

# Composition of the adhesives used in food packaging multilayer materials and migration studies from packaging to food

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A wide variety of adhesives can be used to manufacture multilayer food packaging materials. Since these materials are usually in direct contact with the packed food, compounds from the adhesive may migrate into it. Therefore it is important to determine the composition of the adhesives used. The main aims of this work were to determine the compounds present in the adhesives used in the food packaging, to study their migration to food simulants and finally to use these data to test a mathematical tool designed for predicting migration to food from laminates containing adhesives. For this purpose a total of 45 market samples of multilayer materials (laminates and other glued materials) produced with 29 different adhesives were studied. A total of 55 different compounds were detected in these adhesives, 57% of these compounds migrated into a dry food simulant (Tenax®) through the food contact layer. These data were also used to compare it with the theoretically estimated migration of the adhesive compounds using “upper-bound reference” values for the diffusion and partition coefficients implied in a multilayer migration model. In 93% of the cases the estimated migration results met or exceeded the experimental ones. This is an important requirement for testing the applicability of these theoretical migration estimations for compliance decisions which aim to protect the consumer’s health.

## 1. Introduction

Multilayer materials are commonly used in the packaging industry to obtain specific food packaging properties. They can be structured as the joint of two or more substrates glued by the addition of an adhesive [substrate1–adhesive–substrate 2]. When the adhesives are applied on the full area of the packaging, they are called laminates. If the adhesives are applied on a partial area of the packaging (*e.g.* for forming boxes or pouches) they can be called seams. Different materials can be used as substrates according to the final use of the packaging, such as polyethylene, polypropylene, polyamide, polyesters, cardboard, paper or barrier materials such as aluminium, polyethylene terephthalate or ethylene vinyl alcohol. Many types of adhesives are available for any specific application. Adhesives can be classified according to their intended function, their chemical composition, method of curing, and physical form or their applications.<sup>1</sup> A first classification could be done between natural or synthetic adhesives. Natural adhesives are manufactured from naturally occurring materials such as animal or agricultural products (starch, casein,

animal glue, fish glue, blood glues, natural rubber, *etc.*). Synthetic adhesives include a broad spectrum of adhesives and can be sub-classified according to their method of curing: chemical reaction, cooling from a melt, loss of solvent or loss of water. Examples of adhesives that harden by chemical reaction are polyurethanes and epoxy resins. Hotmelt adhesives harden by cooling from the melt. Adhesives which harden by water or solvent loss can be further classified according to their chemical structure, such as acrylic adhesives or vinylic adhesives. In this case the base polymer of the adhesives is an acrylate or a vinylic polymer respectively. Polyvinyl acetate (PVAc), polyvinyl alcohol (PVOH) and vinyl acetate ethylene (VAE) are all adhesives derived from vinyl monomers ( $-\text{CH}=\text{CH}_2$ ) and have been summarized as vinyl adhesives. PVAc is made by polymerization of vinyl acetate, PVOH is produced by hydrolysis of PVAc and VAE is the copolymer of vinyl acetate and ethylene.

It is very important to identify the compounds present in the adhesives due to their possible risk as potential migrants to the food when the laminates are used as food packaging materials. Although adhesives are used in most of the food packaging materials there is not much information about the likely migration of chemicals involved in adhesives to the food. Adhesives used in the European Union (EU) must fulfill the Framework Regulation (EC) no. 1935/2004<sup>4,2</sup> and the “Plastics Directive” 2002/72/EC<sup>3</sup> when adhesives are applied on plastic materials. The migration of a compound from a food contact material into food depends on the chemical and physical properties of the

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compound and the food as well as on the nature of materials used to manufacture the laminate.<sup>4-6</sup> Using test systems with adhesives applied on laboratory scale, it was shown that migration from laminates into foods can be estimated using appropriate mathematical models.<sup>7,8</sup> In fact, the estimation of migration values is accepted in the EU legislation (Art. 8 of Plastics Directive 2002/72/EC).<sup>3</sup> For monolayer materials migration models are generally accepted as well as the estimation of diffusion coefficients in common plastic materials by the Piringer model.<sup>9-11</sup> However the complex structure of the multilayer materials makes it necessary to develop appropriate mathematical tools that allow the prediction of migration in these systems.

The first aim of this work was to carry out a screening analysis of different adhesive types from market samples in order to obtain a list of the possible migrant compounds that can be found in laminates containing adhesives. In this work, 29 different adhesives were studied, which completed the previous works done in the frame of adhesives screening in test systems where the adhesives were applied in the laboratory.<sup>12-15</sup> The technique selected for this purpose was the solid phase microextraction of the samples headspace coupled to gas chromatography and mass spectrometry detection (HS-SPME-GC-MS). It is a fast technique that provides a high pre-concentration factor of the analytes previous to the GC-MS analysis.<sup>16</sup> Migration experiments carried out with Tenax as dry food simulant were performed in order to evaluate the possible mass transfer of the compounds detected in the adhesives to the packed food. In these experiments the influence of different packaging conditions on migration to Tenax® was also determined. The compositional and migration data from the market samples were used to check the applicability of the model developed for predicting migration from adhesives applied in multilayer materials.

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## 2. Materials and methods

### 2.1. Reagents

Decamethylcyclopentasiloxane (CAS 541-02-6), diethylene glycol butyl ether (CAS 112-34-5), 2-(2-butoxyethoxy) ethyl acetate (CAS 124-17-4), biphenyl (CAS 92-52-4), 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (CAS 6846-50-0), bis(2-ethylhexyl) adipate (CAS 103-23-1), phthalic acid mono-2-ethylhexyl ester (CAS 4376-20-9), glyceryl triacetate (CAS 102-76-1), decahydro naphthalene (CAS 91-17-8), dibutyl phthalate (CAS 84-74-2), 2,6-di-*tert*-butyl-1,4-benzoquinone (CAS 719-22-2), butylated hydroxyl toluene (CAS 128-37-0), hexadecane (CAS 544-76-3), eicosane (CAS 112-95-8), retene (phenanthrene, 1-methyl-7-(1-methylethyl)) (CAS 483-65-8), octadecane (CAS 593-45-3), docosane (CAS 629-97-0), tetracosane (CAS 646-31-1), 4-*tert*-butylphenol (CAS: 98-54-4), dodecane (CAS: 112-40-3), caprolactam (CAS: 105-60-2), triacetin (CAS: 102-051-9), benzene,1,3-disocyanate-2-methyl (CAS: 91-08-7), hexane,1,6-diisocyanate (CAS: 133394-59-9), phenol,2,4-bis(1,1-dimethylethyl) (CAS: 96-76-4), and diphenylmethylenediisocyanate (CAS: 91-97-4) were purchased from Sigma-Aldrich Química S.A. (Madrid, Spain), all of them had analytical quality. Acetone, methanol and hexane were supplied by Scharlau Chemie S.A. (Sentmenat, Spain). Tenax TA 80/100 mesh

supplied by Supelco (Bellefonte, USA). Solution A: solution of 4-*tert*-butylphenol at 1000 µg g<sup>-1</sup> in acetone.

### 2.2. Market samples

Forty five three-layer laminates or three layer glued samples forming the structure [substrate 1–adhesive–substrate 2] have been studied in this work. The samples were market samples provided by different European companies. Among the market samples there were multilayer films, folding boxes or corrugated board samples. Most of them were not printed but produced in the same run as regular packages. The substrates and the adhesives used for their manufacturing were also separately provided. Twenty nine different adhesives had been used in the manufacture of the laminates: 9 polyurethanes (PUs), 6 acrylics (AC), 2 hot-melts (HM), 1 starch, 5 based on vinyl acetate ethylene (VAE), 4 based on polyvinyl acetate (PVAc), 1 based on polyvinyl alcohol (PVOH) and 1 mixture of vinylic adhesive and starch (VS). The substrates used were cardboard (CB), polypropylene coated cardboard (c\_CB), corrugated paper (corrpaper), polypropylene (PP), polyethylene (PE), polyamide (PA), polyethylene terephthalate (PET), metalized PET (PET-met), polyester (Pester), aluminium (Al) and ethyl vinyl alcohol (EVOH).

Table 1 shows the substrates and adhesives used in the manufacture of the samples analyzed, the amount of adhesive applied per m<sup>2</sup> of the laminate, calculated from the mass difference of the glue samples and the pure substrates; and the volume to surface factor ( $d_F$ ) calculated as the volume of food inside the packaging (dm<sup>3</sup>) divided by the surface of the packaging that contained the adhesive (dm<sup>2</sup>). For each laminate, the substrate listed in Table 1 on the right (2<sup>nd</sup> column) was the one which, in a packaging application, comes into contact with the food. Such layers of the laminates will be called “contact layers”. From Table 1 it can be seen that for laminates in which vinyl, HM and starch were used as adhesives, cardboard or paper were the contact layers, and for laminates with PU and AC as adhesives the contact layers were PE, PET and PP.

### 2.3. GC-MS

A CTC Analytics system from Agilent Technologies (Madrid, Spain) was used as autosampler. The gas chromatograph system was a HP 6890 series connected to 5973 series mass selective detector. Chromatographic separations were carried out on a DB-5 (30 m × 0.25 mm × 0.25 µm) from Agilent Technologies (Madrid, Spain). The oven temperature program was as follows: initial temperature at 40 °C (2 min), a temperature rate of 10 °C min<sup>-1</sup> from 40 to 300 °C, and 2 minutes at the final temperature. Helium was used as gas carrier at a flow of 1 mL min<sup>-1</sup>. Injection was carried out by headspace solid phase microextraction (HS-SPME), static headspace (HS) and liquid injection.

HS-SPME-GC-MS analyses were carried out with a polydimethylsiloxane (PDMS) fiber of 100 µm of thickness. Injection was performed in splitless mode, and extraction conditions were as follows: 80 °C extraction temperature, 25 min extraction time and 1 min desorption time at 250 °C. Detection was performed in SCAN mode (50–350 *m/z*).

HS injection was carried out in splitless mode and the extraction conditions were as follows: 150 °C extraction

**Table 1** Samples codes, substrates and adhesives used for the laminates manufacture, volume to surface factor ( $d_F$ ) and grams of adhesive per m<sup>2</sup> of laminate<sup>a</sup>

Sample code	Substrates	Adhesive type	Adhesive code	$d_F$ (dm <sup>3</sup> /dm <sup>2</sup> )	Grams of adhesive per m <sup>2</sup> laminate
Lam_01	CB/CB	VAE	VAE_01	52.3	31.8
Lam_02	CB/CB	VAE	VAE_01	52.3	31.8
Lam_03	CB/CB	VAE	VAE_01	52.3	31.8
Lam_04	CB/CB	VAE	VAE_02	57.6	25.3
Lam_05	CB/CB	VAE	VAE_02	30.7	25.3
Lam_06	CB/CB	VAE	VAE_02	18.5	25.3
Lam_07	CB/CB	VAE	VAE_03	37.1	28.5
Lam_08	CB/CB	VAE	VAE_04	63.9	49.1
Lam_09	CB/CB	VAE	VAE_04	34.1	49.1
Lam_10	CB/CB	VAE	VAE_04	70	49.1
Lam_11	CB/CB	VAE	VAE_05	96.7	30.7
Lam_12	CB/CB	PVAc	PVAc_01	52.3	101.5
Lam_13	CB/CB	PVAc	PVAc_01	52.3	101.5
Lam_14	CB/CB	PVAc	PVAc_01	52.3	101.5
Lam_15	CB/paper/CB	PVAc	PVAc_02	1.6	Na
Lam_16	CB/paper/CB	PVAc	PVAc_03	1.6	Na
Lam_17	CB/paper/CB	PVAc	PVAc_04	1.6	Na
Lam_18	Paper/paper	PVOH	PVOH_01	223.3	38.9
Lam_19	Paper/paper	PVOH	PVOH_01	74.5	38.9
Lam_20	Paper/paper	PVOH	PVOH_01	185.6	38.9
Lam_21	Paper/paper	Starch	Starch_01	97.8	38.9
Lam_22	Paper/paper	Starch	Starch_01	398.5	38.9
Lam_23	Paper/PP	Acrylic	AC_01	2604	38.9
Lam_24	Paper/PP	Acrylic	AC_02	300.5	38.9
Lam_25	Al/PE	Acrylic	AC_03	0.17	45
Lam_26	Paper/PP	Acrylic	AC_04	0.17	18
Lam_27	Paper/PET	Acrylic	AC_05	0.17	20
Lam_28	Paper/PP	Acrylic	AC_06	0.17	20
Lam_29	Paper/corrpaper/paper	Vinylic + Starch	VS_01	0.17	Na
Lam_30	Paper/corrpaper/paper	Vinylic + Starch	VS_01	0.17	Na
Lam_31	Paper/corrpaper/paper	Vinylic + Starch	VS_01	0.17	Na
Lam_32	CB/CB	Hotmelt	HM_01	0.17	31.3
Lam_33	c_CB/c_CB	Hotmelt	HM_01	0.17	31.3
Lam_34	CB/CB	Hotmelt	HM_02	8.5	68.2
Lam_35	PA/PE	Polyurethane	PU_01	0.17	2.5
Lam_36	PA/PE	Polyurethane	PU_02	0.17	2
Lam_37	Pester/PE	Polyurethane	PU_02	0.17	1.9
Lam_38	PET/[PE-EVOH-PE]	Polyurethane	PU_03	0.17	1.8
Lam_39	[PA-EVOH-PA]/PE	Polyurethane	PU_04	0.17	1.8
Lam_40	PET-met/PE	Polyurethane	PU_05	0.17	1.6
Lam_41	PET/Al/PE	Polyurethane	PU_06	0.17	4.3
Lam_42	PET/Al/PE	Polyurethane	PU_06	0.17	4.3
Lam_43	PET/Al/PE	Polyurethane	PU_07	0.17	5
Lam_44	PET-met/PE	Polyurethane	PU_08	0.17	2.5
Lam_45	PA/Al/PE	Polyurethane	PU_09	0.17	6.7

<sup>a</sup> Na: data not available; CB: cardboard; c\_CB: coated cardboard; corrpaper: corrugated paper; PP: polypropylene; PE: polyethylene; PA: polyamide; PET: polyethylene terephthalate; PET-met: metalized PET; Pester: polyester; Al: aluminium; EVOH: ethyl vinyl alcohol; VAE: vinyl acetate ethylene; PVAc: polyvinyl acetate; PVOH: polyvinyl alcohol.

temperature, 10 min extraction time and 1 mL of extraction volume. Detection was performed in SCAN mode (50–350  $m/z$ ). Liquid injection was carried out in split mode (1 : 20), 1  $\mu$ L of the sample was injected. Acquisition was performed in SCAN mode for the optimization and in SIM mode for the quantification. Two different acquisition methods were used for the quantification, one for PU adhesives and other for the rest of the adhesives. Quantification ions are shown in Table 2, 3 and 4.

#### 2.4. Identification of the compounds present in the adhesives samples

The first aim of this work was to identify the potential migrant compounds from the adhesives used in the manufacture of the laminates. For this purpose, 3 cm  $\times$  0.5 cm cut-outs of the

laminates were analyzed by HS-SPME-CG-MS and compared with similar size cut-outs of the substrates used in the laminate. The pure adhesive was also analyzed by HS-SPME-GC-MS in order to check the origin of the compounds detected. Toxicity of the compounds identified was evaluated according to Cramer rules<sup>18</sup> with the software Toxtree v1.51 (Idea consult Ltd.).

#### 2.5. Determination of the initial concentration profile of adhesives ( $CP_0$ )

To determine  $CP_0$ , a liquid extraction of the laminates was carried out. The methodology was as follows: 0.5 grams of laminate were cut into small pieces and extracted three consecutive times with 2.5 mL of dichloromethane (24 hours, 40 °C), the three extracts were mixed and 10  $\mu$ L of internal standard

**Table 2** Compounds identified in the polyurethane adhesives (PU), toxicity class according to Cramer rules (TC), quantification ions (QI) and concentration expressed as  $\mu\text{g}$  of compound per  $\text{dm}^2$  of laminate

Compounds (TC)	QI ( <i>m/z</i> )	PU_01	PU_02	PU_03	PU_04	PU_05	PU_06	PU_07	PU_08	PU_09
Dodecane (I)	168.2		0.19							
Glyceryl triacetate (triacetin) (I)	103.1	0.57				3.21				
2,6-Toluene diisocyanate (2,6-TDI) (III)	174.0				9.95	15.3	6.28	14.4	14.1	8.85
Butylated hydroxyl toluene (BHT) (II)	205.2	0.05	0.11	0.35	0.10	0.26	0.07	0.07	0.13	0.08
Unknown 1 (adipate structure) <sup>a</sup>	129.0			10.6		24.1				
Unknown 2 (adipate structure) <sup>a</sup>	129.0	12.7				9.7				
Unknown 3 (isocyanate structure) <sup>c</sup>	99.0		9.78		28.9		7.8	34.4		
Unknown 4 (adipate structure) <sup>a</sup>	82.1			4.0		21.7	12.9		14.3	36.5
Unknown 5 (phthalate structure 1) <sup>b</sup>	149.0		0.46							
Unknown 6 (phthalate structure 2) <sup>b</sup>	149.0		4.40	7.89		23.5	12.4	0.06		
3,3'-Dimethyl-4,4'-biphenylene diisocyanate (TODI) (III)	250.1		4.86	34.6		71.4	22.7		28.0	23.7

<sup>a</sup> Quantified with bis(2-ethylhexyl) adipate as standard. <sup>b</sup> Quantified with dibutyl phthalate as standard. <sup>c</sup> Quantified with 3,3'-dimethyl-4,4'-biphenylene diisocyanate as standard; nq: not quantified.

solution were added. The total solution was concentrated under a stream of pure  $\text{N}_2$  to 200  $\mu\text{L}$  and analyzed by GC-MS. Two replicates of each sample were analyzed. For building the calibration curves, solutions of the compounds at different concentration levels were prepared in acetone and analyzed by GC-MS. Three replicates of each concentration level were analyzed.

## 2.6. Migration tests

The migration experiments were designed to be performed with Tenax® as food simulant. Tenax® is composed of small granules of modified polyphenylene oxide. The density of this material is about  $0.25 \text{ g cm}^{-3}$  which roughly means that about 75% of the Tenax® is air. One of the main properties of Tenax® is its high adsorption potential. Tenax® was extracted following the procedure optimized by Vera *et al.*<sup>15</sup> It was extracted two consecutive times with 3.4 mL of acetone, solutions were put together and 10  $\mu\text{L}$  of internal standard solution A were added. Finally, the total solution was concentrated under a stream of  $\text{N}_2$  to 200  $\mu\text{L}$ .

For the migration experiments, cut-outs of the laminates with a 100% of its surface containing adhesive were selected. The surface of these laminates was fully covered with Tenax® which had been previously purified by Soxhlet extraction with acetone during 6 hours. For migration tests of lam\_01 to lam\_34,  $1 \times 8.5 \text{ cm}$  cut-outs of laminates were covered with 0.34 grams of Tenax® forming a uniform layer ( $4 \text{ g}_{\text{Tenax}}$  per  $\text{dm}^2$  laminate according to UNE-EN 14338<sup>19</sup>). This system was placed inside a Petri dish and kept in the oven at  $40 \text{ }^\circ\text{C}$  for 10 days. After this period, Tenax® was extracted following the previous methodology and analyzed by GC-MS. Migration tests for laminates lam\_35 to lam\_45 with PU adhesives were carried out using both Tenax® and isooctane as food simulants. The laminates were thermo sealed to manufacture pouches of  $5 \times 2 \text{ cm}$  in which 0.4 g of Tenax® ( $2 \text{ g}_{\text{Tenax}}$  per  $\text{dm}^2$  laminate) or 0.64 g of isooctane ( $3.2 \text{ g}_{\text{isooctane}}$  per  $\text{dm}^2$  laminate) were filled. The pouches containing Tenax® were kept in an oven at a constant temperature of  $40 \text{ }^\circ\text{C}$  for 10 days. After this period, the pouches were opened and emptied. The Tenax® was extracted following the previous

**Table 3** Compounds identified in the VAE and PVAc adhesives, toxicity class according to Cramer rules (TC), quantification ions (QI) and concentration expressed as  $\mu\text{g}$  of compound per  $\text{dm}^2$  of laminate

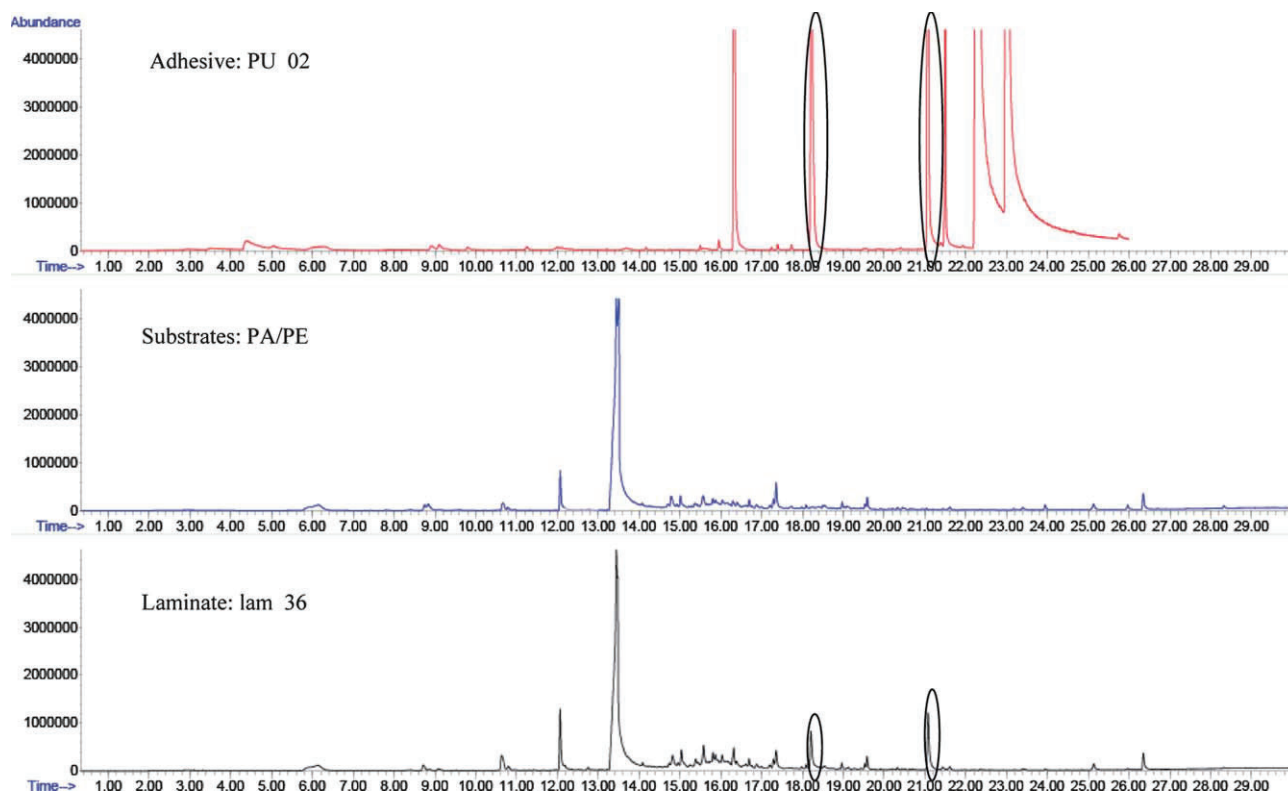
Compounds (TC)	QI ( <i>m/z</i> )	VAE_01	VAE_02	VAE_03	VAE_04	VAE_05	PVAc_01	PVAc_02	PVAc_03	PVAc_04
Decamethylcyclopentasiloxane (III)	355.1	1.57	1.30	1.40			1.17			
Glyceryl triacetate (triacetin) (I)	103.1	6170	3300	12 400	545	4430	10 100	41.9	18 100	26.3
Diethylene glycol butyl ether (I)	57.1							455	526	325
2-(2-Butoxyethoxy) ethyl acetate (I)	87.1							2990	3130	2270
Biphenyl (II)	154.1				1.37			0.97	0.83	0.81
2,2,4-Trimethyl-1,3-pentanediol	111.2							11.0	17.9	21 400
Diisobutyrate (TXIB) (I)										
Isobutyl nonyl phthalate <sup>a</sup> (I)	149.1				110	11.8		613	622	645
Dibutyl phthalate (I)	149.0				41.2	2.85		66.0	70.3	64.1
Docosane (I)	57.1				24.8	4.93		58.1	82.8	73.3
Tricosane <sup>b</sup> (I)	57.1				42.7	6.26		165	163	141
Tetracosane (I)	57.1				185	161		243	201	173
Bis(2-ethylhexyl) adipate (I)	147.1				60.5	15.8				
Pentacosane <sup>b</sup> (I)	57.1				65.2	6.34		305	243	201
Diethylene glycol dibenzoate <sup>c</sup> (I)	105.1				14 900	38 400		8080	9360	5440
2-Ethylhexyl phthalate (I)	149.0				1157	1232		10 800	11 700	8030

<sup>a</sup> Quantified using dibutyl phthalate as standard. <sup>b</sup> Quantified using tetracosane as standard and. <sup>c</sup> Quantified using 2-ethylhexyl phthalate as standard.

**Table 4** Compounds identified in the PVOH, starch, acrylic, vinylic and hotmelt adhesives, toxicity class according to Cramer rules (TC), quantification ions (QI) and concentration expressed as  $\mu\text{g}$  of compound per  $\text{dm}^2$  of laminate

Compounds (TC)	QI ( <i>m/z</i> )	PVOH_01	Starch_01	AC_01	AC_02	VS_01	HM_02
Biphenyl (II)	154.1					1.54	
1,4-Methanobenzocyclodeceine-1,2,3,4 <sup>a</sup> , <i>b</i> ,8,9,12,12 <sup>a</sup> decahydro <sup>a</sup> (I)	134.1			37.4	392		
Naphthalene decahydro (I)	257.2			59.1			
Isobutyl nonyl phthalate <sup>b</sup> (I)	149.1	2.69		4.23			
Kaur-16-ene <sup>a</sup> (I)	257.2						
Dibutyl phthalate (I)	149.0	0.47	2.03				
Bis(2-ethylhexyl) adipate (I)	147.1	6.89					
2-Ethylhexyl phthalate (I)	149.0	115	4.39				
2,5-Di- <i>tert</i> -butyl-1,4-benzoquinone (II)	220.1						32.6
Butylated hydroxyl toluene (BHT) (II)	205.2						1.34
Hexadecane (I)	57.1						18.4
Octadecane (I)	57.1						96.6
Eicosane (I)	57.1						34.6
4b-8-Dimethyl-2-isopropylphenanthrene <sup>a</sup> (II)	241.2						5.05
Dehydroabietin <sup>a</sup> (II)	227.2						9.33
Docosane (I)	57.1						58.6
1-Methyl 10,18-bisnorabieta 8,11,13-triene <sup>a</sup> (II)	241.2						2.01
Retene (III)	219.0						1.09
Dehydroabietal <sup>a</sup> (II)	269.2						7.49
Dehydroabietic acid methyl ester <sup>a</sup> (II)	239.2						43.8
Tetracosane (I)	57.1						141

<sup>a</sup> Quantified using retene as standard. <sup>b</sup> Quantified using dibutyl phthalate as standard.



**Fig. 1** Chromatogram of the laminate lam<sub>36</sub>, its substrates (PA/PE) and its adhesive (PU<sub>02</sub>), analyzed by HS-SPME-GC-MS.



**Table 5** Migration values in Tenax® and isooctane from laminates made of polyurethane adhesives and limits of detection of the quantification method (LODs), all expressed as  $\mu\text{g}$  compound per  $\text{dm}^2$  laminate

Compounds		LOD	Lam_35	Lam_36	Lam_37	Lam_38	Lam_39	Lam_40	Lam_41	Lam_42	Lam_43	Lam_44	Lam_45
Triacetin	Tenax	0.03	Nd <sup>a</sup>					2.05					
	Isooctane	0.14	Nd					Nd					
Unknown 1 (adipate structure) <sup>b</sup>	Tenax	0.02				Nd		15.4					
	Isooctane	0.09				Nd		15.6					
Unknown 2 (adipate structure) <sup>b</sup>	Tenax	0.02	12.0					5.0					
	Isooctane	0.09	12.2					5.1					
Unknown 3 (isocyanate structure) <sup>d</sup>	Tenax	0.06	5.1	4.2			1.7		1.8	1.9	26.7		
	Isooctane	0.29	2.4	2.4			13.1		1.9	1.7	16.4		
Unknown 4 (adipate structure) <sup>b</sup>	Tenax	0.02				Nd		9.1	6.1	9.7		10.0	34.6
	Isooctane	0.09				Nd		14.3	3.7	1.9		13.7	32.8
Unknown 5 (phthalate structure 1) <sup>c</sup>	Tenax	$0.1 \times 10^{-3}$	0.15	0.23									
	Isooctane	$0.5 \times 10^{-3}$	0.07	0.06									
Unknown 6 (phthalate structure 2) <sup>c</sup>	Tenax	$0.1 \times 10^{-3}$	1.54	1.68	Nd		4.37	Nd	Nd	Nd			
	Isooctane	$0.5 \times 10^{-3}$	0.21	0.24	Nd		0.39	Nd	Nd	Nd			
TODI	Tenax	0.06	2.21	2.49	Nd			Nd	Nd	Nd		Nd	Nd
	Isooctane	0.29	Nd	Nd	Nd			Nd	Nd	Nd		Nd	Nd

<sup>a</sup> Nd: not detected. <sup>b</sup> Quantified with a bis(2-ethylhexyl) adipate standard. <sup>c</sup> Quantified with dibutyl phthalate standard. <sup>d</sup> Quantified with TODI standard.

methodology and analyzed by GC-MS. Isooctane pouches were kept at 20 °C for 2 days. Afterwards isooctane was directly analyzed by GC-MS.

For laminates lam\_37 and lam\_42 (based both in PU), a series of experiments was carried out to determine the influence of different packaging conditions on migration to Tenax®. Vacuum, pasteurization and vacuum plus pasteurization were applied to two replicates of each sample and then the pouches were kept at 40 °C for 10 days. Vacuum was applied after filling the pouches with Tenax® with a home vacuum system. Pasteurization was applied by keeping the pouches at 75 °C in a water bath for 10 minutes.

For building the calibration curves, standard solutions of the compounds at different concentration levels were prepared in acetone and analyzed by GC-MS. Three replicates of each concentration level were analyzed to determinate the reproducibility.

## 2.7. Theoretical estimation of the migration from the laminates

The amount of substance migrating from a three-layer laminate into a food or food simulant can be calculated by solving an appropriate time dependent mass-transport (Fick's 2<sup>nd</sup>) equation.<sup>8,20</sup> In our case the assumptions made to solve this equation are: all layers of the laminate and the food simulant are homogenous and of constant thickness, at a given temperature all migration parameters (diffusion and partition coefficients) in the laminate–food simulant system are constant and there is no loss of migrant/substance in the system due to degradation or another process. With these assumptions and the initial and boundary conditions which are appropriate for the migration experiments, Fick's equation can be solved with numerical

methods.<sup>20,21</sup> In this work a one-dimensional finite differences, FD, method was used for this purpose.<sup>21</sup>

To perform a migration computation a series of input parameters for the FD algorithm are needed. Some of them, the thickness and density of each layer of the laminate–food system as well as the initial concentration,  $CP_0$ , of the various migrants in the adhesives, are known from the analytical and laboratory work done in the project. The experimental determination of each diffusion,  $D$ , and partition,  $K$ , coefficient involved in a migration process is a challenging, time consuming and expensive task. It was beyond the scope of this project to determine experimentally the  $D$  and  $K$  coefficients for the 45 market samples investigated here. Because of that a different approach was followed by estimating the parameters from that of previously investigated test samples.

In a first approximation the  $D$  and  $K$  coefficients for the polymeric substrates were known from previous experimental results and/or from published data. However it was necessary to agree upon an approximation in describing the  $D$  and  $K$  coefficients in the cardboards used in the laminates and the solid dry food simulant Tenax®.

Cardboard and paper are made of macroscopic fibers, binding materials, “free-volumes” and even adhesives and fillers. In such a structure the local diffusional motions of a molecule may differ quite strongly in the different components of the material. That means that the overall macroscopic mass diffusion in the material is in fact the result of several diffusion mechanisms occurring at the same time. These mechanisms are quantified by different local diffusion coefficients which may show different functional dependencies on the nature and concentration of the diffusing species, the temperature and/or pressure. Strictly speaking such a material cannot be regarded as “homogeneous” from the point of view of a mass diffusion process. However, in order to be able

**Table 6** Migration values in Tenax® from laminates made of VAE and PVA adhesives and limits of detection of the quantification method (LODs), all expressed as µg of compound per dm<sup>2</sup> of laminate

Compounds	LOD	Lam_01	Lam_02	Lam_03	Lam_04	Lam_05	Lam_06	Lam_07	Lam_08	Lam_09	Lam_10	Lam_11	Lam_12	Lam_13	Lam_14	Lam_15	Lam_16	Lam_17	
Decamethylcyclopentasiloxane	0.009	0.62	Nd <sup>a</sup>	Nd	Nd	Nd	Nd	0.34	Nd	Nd	Nd	0.92	Nd	Nd	Nd	Nd	Nd	Nd	
Triacetin	0.90	1120	233	1040	109	97.2	701	1220	116	44.0	0.15	388	255	169	2.05	154	3.79	Nd	
Diethylene glycol butyl ether	0.79																		
2-(2-Butoxyethoxy) ethyl acetate	0.32															17.9	30.4	42.9	
Biphenyl	0.01															0.03	0.04	0.07	
TXIB	0.03															5.01	7.03	349	
Isobutyl nonyl phthalate <sup>b</sup>	0.04															120	305	114	
Dibutyl phthalate	0.04															8.26	9.61	10.3	
Docosane	0.15															57.5	80.8	59.5	
Tricosane <sup>c</sup>	0.24															84.8	85.1	91.3	
Tetracosane	0.24															44.2	42.9	36.4	
Bis(2-ethylhexyl) adipate	0.001																		
Pentacosane <sup>c</sup>	0.24															50.6	43.8	45.9	
Diethylene glycol dibenzoate <sup>d</sup>	0.11															113	95.7	117	
2-Ethylhexyl phthalate	0.11															395	386	440	

<sup>a</sup> Nd: not detected). <sup>b</sup> Compounds quantified using dibutyl phthalate as standard. <sup>c</sup> Compounds quantified using tetracosane as standard. <sup>d</sup> Compounds quantified using 2-ethylhexyl phthalate as standard.

to use for laminates with cardboard and paper the FD method as developed for homogeneous media, one can assign to a cardboard and/or paper an overall “apparent” diffusion coefficient,  $D^*$ . This diffusion coefficient will be in fact the result of a weighted contribution of diffusion coefficients from the different components of the “non-homogeneous” material.

Using a similar concept one can assign, at a fixed temperature  $T$ , to a heterogeneous medium (powder) like the food stimulant Tenax® an “apparent” overall diffusion coefficient  $D_F^*$ . Similar theoretical considerations can be applied to define for a migrating species “apparent partition coefficients”,  $K_{ij}^*$ , at boundaries where non-homogeneous materials like paper, cardboard and Tenax® are present.

The computation procedure was applied to 142 experimental results obtained in the migration experiments with Tenax®.

### 3. Results and discussion

The main aims of this work were to determine the migratable compounds in the adhesives used in multilayer food packaging materials with the structure [substrate1–adhesive–substrate2] and to study their migration to food simulants. Finally the migration results were compared to estimates obtained from a mathematical tool designed to predict “upper-bound” migration to food and food simulants from multilayer materials containing adhesives. The multilayer materials selected were market samples (without inks) and included a wide variation of adhesives and types of substrates. They had been manufactured for different packaging purposes. Some of them were elaborated for packaging dry food (breadcrumbs, flour, jelly powders and mash potato powders) and others for fresh food (pizza and pastry). Some of them allowed special packaging conditions such as vacuum (for coffee), vacuum and pasteurization (for cheese, potato omelet and sausages) and deep freeze (for ice lollies).

Some of the laminates shown in Table 1 had been previously studied in our laboratory (lam\_25, lam\_26, lam\_27, lam\_28, lam\_32 and lam\_33) and their  $CP_0$  and migration to Tenax® values had been reported.<sup>6,15</sup> The values have been included in this work in order to obtain a better testing of the mathematical model for the prediction of migration.

#### 3.1. Identification and $CP_0$

Comparison of laminate, substrates and adhesive chromatograms allowed determining which compounds came from the substrates, which ones from the adhesives and which were neo-formed compounds released during the manufacturing process of the laminate (Fig. 1). The identification of these compounds was carried out by comparing their retention times and mass spectra with those of the pure standards. A total of 55 different compounds were detected in the adhesives analyzed. Thirty three of these compounds were identified. For six substances just its main chemical structure could be obtained from the mass spectra. Four compounds showed a class III toxicity according to Cramer rules,<sup>18</sup> 2,6-toluene diisocyanate (2,6-TDI), 3,3'-dimethyl-4,4'-biphenylene diisocyanate (TODI), decamethylcyclopentasiloxane and retene.

Among the compounds identified, only two compounds were present simultaneously in two different types of adhesives,

**Table 7** Migration values in Tenax® from laminates made of PVOH, starch, acrylic, vinylic and hotmelt adhesives and limits of detection of the quantification method (LODs), all expressed as  $\mu\text{g}$  of compound per  $\text{dm}^2$

Compounds	LOD	Lam_18	Lam_19	Lam_20	Lam_21, 22	Lam_23	Lam_24	Lam_29	Lam_30	Lam_31	Lam_34
Biphenyl	0.01							0.91	0.91	0.69	
1,4-Methanobenzocyclodecine-1,2,3,4 <sup>a</sup> ,6,8,9,12,12 <sup>a</sup> decahydro <sup>b</sup>	0.24					18.0	170				
Naphthalene decahydro	0.03					32.0					
Isobutyl nonyl phthalate <sup>c</sup>	0.04	Nd <sup>a</sup>	2.11	Nd							
Kaur-16-ene <sup>b</sup>	0.24					2.04					
Dibutyl phthalate	0.04	Nd	0.31	Nd	Nd						
Bis(2-ethylhexyl) adipate	0.01	Nd	2.82	Nd							
2-Ethylhexyl phthalate	0.11	Nd	95.1	Nd	Nd						
2,5-Di- <i>tert</i> -butyl-1,4-benzoquinone	1.49										7.20
BHT	0.07										0.20
Hexadecane	0.64										17.6
Octadecane	2.21										68.8
Eicosane	0.30										22.0
4 <i>b</i> -8-Dimethyl-2-isopropylphenanthrene <sup>b</sup>	0.24										2.46
Dehydroabietin <sup>b</sup>	0.24										4.93
Docosane	0.15										1.14
1-Methyl-10,18-bisnorabieta-8,11,13-triene <sup>b</sup>	0.24										0.89
Retene	0.24										0.26
Dehydroabietal <sup>b</sup>	0.24										0.83
Dehydroabietic acid methyl ester <sup>b</sup>	0.24										10.6
Tetracosane	0.24										Nd

<sup>a</sup> Nd: not detected. <sup>b</sup> Compounds quantified using retene as standard. <sup>c</sup> Compounds quantified using dibutyl phthalate as standard.

glyceryl triacetate (triacetin) and butylated hydroxyl toluene (BHT), both present in some vinyl adhesives and in some PU adhesives. Nevertheless, triacetin concentration was above  $10\,000\ \mu\text{g}\ \text{dm}^{-2}$  for some of the vinyl adhesives while it was below  $5\ \mu\text{g}\ \text{dm}^{-2}$  for all the PU adhesives. This compound is commonly used as plasticizer or humectant in adhesives. Table 2, 3 and 4 show the concentrations found in the laminates ( $\text{CP}_0$  values) for all the adhesives studied as well as the limits of detection of the quantification method. Very sensitive limits of detection (LODs) were obtained, reaching values below  $5\ \text{ng}\ \text{dm}^{-2}$  for compounds such as 2,6-TDI, phenol,2,4-bis(1,1-dimethylethyl), BHT, and bis(2-ethylhexyl) adipate.  $\text{CP}_0$  values were much higher in general for adhesives VAE and PVAc than in PVOH, PU, AC, starch and HM. The plasticizer concentration in VAE and PVAc reached values of  $10\ \text{mg}\ \text{dm}^{-2}$ , for the rest of the adhesives the concentration of single substances was never above  $0.4\ \text{mg}\ \text{dm}^{-2}$ .

**3.1.1. Polyurethane adhesives.** Polyurethane (PU) adhesives are produced by the reaction of the NCO group of isocyanates and any organic compound containing a reactive hydroxyl group such as polyether and polyester polyols in the presence of a catalyst. Table 2 shows the compounds detected in PU adhesives. A total of 11 compounds were detected in the PU adhesives. Some adhesives additives were detected such as an antioxidant compound, BHT, and a plasticiser, glyceryl triacetate (triacetin). BHT was found in all the PU adhesives. Two isocyanates coming from the PU synthesis were found, 2,6-TDI and TODI. These compounds had a high toxicity level according to Cramer rules. Both are approved as monomers in the Plastics Directive 2002/72/EC,<sup>3</sup> with the restriction that the sum of isocyanate compounds have a maximum permitted quantity in the finish material or article of  $1\ \text{mg}\ \text{kg}^{-1}$ , QM(T), expressed as

NCO equivalents. But for adhesive layers this restriction is not applicable. Both isocyanates in contact with water or humidity form primary aromatic amines. According to annex V of the Plastics Directive primary aromatic amines may not migrate into food over  $10\ \mu\text{g}\ \text{kg}^{-1}$  food. The amount of residual isocyanates in a laminate with PU adhesive depends on the curing conditions and time. Compliance with the Plastics Directive should be monitored *via* the primary aromatic amines.

Seven compounds could not be identified. Nevertheless, for six of them it was possible to elucidate its main chemical structure. Unknowns 1, 2 and 4 had very similar mass spectra with common  $m/z$  values such as 129, 111, 101 and 83. Probably they were isomers. These masses are typical in ethyl adipates, commonly used as plasticizers. The mass spectrum of unknown 3 showed a typical mass of linear isocyanates ( $m/z$  99). Unknowns 5 and 6 showed a typical mass of phthalates ( $m/z$  149). MS/MS experiments over the masses 129, 99 and 149 in the unknown peaks and in an ethyl adipate, a linear isocyanate and a phthalate standard were performed. The mass spectra were compared and results confirmed the base structures proposed.

**3.1.2. Vinyl adhesives.** Table 3 and 4 show the compounds detected in the vinyl adhesives. Fifteen compounds were identified. Additionally three unknown compounds were detected. Vinyl adhesives (PVOH, PVAc and VAE) showed common compounds, probably because they all have similarities in their structure. All the compounds detected in PVOH and PVAc were also found in VAE adhesives. Three of the compounds detected were present in the three type of vinyl adhesives, isobutyl nonyl phthalate, dibutyl phthalate and 2-ethylhexyl phthalate, with concentrations ranging from  $0.47\ \mu\text{g}\ \text{dm}^{-2}$  to  $11\,700\ \mu\text{g}\ \text{dm}^{-2}$ . Triacetin was found in all PVAc and VAE adhesives, with



concentrations reaching values of 18 100  $\mu\text{g dm}^{-2}$ . This compound, used as plasticizer, is able to provide flexibility and/or elongation to the adhesive by separating the polymer chains and allowing their deformation.<sup>1</sup> Other plasticizers found in these adhesives were 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (called TXIB) and diethylene glycol dibenzoate. One compound with class (III) and one with class (II) toxicities according to Cramer's rules were detected, decamethylcyclopentasiloxane and biphenyl, respectively, which were found in traces of 1–2  $\mu\text{g dm}^{-2}$ . Methyl siloxanes are commonly used as solvents and biphenyl is commonly used as an emulsifier for the manufacture of these kinds of adhesives.

**3.1.3. Other adhesives.** The compounds identified in the HM adhesive were similar to those found previously by Vera *et al.*<sup>15</sup> Most of the compounds were derivatives of abietic acid. Their concentrations ranged from 1.09  $\text{ng dm}^{-2}$  (retene) to 43.8  $\text{ng dm}^{-2}$  (dehydroabietic acid methyl ester). Abietic acid is used as tackifier in HM adhesives in order to reduce the adhesive viscosity, improving the wetting properties and therefore its adhesion.<sup>1</sup> Abietic acid undergoes a thermal degradation when the adhesive is heated to be cured, forming intermediate compounds such as 4b-8-dimethyl-2-isopropylphenanthrene, dehydroabietin, 1-methyl-10,18-bisnorabieta-8,11,13-triene, retene, dehydroabietal and dehydroabietic acid methyl ester.<sup>22–24</sup> Also BHT, an antioxidant, was found. Only one compound with suspected high toxicity according to Cramer rules was found, retene.

Only two compounds were identified in the starch adhesive, two phthalates, and one in the vinylic plus starch adhesive, this compound was biphenyl, which was found in vinylic adhesives too. Three compounds were identified in the two acrylics, naphthalene, that is used for synthesis of phthalate compounds, 1,4-methanobenzocyclohexene-1,2,3,4<sup>a</sup>,<sup>b</sup>,8,9,12,12<sup>a</sup> decahydro and kaur-16-ene. These two last compounds are probably derivative products of the resinous emulsion added by the manufacturer to the acrylic adhesive.

Six unknown compounds were also detected in the acrylic adhesives and two in the adhesive vinylic plus starch.

## 3.2. Migration

Tenax® was selected as food simulant since most of the laminates contained paper or cardboard in their structure. Thus the use of liquid food simulants was not possible because they would have damaged the substrates and/or structures of these laminates. Migration results are shown in Table 5, 6 and 7. Migration is expressed as  $\mu\text{g}$  compound per  $\text{dm}^2$  laminate cut-out used in the migration experiment. To convert these values into  $\mu\text{g}$  compound per  $\text{kg}$  food they have to be divided by the volume to surface factor ( $d_F$ ) of Table 1 (assuming a food density of 1  $\text{kg dm}^{-3}$ ). Fifty seven percent of the number of compounds detected in the laminates migrated to Tenax®, which means that even though adhesives are not in direct contact with food, migration to food is possible and therefore the determination and quantification of the compounds present in these adhesives is necessary. For some kind of adhesives the percentage of the number of migrated compounds was even higher, 89% for PVAc adhesives (40 out of 45 compounds detected), 92% for HM (12 out of 13

compounds detected) and 100% for VS and AC (5 out of 5 compounds detected in both adhesives). These results agree with the results recently reported on the migration in HM adhesives.<sup>15</sup> Here 27 out of the 28 compounds detected in the adhesives were found to migrate to Tenax®. Taking into account the final number of migrated compounds per laminate, the HM and PVAc were the adhesives with more migrated compounds per laminate, 12 and 7 respectively. These differences in the migration percentage among the laminates studied can be due to different reasons such as the initial concentration of the compound in the laminate, the nature of the compounds detected, the kind of adhesive or the materials used in the laminates manufacture. PU adhesives, for example, had a low initial concentration values for most of the compounds detected. Consequently only 40% of the substances found in the laminates were detected in the migration. The higher concentration migration values were found for VAE and PVAc laminates with values above 200  $\mu\text{g dm}^{-2}$  for PVAc laminates and even above 1000  $\mu\text{g dm}^{-2}$  for VAE laminates corresponding to the high initial concentrations.

**3.2.1. Migration from polyurethane adhesives.** Migration experiments for laminates elaborated with PU adhesives were carried out using two different food simulants, Tenax® and isooctane (simulant D alternative). A paired *t*-Student's statistical analysis showed significant differences ( $p < 0.01$ ) between the migration in Tenax® and in isooctane, reaching always higher values when Tenax® was used as simulant.

The compounds with the highest Cramer toxicity, 2,6-TDI and TODI (class III), showed a low tendency to migrate to Tenax® or isooctane. 2,6-TDI was below the limit of detection in all the laminates (LOD 4.97  $\text{ng dm}^{-2}$ ) and TODI just migrated from 2 of them and at very low levels, around 2.5  $\mu\text{g dm}^{-2}$  (equivalent to 0.8  $\mu\text{g NCO}$  per  $\text{kg}$  laminate). Both isocyanates are highly reactive so that it can be assumed that they are not stable in the migration test. The unknown compound 3, that showed an isocyanate structure and therefore it is expected to have a class III toxicity, showed migration from all the laminates. BHT was below the limit of detection (4.95  $\text{ng dm}^{-2}$ , equivalent to 0.025  $\text{mg kg}^{-1}$  food simulant) for all the laminates, that means migration values far below its specific migration limit (SML = 3  $\text{mg kg}^{-1}$ ). The compounds with phthalate structure (unknown compounds 6 and 7) showed a low tendency to migrate to the food simulants, only three out of seven laminates showed migration to Tenax®. Moreover, migration values for phthalates, expressed as  $\text{mg kg}^{-1}$  simulant, ranged from 0.0004 to 0.03  $\text{mg kg}^{-1}$  simulant, so they were below the specific migration limit of dibutyl phthalate used as the reference of phthalates (SML = 0, 3  $\text{mg kg}^{-1}$  food). Compounds with adipate structure (unknown compounds 1, 2 and 4) had in general a high tendency to migrate to the food. In fact, the percentages of these compounds migrating from the laminates to the food simulants range from 42% to 96% with the exception of laminate lam\_38. Nevertheless, migration values for adipates expressed as  $\text{mg kg}^{-1}$  simulant ranged from 0.02 to 0.2  $\text{mg kg}^{-1}$ , so they were below the limit of migration of bis(2-ethylhexyl) hexanedioate used as the reference of adipates (SML = 18  $\text{mg kg}^{-1}$ ). It is remarkable that none of the compounds detected in the lam\_38 (PU\_03) migrated to Tenax®. This was probably because for this laminate the substrate in

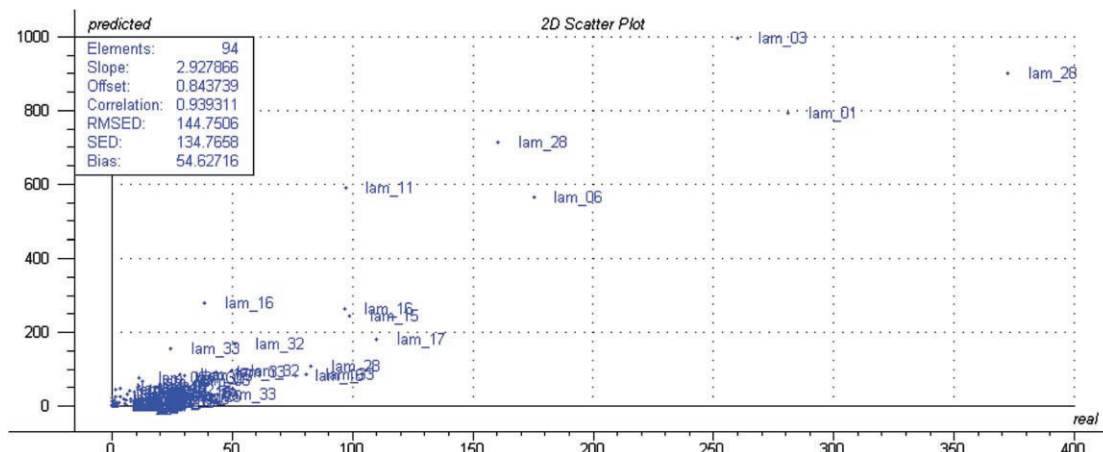


Fig. 2 2D scatter plot of real migration values versus predicted migration values in the 44 laminates studied.

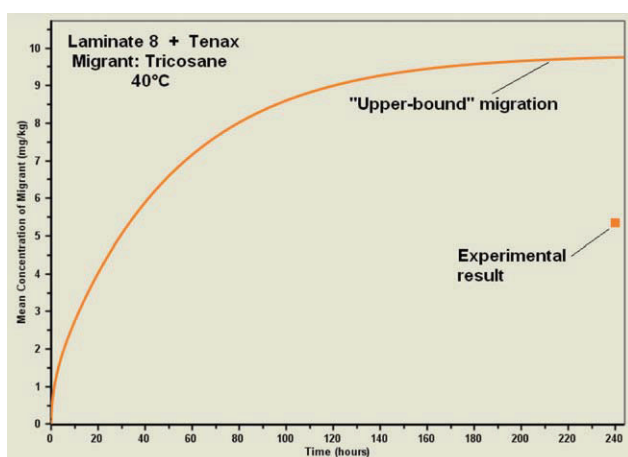


Fig. 3 Estimated time dependent “upper-bound” migration of tricosane from laminate 8 into Tenax® and experimental value at 40 °C.

contact with the food was PE–EVOH–PE. EVOH provides high barrier properties for gases and it is a very polar material, therefore it will affect the mass transfer between the adhesive and the food simulant.<sup>25</sup>

Migration experiments applying different packaging conditions, vacuum, pasteurization and vacuum plus pasteurization, were also carried out. A paired *t*-Student’s statistical analysis comparing standard conditions with each different treatment showed that there were no significant differences ( $p < 0.05$ ) on migration when these different packaging conditions were applied.

**3.2.2. Migration from vinyl adhesives.** Results from vinyl adhesives are shown in Table 6 and 7. Migration from VAE adhesives corresponds to migration from laminate 1 to laminate 11. The major migrant compound was triacetin (glyceryl triacetate), that migrated from all the laminates with concentrations ranging from 0.15 to 1220  $\mu\text{g}$  of compound per  $\text{dm}^2$  of the laminate. According to the Plastics Directive, triacetin is allowed without SML.<sup>3</sup> Migration values were highly dependent on the

initial concentration in the adhesive, for example lam\_07, elaborated with VAE\_03, presented the highest value of migration as well as the highest initial adhesive concentration. On the contrary, the values of migration for the laminates lam\_08, lam\_09 and lam\_10, elaborated with VAE\_04, presented the lowest migration and also the lowest initial concentration. The only compound with class III toxicity, decamethylcyclopentasiloxane was detected in lam\_01 and lam\_03 at a concentration of 0.62 and 1.33  $\mu\text{g dm}^{-2}$  respectively. In order to study the possible risks of this migrant, the estimated daily intake (EDI) was calculated according to the equation.<sup>26</sup>

$$\text{EDI (mg per person per day)} = \text{Mig (mg kg}^{-1}) \times 3 \text{ kg (total food intake per person per day)} \times \text{CF}$$

where Mig is the migration value and CF is the consumption factor, what means the fraction of the daily diet expected to be in contact with a specific packaging material (for adhesives  $\text{CF} = 0.14$ ). The values of EDI corresponded to 0.005 and 0.009  $\mu\text{g}$  per person per day. These values were far below the exposure value recommended by Cramer of 0.09 mg per person per day.<sup>27</sup> For biphenyl, with class II toxicity, found in lam\_08 at a concentration of 0.34  $\mu\text{g dm}^{-2}$ , EDI was also calculated and the valued obtained (0.002  $\mu\text{g}$  per person per day) was below the value recommended by Cramer (0.54 mg per person per day). Other compounds that migrated to Tenax® were dibutyl phthalate and bis(2-ethylhexyl) adipate (lam\_08, lam\_09 and lam\_11), but migration was always below the SML values established by the Plastics Directive<sup>3</sup> that corresponds to 0.3 and 1.5  $\text{mg kg}^{-1}$  respectively.

Migration from PVAc adhesives corresponds to migration from lam\_12 to lam\_17. A similar behavior to VAE laminates was observed. Triacetin, as in VAE laminates, migrated to Tenax® from all the laminates, with values ranging from 2.05 to 255  $\mu\text{g dm}^{-2}$ . There was also migration from the two most toxic compounds according to Cramer, decamethylcyclopentasiloxane and biphenyl, but EDI values, like for VAE, were far below the recommended Cramer exposure values. Dibutyl phthalate and TXIB also migrated from lam\_15, lam\_16 and lam\_17 but migration values were below the SML established in the Plastics

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Directive 2002/72/EC (0.3 and 5 mg kg<sup>-1</sup>).<sup>3</sup> The migration of alkanes such as docosane, tricosane and tetracosane was quite high with respect to their initial concentration (Table 3) and these values of migration decreased, as expected, with increasing molecular weight.

Migration from PVOH adhesives, corresponding to lam\_18, lam\_19 and lam\_20, are shown in Table 7. Only four compounds migrated from lam\_19 and all of them with a low Cramer toxicity class.

**3.2.3. Migration from other adhesives.** In laminates made with the starch adhesive (lam\_21 and lam\_22) migration of any compound was not detected. In the laminates made with the starch plus vinylic adhesive (VS) (lam\_29, lam\_30 and lam\_31) only biphenyl was detected, but its maximum EDI (0.002 mg per person per day) was below the recommended Cramer exposure limits (0.09 mg per person per day).

In lam\_34, made with a hotmelt adhesive, a great number of compounds migrated to Tenax®, and they were similar to those found previously in the migration of an EVA based hotmelt.<sup>15</sup> Most of the compounds were alkanes or derivatives of abietic acid. Only BHT had a SML according to the Plastics Directive 2002/72/EC<sup>3</sup> (3 mg kg<sup>-1</sup>). For laminate lam\_34 the migration value was 0.2 µg dm<sup>-2</sup>, corresponding to 0.02 µg kg<sup>-1</sup> of food, a value far below the SML value. For the rest of compounds with medium and high toxicity EDI values were calculated and all of them were below the recommended Cramer exposure values.

### 3.3. Migration modeling

A proprietary FD method was used to estimate the migration level from the investigated samples. Some of the input parameters for the calculations were determined experimentally (thickness and density of substrates and adhesive as well as the initial concentration of migrant in the adhesives). However the FD algorithm also needs as input data the diffusion coefficients of the migrant in each layer of the laminate–food system as well as migrant partition coefficients at each boundary of this system. For non-homogeneous media like cardboard and paper and, respectively, Tenax® so-called “apparent” diffusion and partition coefficients, see above § 2.8, were used for the calculations. The “exact” value of all these coefficients can be determined by experimental work or can be taken from available literature data. Usually the “exact” value of such diffusion and partition coefficients strongly depends on the very nature of the materials and migrants in a laminate–food system and on the temperature conditions. Changing for example in a laminate a cardboard or polymer layer with another type of cardboard or a similar polymer with a higher density may strongly influence the migration level in the same food. Therefore using diffusion and partition coefficients which were determined from experiments for certain types of materials to other related ones often leads to severe miss estimations of migration. Because of that it was not intended in this work to perform “scientifically exact” migration estimations but computations of so-called “upper-bound” migration levels which are needed for legislative and standardization purposes. The same concept is used in the framework of the Plastics Directive EC/72/2002<sup>3</sup> where migration estimation is recognized as a tool for verification of compliance of a series of

mono-layer plastic materials in contact with liquid food simulants. In the Technical Guide of this Directive recommendations are made on how to obtain for a certain migrant so-called “upper-bound” diffusion and partition coefficients for a specific polymer–food simulant system. The methodology behind the deriving of these “upper-bound” coefficients was to assure that at least 95% of these coefficients have higher values than the real ones found by experimentations and reported in the literature. Using these coefficients in the migration calculations assures in principle that the calculated “upper-bound” migration level are, with a certainty of at least 95%, higher than the migration occurring in reality. This assures a certain consumer safety margin when one compares, in the framework of a compliance test, the calculated “upper-bound” migration level with the specific migration limit (SML) imposed by the EU consumer protection law.

The same rationale was applied in the framework of the MIGRESIVES project. The investigated substrates and adhesives were grouped according to their physical–chemical resemblances. Then, from about 1200 diffusion and partition coefficients obtained from the experimental work done in the project, so-called “reference upper-bound” parameters were specifically derived for each of these groups of substrate materials and adhesives. A list of these groups and the “reference” parameters associated to them is given in the final report of this project.<sup>28</sup> These parameters can now be used to derive case-by-case “upper-bound” diffusion and partition coefficients for compounds migrating from materials and adhesives which are either identical or only similar with those summarized in the said groups. As already mentioned above in the case of cardboards, paper and Tenax® these coefficients are “apparent” ones. For laminates which contained a layer made from a polymer listed in the Technical Guide to the Plastics Directive EC/72/2002 the “upper-bound” diffusion and partition coefficients were calculated with the input parameters specified in this Guide.

The “upper-bound” migration calculation procedure followed in this work is exemplified for one of the investigated laminates. Laminate 8 was made of two cardboards of 479 µm thickness and having a specific weight of 350 g m<sup>-2</sup>. The cardboards were glued with a VAE adhesive using about ~49 g adhesive per m<sup>2</sup>. This adhesive contained initially a series of compounds which might migrate through the cardboard contact layer into a food. One of these compounds is tricosane which had in the VAE adhesive an initial concentration of CP<sub>0</sub> ≈ 87 mg kg<sup>-1</sup>. Tricosane is a non-polar migrant with a molecular weight of M<sub>w</sub> = 324.63 g mol<sup>-1</sup>. Similarly to all laminates investigated in this work laminate 8 was stored in the laboratory at least for one month before starting the migration experiment with Tenax®. It is obvious that during this time tricosane can diffuse from the adhesive and contaminate the two cardboard substrates. The level of contamination with tricosane of the contact layer cardboard has eventually an influence on the time dependent migration of tricosane into Tenax®. The process of cardboard contamination with Tenax® diffusing from the VAE adhesive during the storage in the laboratory can be also simulated with the numerical FD algorithm developed for the migration calculation. Using for cardboard and the VAE adhesive the “reference upper-bound” parameters derived in MIGRESIVES project for this type of materials one obtains, at an assumed mean laboratory temperature of about T = 22 to

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24 °C, the “upper-bound” diffusion and partitioning coefficients for tricosane in laminate 8. The diffusion coefficients are:  $D^* = 4.6 \times 10^{-9} \text{ cm}^2 \text{ s}^{-1}$  for cardboard and  $D = 8.8 \times 10^{-10} \text{ cm}^2 \text{ s}^{-1}$  for the adhesive. The “upper-bound” apparent partition coefficient for tricosane at the adhesive–cardboard interface was taken  $K^*=10$ . The simulation of this process shows that at the end of the 30 days of storage the cardboards exhibit a homogeneous “upper-bound” contamination of  $\sim 4.1 \text{ mg kg}^{-1}$  of tricosane and in the adhesive the concentration of tricosane decreased to a homogeneous level of  $\sim 28.6 \text{ mg kg}^{-1}$ . In reality the contamination with tricosane of the cardboard substrates may be somewhat lower because the real diffusion and partition coefficients are lower than the “upper-bound” ones used in the calculations.

Starting from this result one can now simulate the migration experiments in which on a piece of  $10 \times 10 \text{ cm}^2$  of laminate 8, 4 grams of Tenax® (about  $16 \text{ cm}^3$ ) were poured and spread to form a uniform layer. The thickness of the resulted Tenax® layer is about 1.6 mm. As already mentioned this laminate–food simulant system is then placed for 10 days in an oven thermostatted at 40 °C. Subsequently the amount of tricosane migrated into Tenax® is determined as described above in § 2.6. The input parameters for the numerical simulation of this migration process were again derived from the “reference upper-bound” values listed in the MIGRESIVES project.<sup>28</sup> The diffusion coefficients for tricosane at 40 °C are:  $D^* = 2.9 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$  in cardboard and  $D = 6.0 \times 10^{-9} \text{ cm}^2 \text{ s}^{-1}$  for the adhesive. The apparent “upper-bound” diffusion coefficient of tricosane in Tenax® was taken  $D_F^* = 9.2 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ . The “upper-bound” apparent partition coefficients for tricosane were taken  $K^* = 10$  and  $K^* = 0.1$  at the adhesive–cardboard and, respectively, the cardboard–Tenax® interface. The  $K^*$  at the cardboard–Tenax® boundary can be brought in relationship with the high adsorption potential of Tenax®.

The results of the migration simulation are shown in Fig. 2 along with the result obtained experimentally  $C_F \approx 5.3 \text{ mg kg}^{-1}$ . From Fig. 3, one can see that, as expected, the “upper-bound” migration estimation lead to a higher migration level as that determined experimentally. Moreover one can see that after 10 days at 40 °C the “upper-bound” migration process reaches almost equilibrium at a concentration level of  $\sim 9.7 \text{ mg kg}^{-1}$ . However in reality this may not be the case because the real diffusion coefficients in the experiment are lower than the “upper-bound” ones. Therefore one can assume that in reality the migration of tricosane in Tenax® proceeds at a lower pace and thus after 10 days at 40 °C the laminate 8–Tenax® system is not yet close to a thermodynamic equilibrium. The same procedure was applied to 142 experimental results obtained in the migration experiments with Tenax®.

A Pearson correlation between predicted and real migration values was carried out obtaining a correlation factor of 0.94 (Fig. 2). Most of the calculated “upper-bound” migration levels exceeded the measured values. In 93% of cases the ratio calculated *versus* experimental migration,  $C_F^{\text{calc}}/C_F^{\text{exp}}$ , was bigger than one. Taking into account the analytical tolerance of the migration measurements as well as the accuracy of determining experimentally the thickness, density and initial concentration of migrant in each layer of the laminates, for  $0.8 < C_F^{\text{calc}}/C_F^{\text{exp}} < 1.2$ , one can consider that the modelling reflects directly the

measurement. 8% of the calculated migration levels were in this range. Thus one can state that 95% of all simulations met or overestimated the measured migration. 87% had a  $C_F^{\text{calc}}/C_F^{\text{exp}}$  higher than 1.2.

#### 4. Conclusions

A wide variety of compounds was found in the adhesives study. Their composition highly depends on the nature of the adhesive. A 57% of the number of compounds detected in the materials itself migrated onto the Tenax®, even though the adhesives were not in direct contact with food, which confirms the necessity of controlling the composition of the adhesives used for food contact materials. These 45 market samples, manufactured with 29 different adhesive formulations (belonging to seven different adhesive types) and various materials from cardboard and paper to plastic films and combinations of both, provided a set of 142 initial concentrations and migration data. These data give a valuable and broad base for checking the applicability of the migration model and the upper-bound reference parameters to real market samples. Using these data the modelled and the measured ones showed a good correspondence or slight overestimation by modelling in most cases.

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