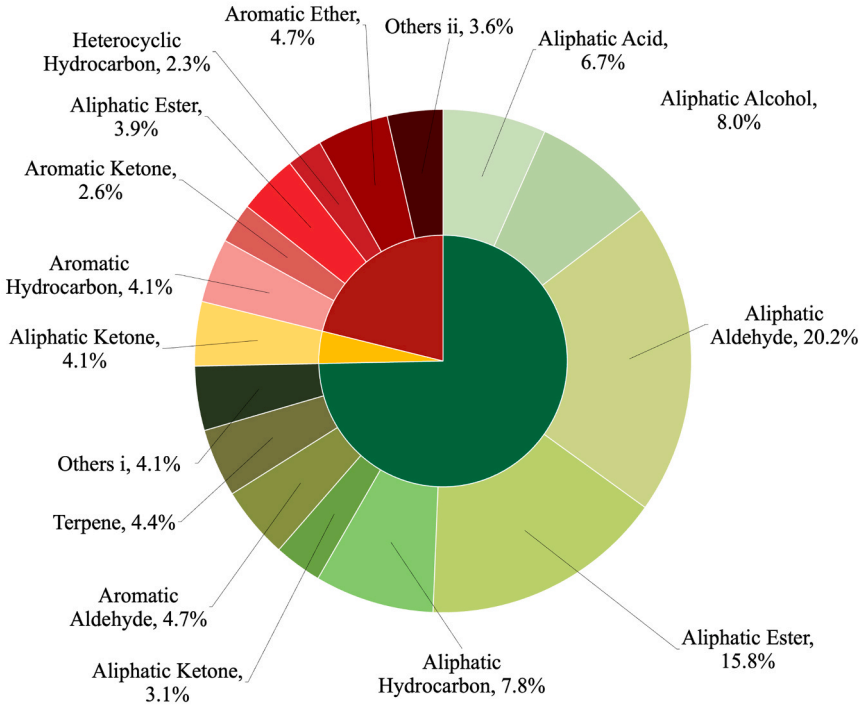

Fig. 7. Overall GC-MS findings according to chemical classes and corresponding toxicity. Toxicity Cramer class I: green tones, class II: yellow tones and class III: red tones. Other i: aromatic ether, aromatic hydrocarbon, aromatic ketone, aliphatic ether, aliphatic amine. Other ii: aliphatic alcohol, aliphatic amine, aliphatic ether, aliphatic sulphide, aromatic amine, terpene alcohol).

Table 3
Relative abundance of substances based on their technological function (as detected by GC-MS).

Toxicity class	Probable function	Count	Abundance (%)
I	Additive	82	**21.24**
	Cellulose degradation	90	**23.32**
	Natural compound	44	**11.40**
	NIAS	14	3.63
	Photoinitiator	3	0.78
	Plasticizer	33	**8.55**
	Styrene-based	7	1.81
	Residual solvent	9	2.33
	Coating aid	6	1.55
II	Cellulose degradation	4	1.04
	Sizing	11	2.85
	Residual solvent	1	0.26
III	Additive	5	1.30
	Cellulose degradation	9	2.33
	Lignin degradation	1	0.26
	Natural compound	19	**4.92**
	NIAS	3	0.78
	Photoinitiator	2	0.52
	Pigments	3	0.78
	Plasticizer	12	3.11
	Printing inks	12	3.11
	Residual solvent	9	2.33
	Biocide	1	0.26
	BPA replacer	6	1.55

Panel on Food Contact Materials et al., 2020).

Benzaldehyde was detected in 13/18 samples. It is classified as a NIAS and was detected at the maximum level of 0.43 mg kg^{-1}. Benzaldehyde was previously reported in paper and board (Koster et al., 2014). In 2019, a study on recycling behaviour of polystyrene highlighted benzaldehyde as a degradation product of styrene (Song et al., 2019).

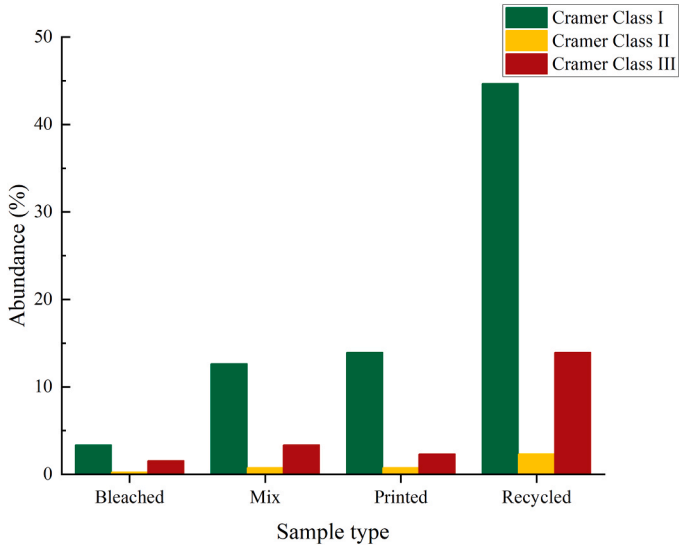

Fig. 8. Sample type and toxicity. Toxicity Cramer class I (●), class II (●) and class III (●).

The compound 6-Methyl-5-heptene-2-one was detected in 10 samples and is a cellulose degradation compound. This compound is also mentioned in the literature as a volatile component produced by lycopene degradation in tomatoes (Stingone et al., 2017). This could also be a potential source as these packages were packed with tomatoes prior to testing. An analysis was also performed to verify if any substance from the packages could be found in the tomato skin.

The tomato was washed with ethanol 50 % solutions. The GC-MS of

this solution showed no related migration. This finding showcases the minimal risk of chemical transfer to tomatoes under the conditions tested.

4. Conclusion

The study was focused on paperboard packaging used to pack fresh cherry tomatoes, a product widely consumed and available in both low-cost and high-cost supermarkets. Based on the limited sample collection, from only four EU countries, it was concluded that there is a significant variation of paperboard FCMs in the market. Packaging requirements, such as moisture resistance, ventilation, and surface protection need to be assured by the overall packaging system. It should be noted that in most of the samples studied the trays are additionally protected with a perforated plastic bag. However, this work focused only on the cellulose component.

A thorough physical and chemical analysis was conducted highlighting the differences in the performance regarding moisture resistance and in terms of fibre origin, composition, treatments (bleaching), hydrophobing agents (surface or bulk agents) and incorporation of high content of recycled fibres. As a result, different substances were detected that affect potential migration and chemical safety. A number of chemicals of concern with Class III toxicity such as mineral oil hydrocarbon, biocide, DiPN isomers and BPA replacers were observed. Additionally, high concentrations were recorded for several compounds, highlighting the significance of this inter-European study.

Most of the different production features such as the incorporation of high content of recycled fibres, use of specific type of surface sizing and plasticizers, aligned within the group of samples from the same country in some cases, indicating regional consistency in packaging practices and material formulations.

Incorporation of recycled fibre in cellulosic packages for tomato is widely adopted. This has a major effect on material interaction with water and moisture, on chemical characteristics and safety. Packaging samples showing low moisture sorption are the preferred for designs that avoid the plastic bag, by using bleached fibre, printing or showing specific geometric features for closing. In other cases, less moisture resistat paperboard is used, but the system includes a plastic overwrap.

All samples showed repulpability, although with noted differences in deinking steps and extent of recycling. Differences in repulpability may led to production of low-grade fibres compromising product recycling after use. Despite the holistic analytical scheme followed, this study could benefit of a detailed end-of-life assessment which was beyond the scope of the current paper.

The physical and chemical analysis was conducted using different complementing analytical techniques. This multidisciplinary approach to characterise the samples in relation to performance, safety and features driven by legislation is not often applied in the food packaging area. However, it needs to be recognised that the study was limited to a small number of samples per country and only tomato was considered.

CRediT authorship contribution statement

Ece Sögut: Writing – original draft, Data curation, Investigation. **Srishti Singh:** Writing – original draft, Investigation, Data curation, Writing – review & editing, Methodology, Formal analysis. **Karlovits Igor PhD:** Validation, Investigation, Conceptualization, Writing – review & editing, Supervision, Data curation. **Ilke Uysal-Unalan:** Supervision, Funding acquisition, Writing – review & editing, Methodology, Data curation. **Milena Corredig:** Writing – review & editing, Supervision, Conceptualization, Validation, Funding acquisition. **Véronique Coma:** Visualization, Methodology, Conceptualization, Writing – review & editing, Supervision, Data curation. **Fátima Poças:** Validation, Resources, Funding acquisition, Writing – review & editing, Supervision, Methodology, 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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fpsl.2025.101572.

Data availability

Data will be made available on request.

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