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ARTICLE

Study of the Migration of Photoinitiators Used in Printed Food-Packaging Materials into Food Simulants

Ana Sanches-Silva,[†,§] Catarina Andre,[§] Isabel Castanheira,[§] José Manuel Cruz,[†,#] Sarah Pastorelli,[⊥] Catherine Simoneau,[⊥] and Perfecto Paseiro-Losada*[,†]

[†]Department of Analytical Chemistry, Nutrition and Food Science, Faculty of Pharmacy, University of Santiago de Compostela, E-15782 Santiago de Compostela, Spain, [§]National Institute Dr. Ricardo Jorge, Lisbon, Portugal, [#]Chemical Engineering Department, ETSEI, University of Vigo, Pontevedra, Spain, and [⊥]Joint Research Centre (JRC), Ispra, Italy

Photoinitiators (PIs) are used as catalyzers for inks and lacquers that are cured with ultraviolet (UV) light, and they can contaminate foodstuffs by mass transference.The aim of the present paper is to study the migration of six photoinitiators (Irgacure 184, benzophenone, Irgacure 651, Irgacure 907, ITX, and EHA) into food simulants [distilled water, 3% acetic acid (w/v) in aqueous solution, 10, 20, 30, 60 and 95% ethanol (v/v) in aqueous solution]. Migration levels of the six PIs into different food simulants were compared after a 30 day contact period with the additivated plastic. A relationship between R (ratio between log $K_{o/w}$ and MW) and total migration was found for PIs with log $K_{o/w} < 5$. Key parameters of migration processes were calculated according to a mathematical model based on Fick's second law. Diffusion (D) and partition coefficients were estimated and compared among different simulants, temperatures, and PIs to understand better the mechanisms of the migration process and the physicochemical properties that most influence this phenomenon. For instance, at 5 °C, in ethanol 95% (v/v), D ranged between 4.2×10^{-11} cm/s for Irgacure 907 and 3.0×10^{-9} cm/s for benzophenone.

KEYWORDS: Photoinitiators; food packaging; food simulants; high-performance liquid chromatography; ultraviolet detection

INTRODUCTION

Until now, the European Union (EU) has not defined specific legislation on printing inks for food-packaging materials, with the exception of Directive 93/10/EEC related to materials and articles made of regenerated cellulose film. This directive states that "to protect the health of the consumer, direct contact between foodstuffs and the printed surfaces of regenerated cellulose film should be avoided" (*1*).

Frame Regulation (EC) No. 1935/2004, which concerns materials and articles intended to come into contact with foodstuffs, requires that food contact materials should not endanger human health, change the composition of the food, or alter the organoleptic properties of the food (*2*). All food contact materials, even printing inks applied on the non-food-contact surface of packaging, must satisfy the requirements of the regulation. Additionally, European Commission Regulation (EC) 2023/2006 related with good manufacturing practice (GMP) for materials and articles intended to come into contact with food also makes specific reference to printing inks applied to the non-food-contact side, indicating that GMP should ensure that these substances are not transferred into food by set-off (effects that result from the contact of the external printed face of the packaging with the inner nonprinted face) or transfer through the substrate (*3*).

*Corresponding author (telephone +34 981 598 450; fax + 34 981 594 912; e-mail perfecto.paseiro@usc.es).

The European Council has approved Resolution ResAP-(2005)2 on packaging inks applied to the non-food-contact surface of food-packaging materials and articles intended to come into contact with foodstuffs, which, although not legally obligatory, can be considered as a reference text until the European Union establishes specific regulations relating to inks (*4*).

Photoinitiators (PIs) are used as catalyzers for inks and lacquers that are cured with ultraviolet (UV) light, and they can contaminate foodstuffs by mass transference (*5*, *6*). PIs may be present in paper, cartonboard, or plastic food-packaging materials as a residue from UV-cured inks and lacquers used to print on the packaging. PIs may also be present in printed secondary packaging and in recycled printed paper or board if the recycling process has not fully eliminated it.

One of the most common PIs is benzophenone, which has been shown to migrate from such secondary packaging through the packaging layer in direct contact with food and into the food itself (*7*). Although there are no specific EU controls for migration from inks to foodstuffs, there is a Group Tolerable Daily Intake (Group TDI) for benzophenone of 0.01 mg/kg of body weight. Moreover, there is a specific migration limit (SML) for benzophenone of 0.6 mg/kg according to Directive 2002/72/EC.

Isopropylthioxanthone (ITX) has been the target of a food alert, notified by the Rapid Alert System for Food and Feed

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(RASFF), because it has been found in milk and fruit beverages packed in UV-printed cartons (*8*). As a consequence of this alert, over 30 million liters of ready-to-feed infant formula was taken back by producers in Portugal, Italy, France, and Spain in 2005 (*9*, *10*). The European Food Safety Authority (EFSA) has carried out a risk assessment on ITX by request of the European Commission; the opinion of the scientific panel on food additives, flavorings, processing aids, and materials in contact with food and the existing in vivo genotoxicity studies do not indicate a genotoxic potential for ITX (*11*). ITX can be found in foodstuffs as result of the set-off effect (*5*, *9*) or because of migration from the external face if no barrier is applied (*11*). The amount of fat (in the case of milk) or the presence of fibers (in the case of orange juice) can contribute to the ITX migration from packaging to the foodstuff (*12*).

Apart from benzophenone and ITX, we have selected another four PIs to carry out the present work. These PIs are Irgacure 184, Irgacure 651, Irgacure 907, and EHA. Anderson and Castle (*13*) have developed one of the few available methods for the determination of benzophenone in food-packaging materials (cartonboard) samples by GC-MS. For food analysis the detection limit was 0.01 mg kg^{-1} and the quantification limit 0.05 mg kg^{-1}. Benzophenone has also been determined with compounds in a multilayer plastic−paper food packaging (*14*) and PET flakes (*15*) by GC-MS. Triantafyllou and co-workers (*16*) have also studied benzophenone migration from recycled paperboard packaging materials to solid matrices (semolina, baby cream, and milk powder) together with another nine migrants. As far as we know there are few analytical methods available for the determination of ITX in foodstuffs: milk (*5*, *9*, *10*); beverages (*12*); and just two are multimethods that determine PIs (*17*, *18*) (benzophenone, Irgacure 184, benzylketal BDK, Irgacure 907, ITX) in aqueous simulants, but they do not calculate key parameters (diffusion and partition coefficients) of migration process.

In a previous work carried out in our laboratory, a multimethod was optimized for the detection and quantification by HPLC-DAD of these six photoinitiators in milk and respective packaging (*19*). Confirmation was performed by LC-MS (TOF). The method was applied to baby milks, their respective packaging, and other dairy product packaging from both industry and local supermarkets.

The aim of the present paper is to study the migration of photoinitiators into seven food simulants (three of them are authorized by EU legislation). Migration levels of the six PIs into different simulants were compared after a 30 day contact period with the additivated plastic. Key parameters of migration processes were calculated according to a mathematical model based on Fick's second law. Diffusion and partition coefficients were estimated and compared among different simulants, temperatures, and PIs to understand better the mechanisms of the migration process and the physicochemical properties that most influence this phenomenon.

EXPERIMENTAL PROCEDURES

Chemicals, Standards, and Samples. Six PIs were chosen: Irgacure 184, benzophenone, Irgacure 651, Irgacure 907, ITX, and EHA. Irgacure and quantacure are trademarks. They were all supplied from Aldrich (Madrid, Spain) (purity = 99%). Interesting physicochemical information about these PIs is included in **Table 1**. Acetonitrile (ACN) and ethanol were of analytical grade, and they were purchased from Merck (Darmstadt, Germany). Ultrapure water was prepared using a Milli-Q filter system (Millipore, Bedford, MA).

Calibrations. A primary stock solution of each photoinitiators (1.0 mg/mL) was prepared by dissolving 100 mg of each PI into 100 mL of EtOH. Subsequent dilutions were prepared also in ACN in the range of 0.1−10.9 μg/mL for the HPLC-UV calibration curves. Each calibration curve consisted of a plot of peak area of each photoinitiator against the concentration of the standard calibration solutions. Calibration lines were linear from the lowest concentration to the highest standard (*19*).

Solutions were stored in a refrigerator (5 °C) in glass bottles, and they were stable during the period of study.

Additivation of Films. Films were additivated with PIs using an in-house method optimized in our laboratory and involving the preparation of two reservoirs (sources) with a polyethylene (PE) wax to incorporate model migrants in low-density polyethylene (LDPE) films (*19*) like a sandwich. The PE wax used was Licowax PE 520 (nonpolar and low molecular polyolefin waxes; drop point, 120 °C; density, 0.93 g/cm^3). PE granules were ground with a commercial grinder, and the resulting powder was homogenized. PE waxes were supplied by Clariant Ibérica, S.A. (Barcelona, Spain). To prepare reservoirs of these compounds, 40 g of PE wax was weighed and carefully mixed with approximately 0.5 g of each PI. The film used was a LDPE film (thickness, 450 μm; density, 0.92 g/cm^3). The concentrations of the different PIs achieved in the LDPE film (later called $M_{P,0}$) were 1876 mg/kg for Irgacure 184, 2717 mg/kg for benzophenone, 1976 mg/kg for Irgacure 651, 1787 mg/kg for Irgacure 907, 5223 mg/kg for ITX, and 3254 mg/kg for EHA.

Migration Tests. Strips of plastic film (2 × 1 cm) additivated with the six PIs were used to carry out the kinetic migration. We considered that migration was occurring by both sides (surface area = 4 cm^2). Strips were immersed in 20 mL of simulant, and an aliquot (0.5 mL) of simulant was taken after 1, 2, 4, 10, 20, and 30 days and directly injected in the HPLC-UV after filtration by 0.45 μm filter. Tests were carried out at three temperatures: 5, 25, and 40 °C. Simulants used were distilled water (simulant A); 3% acetic acid (w/v) in aqueous solution (simulant B); and 10, 20, 30, 60, and 95% ethanol (v/v) in aqueous solution. The migration levels calculated for the kinetic curves were corrected by taking into account the volume taken for each measurement.

HPLC-UV Analysis. Separation was achieved on a Kromasil 100 C18 (15 cm × 0.4 cm i.d., 5 μm particle size) analytical column from Teknokrom (Barcelona, Spain). The mobile phase was 20% ACN/80% water in the first two minutes, and then ACN was gradually increased to achieve 80% ACN/20% water at 20 min and 100% ACN at 23 min. The total run time of each analysis was 30 min, to ensure cleaning of the column between samples. The flow rate was 1.0 mL/min, and the injection volume was 50 μL. The HPLC system (Hewlett-Packard, Waldbronn, Germany) was fitted with a HP1100 quaternary pump, a degassing device, an autosampler, a column thermostating system, and a diode array UV detector. The detector was continuously performing a scan in the range from 190 to 400 nm. No reference wavelength was used, and the bandwidth used was 4 nm for all wavelengths. Irgacure 184 was detected at 246 nm, benzophenone and Irgacure 651 were detected at 256 nm, Irgacure 907 was detected at 306 nm, EHA was detected at 310 nm, and ITX was detected at 386 nm. PIs were identified by comparison of their retention time and UV spectra with those of an injected pure standard using the same HPLC conditions.

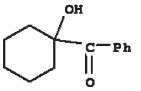
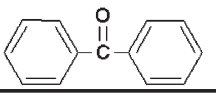
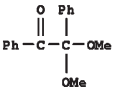
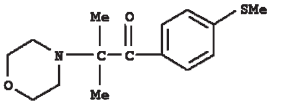
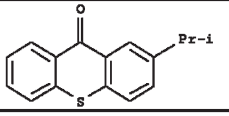
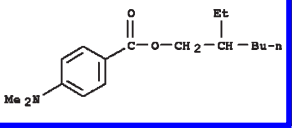
Mathematical Models. A mathematical modeling based on Fick's second law (eq 1) was used to predict PIs migration from food-packaging films into simulants. This differential equation provides a general description of migration of an additive or contaminant from an amorphous polymeric packaging film:

$$\frac{\partial C_P}{\partial t} = D_P \frac{\partial^2 C_P}{\partial x^2} \quad (1)$$

C_P (mg/kg) is the concentration of the migrant in the polymer, P, at time t (s) and position x in P, and D_P is the diffusion coefficient in P (cm^2/s).

In our particular case, to enable use of this model in the case of the polymer−food simulant under study, an effective (for the whole polymer− food simulant system) diffusion coefficient D, rather than D_P,

Table 1. Physicochemical Information about the Selected Photoinitiators

MIGRANTS	CAS N°	Chemical Name	MW	Water solubility* (g/L)	Log $K_{o/w}$**	Structure
Irgacure 184	947-19-3	Methanone, (1-hydroxycyclohexyl)phenyl	204.2	0.49	2.34	
Benzophenone	119-61-9	Metanone Diphenyl	182.2	0.13	3.18	
Irgacure 651	24650-42-8	Ethanone, 2,2-dimethoxy-1,2-diphenyl	256.3	0.06	4.75	
Irgacure 907	71868-10-5	1- propanone, 2- methyl-1-[4-(methylthio)phenyl]-2-(4-morpholinyl	279.4	0.06	3.00	
ITX	5495-84-1	9H- Thioxanthen-9-one, 2-(1-methylethyl)	254.3	5.1 x 10^{-04}	5.33	
EHA	21245-02-3	Benzoic acid, 4-(dimethylamino)-, 2-ethylhexyl ester	277.4	2.1 x 10^{-03}	6.15	

* SciFinder 2006 predicted data at pH 7 and 25 °C. ** Scifinder 2006 predicted data.

was included. In the following discussion, D_P will be replaced when appropriate by this effective D value. In this way a simplified but pragmatic mathematical model can be applied. Equation 1 can be resolved to express the amount of migrant released per area unit (A) from the polymer (P) into food (F) at time t and expressed as (*20*−*22*)

$$\frac{M_{F,t}}{A} = c_{P,0}\rho_P d_P\left(\frac{\alpha}{1+\alpha}\right)\times\left[1-\sum_{n=1}^{\infty}\frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2}\exp\left(-D_P t\frac{q_n^2}{d_P^2}\right)\right] \quad (2)$$

with

$$\alpha = \frac{1}{K_{P/F}}\frac{V_F}{V_P}$$

where $M_{F,t}$ = mass of migrant from P into F after time t (μg); A = area of P in contact with F (cm^2); $C_{P,0}$ = initial concentration of migrant in P (mg/kg); ρ_P = density of P, (g/cm^3); t = migration time (s); d_p = thickness of P (cm); V_P = volume of P (cm^3); V_F = volume of F (cm^3); q_n = the positive roots of the equation tan $q_n = -\alpha q_n$; D_P = diffusion coefficient of migrant in P (cm^2/s); and $K_{P/F}$ = the partition coefficient of the migrant between P and F.

To predict theoretical migration, the first step was to calculate the positive roots of the equation tan $q_n = -\alpha q_n$.

The greater the number of roots, the more reliable the results are. Nevertheless, because of the considerable amount of work involved in the calculation, and to make the estimation feasible, 12 roots ($1 \le n \le 12$) were calculated for $0.01 \le \alpha \le 1000$. To measure the fit between experimental and estimated data, the percent root of the mean-square error (% RMSE) was calculated as (*23*)

$$\mathrm{RMSE}(\%) = \frac{1}{M_{P,0}}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left((M_{F,t})_{\mathrm{exptl}} - (M_{F,t})_{\mathrm{pred},i}\right)^2}\times 100 \quad (3)$$

where N is the number of experimental points per migration curve, i is the number of observations, and $M_{P,0}$ is the initial amount of migrant in the polymer (μg).

RESULTS AND DISCUSSION

Migration Levels. Data from migration into foods is preferred over data from food simulants (*24*, *25*). However, they are still many substances for which there is still no available method of extraction, and in these cases, food simulants are used to carry out kinetic migrations. To evaluate the migration levels and diffusion coefficients of the photoinitiators, migration studies were performed at three temperatures over a wide range of time. A large amount of migration data was obtained, and it was used to calculate the diffusion coefficients according to a mathematical modeling based on Fick's second law. **Figures 1** and **2** show HPLC chromatograms of simulants after 30 days of direct contact with the additivated plastic film. **Figure 1** corresponds to a migration test carried out with distilled water and **Figure 2** the same but with ethanol 95% (v/v). EHA has not migrated into water, acetic acid, ethanol 10%, or ethanol 20%. The same has occurred with ITX into water and acetic acid 3%. This could be due to the very low water solubility of ITX and EHA in water (see data in **Table 1**). All other model migrants have migrated into all simulants.

In the following subsections the different factors that might contribute to differences among migration tests will be evaluated and discussed.

Differences among Food Simulants. The results of the migration levels found in all food simulants at 5, 25, and 40 °C are given in **Figure 3**. Distilled water was the simulant presenting the lowest levels of migrants.

Generally, total migration (M, migration of a certain photoinitiator after 30 days of plastic strip immersion into food simulant) tends to increase with greater percentage of ethanol in the food simulant. However, this effect is not so relevant for Irgacure 184, at all temperatures.

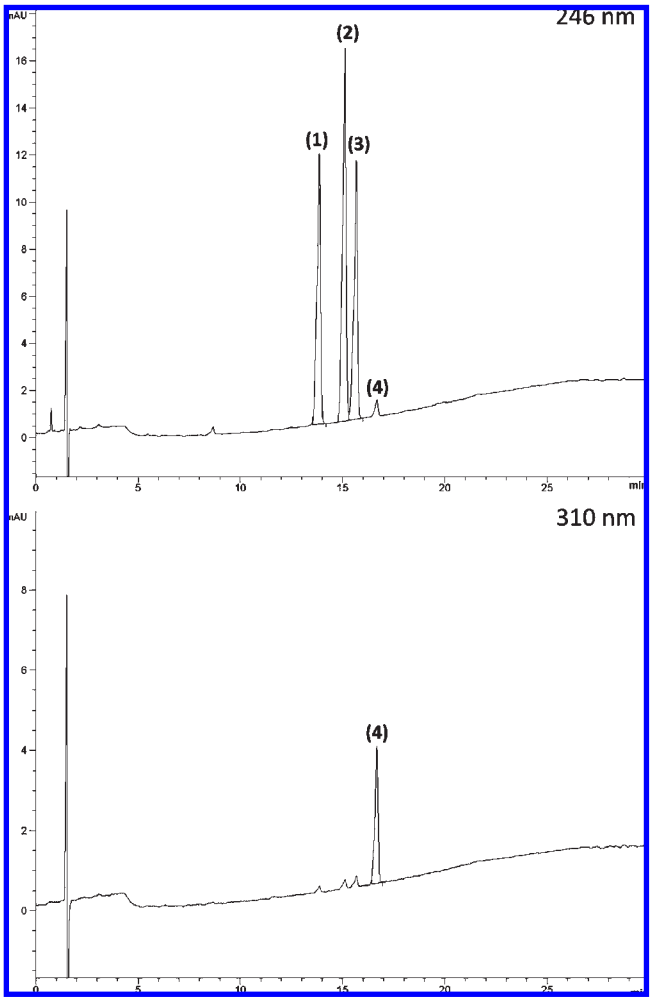


Figure 1. HPLC chromatogram of simulant A (distilled water) after 30 days of contact with the additivated plastic film: (1) Irgacure 184; (2) benzophenone; (3) Irgacure 651; (4) Irgacure 907.

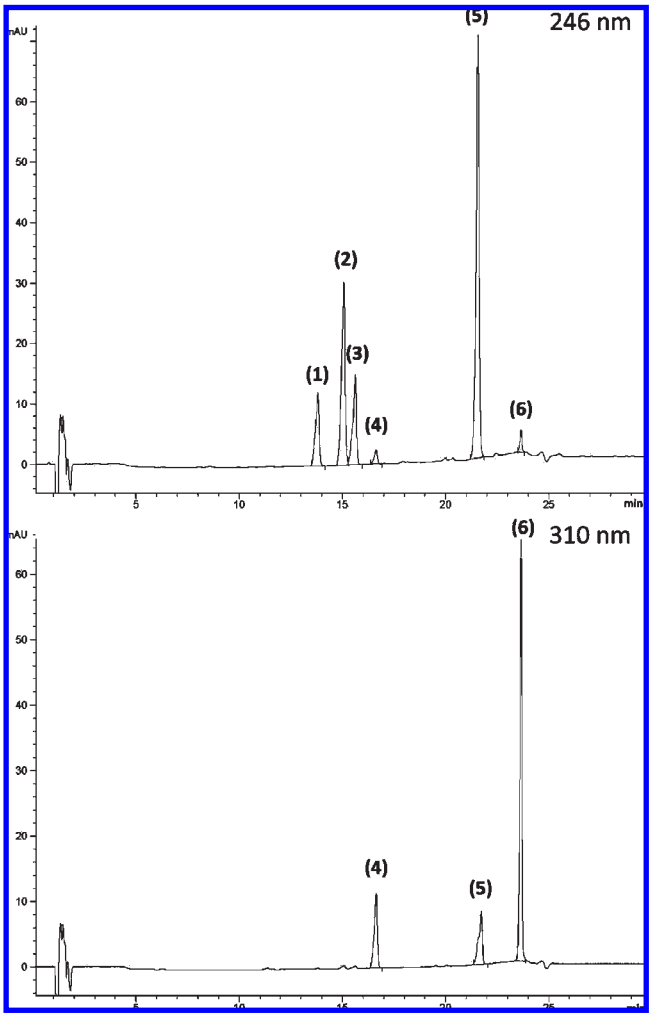


Figure 2. HPLC chromatogram of substitute of simulant D (EtOH 95%) after 30 days of contact with the additivated plastic film: (1) Irgacure 184; (2) benzophenone; (3) Irgacure 651; (4) Irgacure 907; (5) ITX; (6) EHA.

For instance, in the case of benzophenone there is a considerable increase among migration into distilled water and EtOH 10, 20, and 30% (v/v), but at 25 and 40 °C these differences are not so relevant between EtOH 20% and 30%. For Irgacure 651, total migration increases among water, EtOH 10%, and EtOH 20%, and there are very similar migration levels among EtOH 30%, 60%, and 95%.

With ITX there was no migration of this PI into water due to its low water solubility (**Table 1**); however, migration increased with the percentage of EtOH in the simulant. At 5 °C, M was 57, 50, 22, and 5 times higher for EtOH 95%, EtOH 60%, EtOH 30%, and EtOH 20%, respectively, than for EtOH 10%. This has been verified to happen at the three temperatures, but this effect is more relevant at 40 °C. EHA has not migrated into water and EtOH 10% and 20%, also because of its low water solubility (**Table 1**). Migration has increased with EtOH content of food simulant among EtOH 30%, 60%, and 95%. Differences among these simulants are more relevant at 5 °C, at which EtOH 95% and 60% have migration levels about 8.4 and 4.6 times higher than ethanol 30%.

Differences among Photoinitiators (*Effect of the Photoinitiator*). An overview of **Figure 3** let us observe that it is possible to divide PIs into two groups. One group was constituted by Irgacure 184, Irgacure 651, benzophenone, and Irgacure 907, with which differences of the M among different food simulants are not substantial, and a second group, constituted by ITX and EHA, showed relevant differences among different food simulants.

Table 2 shows the relationship among migration levels found for different model migrants. With regard to the first group, among the highest M was found for Irgacure 651 and/or benzophenone and the lowest for Irgacure 907. In the second group, M was always higher for ITX than for EHA. To find an explanation for these findings, physicochemical information was evaluated, and it revealed that the combination of two properties, the molecular weight (MW) and the lipophilicity, may be the responsible for these results. Generally the higher is the MW, the lower is migration, and the higher is lipophilicity, the higher is migration. To simplify, a ratio (R) between log $K_{o/w}$ and MW was calculated. The following relationships were achieved: Irgacure 907 (R = 0.01073) < Irgacure 184 (R = 0.01148) < benzophenone (R = 0.01745) and Irgacure 651 (R = 0.01853) < ITX (R = 0.02096) < EHA (R = 0.02217). For those PIs that correspond to the first group, the lower is R, the lower is M. This relationship between R and M was not found for the second group, which has the PIs with highest log $K_{o/w}$ (> 5). In this group, M is always higher for ITX, which has lower MW than EHA (see **Table 1**).

The ratio R can also be related with the variation among M values. Irgacure 907 and Irgacure 184, which have the lowest R values, presented fewer differences among M, whereas ITX and

EHA (highest R values) presented the most relevant differences among PIs.

Determination of Key Parameters and Prediction of Migration Levels. One of the main difficulties of migration tests is the scarce availability of suitable methods that originate reliable results by means of using simple sample preparation and quantification methods.

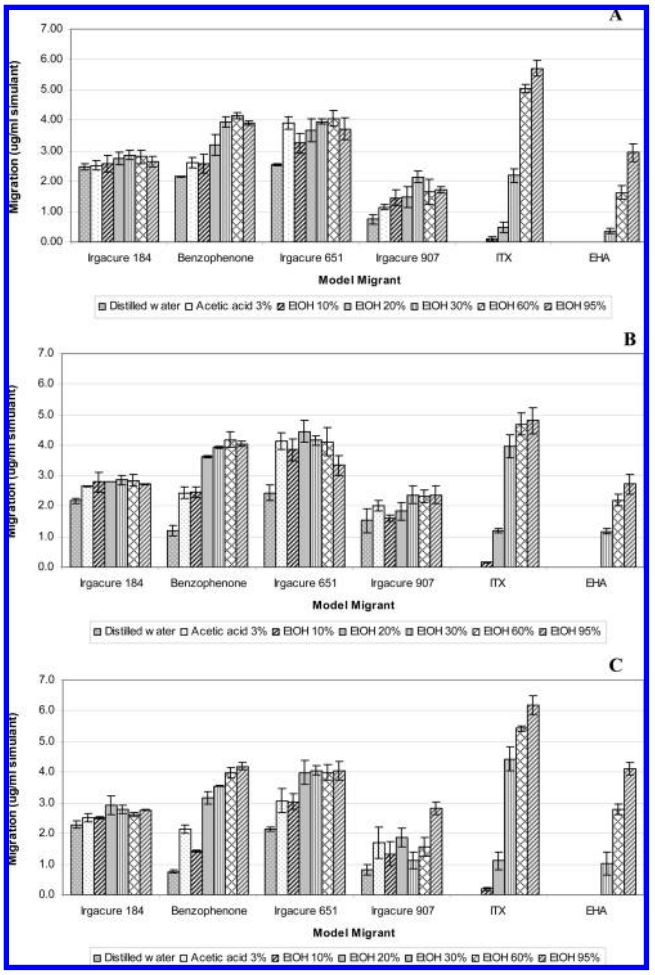


Figure 3. Effect of the simulant on the migration at (**A**) 5 °C, (**B**) 25 °C, or (**C**) 40 °C after 30 days of immersion of the plastic film into the food simulant.

In line with this, the application of recognized models to predict migration can bring great benefits, and it is authorized by the European Union legislation (*26*).

The most relevant advantages of migration prediction are (1) reduction of the number of migration tests required; (2) the time involved in the analysis; (3) the cost of solvents and equipment; (4) the number of qualified technicians required to carry out the analysis.

The food and polymer industries and laboratories (responsible for the compliance of legislation and food safety) are those who can obtain greater and direct profits from the use of this new tool. Moreover, consumers will also receive indirectly the advantages of this new methodology because the money saved by the food industry to check the safety of their products can be derived in new food technology or be reflected in a reduction of food prices.

Calculation of D and $K_{P/F}$ Coefficients. **Tables 3**−**6** present D and $K_{P/F}$ coefficients calculated with eq 2. These key parameters have been calculated for all model migrants into all food simulants except for those with which migration was not found due to the low water solubility of the photoinitiator in the aqueous food simulants and for benzophenone at 25 and 40 °C, because it did not originate any concentration profile into water, acetic acid, ethanol 10%, and ethanol 20%.

Correlation between Predicted and Experimental Data. **Figure 4** shows the migration kinetics with the experimental and predicted migration values of all PIs into EtOH 95% at 5 °C. **Figure 5** shows the migration kinetics with the experimental and predicted migration values of Irgacure 907 into EtOH 95% at 5, 25, and 40 °C.

A good correlation was found between experimental and estimated migration values as can be observed by the low RMSE values (see **Tables 3**−**6**). RMSE values were always lower than 3%, except for Irgacure 651 into acetic acid 3% and Irgacure 184 and Irgacure 907 into ethanol 60% (v/v). This value was calculated by eq 3 as described in a previous section. This indicates that the proposed model can be used to predict PIs migration into different food simulants.

Table 2. Relationship among Photoinititators: Total Migration after 30 Days of Total Immersion of an Additivated Plastic Film into Different Food Simulants at Different Temperatures

food simulant	temp (°C)	relationship among photoinititators total migration after 30 days
distilled water	5 and 25	$M_{\text{Irgacure 651}} \sim M_{\text{Irgacure 184}} > M_{\text{benzophenone}} > M_{\text{Irgacure 907}}$
	40	$M_{\text{Irgacure 651}} \sim M_{\text{Irgacure 184}} > M_{\text{benzophenone}} > M_{\text{Irgacure 907}}$
acetic acid 3%	5, 25, and 40	$M_{\text{Irgacure 651}} > M_{\text{Irgacure 184}} \sim M_{\text{benzophenone}} \sim M_{\text{Irgacure 907}}$
ethanol 10% (v/v)	5 and 25	$M_{\text{Irgacure 651}} > M_{\text{benzophenone}} \sim M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}} > M_{\text{ITX}}$
	40	$M_{\text{Irgacure 651}} > M_{\text{Irgacure 184}} > M_{\text{benzophenone}} \sim M_{\text{Irgacure 907}} > M_{\text{ITX}}$
ethanol 20% (v/v)	5 and 25	$M_{\text{Irgacure 651}} > M_{\text{benzophenone}} > M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}} > M_{\text{ITX}}$
	40	$M_{\text{Irgacure 651}} > M_{\text{benzophenone}} \sim M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}} > M_{\text{ITX}}$
ethanol 30% (v/v)	5	$M_{\text{benzophenone}} \sim M_{\text{Irgacure 651}} > M_{\text{Irgacure 184}} > M_{\text{ITX}} \sim M_{\text{Irgacure 907}} > M_{\text{EHA}}$
	25	$M_{\text{benzophenone}} \sim M_{\text{Irgacure 651}} \sim M_{\text{ITX}} > M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}} > M_{\text{EHA}}$
	40	$M_{\text{ITX}} > M_{\text{benzophenone}} > M_{\text{Irgacure 651}} > M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}} > M_{\text{EHA}}$
ethanol 60% (v/v)	5	$M_{\text{ITX}} > M_{\text{benzophenone}} \sim M_{\text{Irgacure 651}} > M_{\text{EHA}} > M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}}$
	25 and 40	$M_{\text{ITX}} > M_{\text{benzophenone}} \sim M_{\text{Irgacure 651}} > M_{\text{Irgacure 184}} > M_{\text{EHA}} \sim M_{\text{Irgacure 907}}$
ethanol 95% (v/v)	5 and 25	$M_{\text{ITX}} > M_{\text{benzophenone}} > M_{\text{Irgacure 651}} > M_{\text{EHA}} > M_{\text{Irgacure 184}} > M_{\text{Irgacure 907}}$
	40	$M_{\text{ITX}} > M_{\text{benzophenone}} \sim M_{\text{Irgacure 651}} \sim M_{\text{EHA}} > M_{\text{Irgacure 184}} \sim M_{\text{Irgacure 907}}$

Table 3. Key Parameters Calculated for Water and Acetic Acid 3%

food simulant	photoinitiator	temp (°C)	D (cm^2/s)	α	RMSE (%)	$K_{P/F}$
distilled water	Irgacure 184	5	6.3×10^{-10}	0.20	1.66	1111
		25	3.2×10^{-9}	0.20	1.34	1111
		40	4.9×10^{-9}	0.19	1.38	1170
	Irgacure 651	5	2.0×10^{-10}	0.19	1.86	1170
		25	3.6×10^{-9}	0.19	0.61	1170
		40	6.0×10^{-9}	0.18	1.07	1235
	Irgacure 907	5	2.4×10^{-11}	0.05	0.57	4273
		25	2.5×10^{-10}	0.11	0.26	1932
		40	6.8×10^{-10}	0.07	0.21	293
acetic acid 3%	Irgacure 184	5	5.1×10^{-10}	0.20	1.27	1111
		25	1.8×10^{-9}	0.22	1.49	1010
		40	2.5×10^{-9}	0.20	1.51	1111
	Irgacure 651	5	1.5×10^{-10}	0.46	1.77	483
		25	1.2×10^{-9}	0.37	2.61	601
		40	5.9×10^{-9}	0.40	3.69	556
	Irgacure 907	5	3.4×10^{-11}	0.06	1.02	3704
		25	7.0×10^{-10}	0.15	1.59	1481
		40	1.67×10^{-9}	0.11	0.61	2020

Table 4. Key Parameters Calculated for Ethanol 10% (v/v) and Ethanol 20% (v/v)

food simulant	photoinitiator	temp (°C)	D (cm^2/s)	α	RMSE (%)	$K_{P/F}$
ethanol 10% (v/v)	Irgacure 184	5	7.0×10^{-10}	0.20	1.42	1111
		25	1.3×10^{-9}	0.22	1.64	1010
		40	1.7×10^{-9}	0.20	1.09	1111
	Irgacure 651	5	3.1×10^{-10}	0.25	1.56	889
		25	2.1×10^{-9}	0.29	1.60	766
		40	2.5×10^{-9}	0.25	1.57	889
	Irgacure 907	5	1.7×10^{-10}	0.08	0.91	2963
		25	2.4×10^{-10}	0.08	0.73	2963
		40	5.8×10^{-10}	0.10	0.80	2222
ethanol 20% (v/v)	Irgacure 184	5	5.93×10^{-10}	0.24	1.46	926
		25	2.3×10^{-9}	0.27	1.58	823
		40	4.6×10^{-9}	0.24	1.39	926
	Irgacure 651	5	2.7×10^{-10}	0.39	2.96	570
		25	2.6×10^{-9}	0.38	1.68	585
		40	9.1×10^{-9}	0.33	2.01	673
	Irgacure 907	5	9.7×10^{-11}	0.10	0.70	2222
		25	1.4×10^{-10}	0.12	0.36	1778
		40	1.6×10^{-10}	0.12	0.68	1852
	ITX	5	2.5×10^{-12}	0.02	0.61	8889
		25	8.8×10^{-12}	0.03	0.24	7407
		40	1.0×10^{-10}	0.04	0.41	5168

Generally, RMSE values found for food simulants are lower than those found for food matrices such as powdered milk (*27*).

Parameters That May Influence D (*Temperature, Photoinitiator MW, and Food Simulant*). In previous works the molecular weight of model migrants has been correlated with the diffusion coefficients. This influence of MW in the migration process was found in other work carried out with diphenylbutadiene (DPBD) and triclosan (*28*), which has concluded that the higher is the MW, the slower are diffusion rates. In most of the cases, Irgacure 184 and benzophenone presented the highest diffusion coefficients; this is probably due to the lower molecular weight of these two substances compared with the other PIs studied. At 25 and 40 °C an exception was observed; Irgacure 651

Table 5. Key Parameters Calculated for Ethanol 30% (v/v) and Ethanol 60% (v/v)

food simulant	photoinitiator	temp (°C)	D (cm^2/s)	α	RMSE (%)	$K_{P/F}$
ethanol 30% (v/v)	Irgacure 184	5	7.5×10^{-10}	0.22	0.47	1010
		25	2.3×10^{-9}	0.21	0.70	1058
		40	2.4×10^{-9}	0.22	0.86	1010
	benzophenone	5	2.6×10^{-9}	0.21	0.66	1058
		25	3.1×10^{-9}	0.21	0.48	1058
		40	6.2×10^{-9}	0.18	1.11	1235
	Irgacure 651	5	3.5×10^{-10}	0.32	0.51	694
		25	2.9×10^{-9}	0.31	0.72	717
		40	4.4×10^{-9}	0.32	1.04	694
	Irgacure 907	5	9.6×10^{-11}	0.14	1.11	1587
		25	5.0×10^{-10}	0.08	0.27	2963
		40	4.2×10^{-10}	0.05	0.26	4115
	ITX	5	2.8×10^{-11}	0.08	1.24	2963
		25	3.7×10^{-10}	0.10	0.43	2222
		40	2.4×10^{-9}	0.10	1.44	2222
	EHA	5	3.0×10^{-10}	0.01	0.73	22222
		25	5.0×10^{-10}	0.04	0.25	6349
		40	3.3×10^{-9}	0.04	0.25	6349
ethanol 60% (v/v)	Irgacure 184	5	2.9×10^{-10}	0.64	3.09	347
		25	4.0×10^{-10}	0.60	3.76	370
		40	4.2×10^{-10}	0.62	3.75	358
	benzophenone	5	6.2×10^{-10}	0.29	1.07	766
		25	7.0×10^{-10}	0.31	1.62	717
		40	7.1×10^{-10}	0.32	0.91	694
	Irgacure 651	5	3.3×10^{-10}	0.52	2.49	427
		25	1.2×10^{-9}	0.47	1.87	472
		40	1.3×10^{-9}	0.47	2.49	472
	Irgacure 907	5	8.5×10^{-11}	2.00	6.35	111
		25	1.5×10^{-10}	0.60	3.49	370
		40	1.4×10^{-10}	1.00	4.75	222
	ITX	5	1.4×10^{-10}	0.14	0.53	1587
		25	1.3×10^{-9}	0.11	0.20	2020
		40	2.5×10^{-9}	0.13	0.09	1709
	EHA	5	2.3×10^{-11}	0.70	2.22	317
		25	1.3×10^{-10}	0.17	1.11	1307
		40	1.9×10^{-10}	0.20	1.49	1111

Table 6. Key Parameters Calculated for Ethanol 95% (v/v)

food simulant	photoinitiator	temp (°C)	D (cm^2/s)	α	RMSE (%)	$K_{P/F}$
ethanol 95% (v/v)	Irgacure 184	5	5.6×10^{-10}	0.21	0.36	1058
		25	3.6×10^{-9}	0.21	0.49	1058
		40	4.8×10^{-9}	0.21	0.41	1058
	benzophenone	5	3.0×10^{-9}	0.21	0.63	1058
		25	3.6×10^{-9}	0.22	0.66	1010
		40	5.6×10^{-9}	0.22	0.51	1010
	Irgacure 651	5	3.0×10^{-10}	0.31	0.40	717
		25	3.3×10^{-9}	0.31	0.57	717
		40	5.0×10^{-9}	0.31	0.88	717
	Irgacure 907	5	4.2×10^{-11}	0.16	0.51	1389
		25	1.7×10^{-9}	0.16	0.20	1389
		40	4.7×10^{-9}	0.20	0.34	1111
	ITX	5	2.6×10^{-10}	0.15	1.01	1481
		25	1.3×10^{-9}	0.12	0.25	1932
		40	2.0×10^{-9}	0.16	0.36	1389
	EHA	5	1.2×10^{-10}	0.10	0.44	2222
		25	1.2×10^{-9}	0.08	0.45	2963
		40	3.9×10^{-9}	0.13	1.00	1709

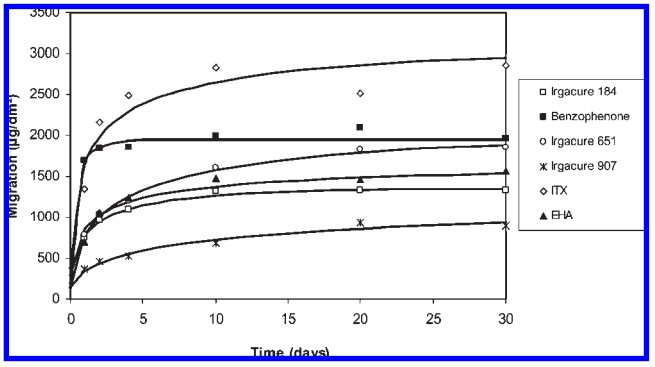


Figure 4. Migration kinetics (experimental and predicted values) of all photoinitiators into EtOH 95% at 5 °C.

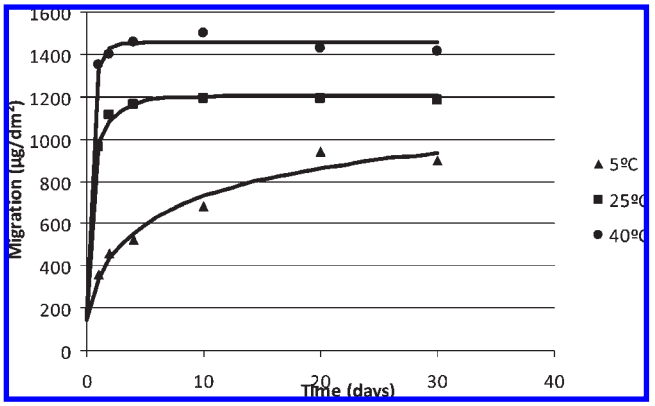


Figure 5. Migration kinetics (experimental and predicted values) of Irgacure 907 into EtOH 95% at 5, 25, and 40 °C during 30 days of contact between plastic and food simulant.

was the PI with highest D in water, ethanol 10%, and ethanol 20%, although these D values are similar to those achieved for Irgacure 184.

We have already verified that migration is influenced by temperature, and after calculating D, we have also verified that temperature influences this key migration parameter. The Arrhenius relationship (eq 4) was used to check for linearity in the range between 5 and 40 °C.

$$D = D_0 \, e^{-E_A/RT} \quad (4)$$

D is the diffusion coefficient (cm^2/s), D_0 is the pre-exponential factor (cm^2/s), E_A is the activation energy (kJ/mol), R is the gas constant (kJ/mol/K), and T is the temperature (K).

Correlation coefficients of the Arrhenius equation (**Table 7**) show this equation can be used to estimate D values at any temperature in the range between 5 and 40 °C. These values are shown in **Table 7** as well as D_0 and E_A.

It seems that diffusion coefficients are not dependent on food simulant, but in the case of ITX at 5 °C, the higher is the amount of ethanol in the simulant, the higher is D. This might happen due to a swelling phenomenon of the polymer in the presence of the ethanol simulant. Comparing the D results with those achieved for the same photoinitiators into powdered milk (*27*), we conclude that they are of the same order of magnitude.

Parameters That May Influence $K_{P/F}$ ($K_{o/w}$). The partition coefficient ($K_{P/F}$), which is the relative solubility of the migrant at equilibrium between the plastic and the foodstuff, was calculated with the polymer and food volumes (*29*). The V_P for all assays was

Table 7

food simulant	photoinitiator	D_0	E_A	r^2
distilled water	Irgacure 184	0.099	43364.5	0.955
	Irgacure 651	9123.8	72085.8	0.930
	Irgacure 907	311.8	69510.8	0.988
acetic acid 3%	Irgacure 184	0.001	33594.0	0.954
	Irgacure 651	21574.8	75332.3	0.999
	Irgacure 907	133361.2	82532.1	0.963
ethanol 10% (v/v)	Irgacure 184	2.2×10^{-6}	18515.8	0.988
	Irgacure 651	0.12	45288.6	0.891
	Irgacure 907	5.4×10^{-6}	24204.6	0.876
ethanol 20% (v/v)	Irgacure 184	0.063	42609.0	0.994
	Irgacure 651	14747.6	72957.3	0.997
	Irgacure 907	8.5×10^{-9}	10254.8	0.944
	ITX	119.5	73312.7	0.912
ethanol 30% (v/v)	Irgacure 184	4.4×10^{-5}	25116.1	0.862
	benzophenone	3.8×10^{-6}	17017.6	0.810
	Irgacure 651	5.28	53756.3	0.939
	ITX	4.1×10^{6}	91341.4	1.000
	EHA	0.14	46718.6	0.821
ethanol 60% (v/v)	Irgacure 184	1.0×10^{-8}	8212.4	0.931
	benzophenone	2.1×10^{-9}	2747.3	0.928
	Irgacure 651	1.5×10^{-4}	29761.6	0.892
	ITX	39.48	60525.0	0.961
	EHA	9.6×10^{-3}	45608.9	0.940
ethanol 95% (v/v)	Irgacure 184	0.22	45943.8	0.920
	benzophenone	6.0×10^{-7}	12364.6	0.876
	Irgacure 651	69.62	60006.3	0.928
	Irgacure 907	3.1×10^{8}	99908.9	0.960
	ITX	0.047	43733.8	0.953
	EHA	6192.2	72877.6	0.995

0.09 cm^3, and the V_F was 20 cm^3. The highest $K_{P/F}$ values were found for ITX and EHA, and they correspond to PIs with higher log $K_{o/w}$.

Concluding Remarks. Few studies have been published regarding the comparison of migration levels into different food simulants (*30*, *31*), and as far as we know, there is no study regarding the prediction of the migration of photoinitiators into food simulants. In line with this, our results contribute to a wider knowledge on the field of diffusion processes of potential migrants into food simulants.

Migration levels of the six PIs into different simulants were compared after a 30 day contact period with the additivated plastic and a relationship between R (ratio between log $K_{o/w}$ and MW) and total migration was found for PIs with log $K_{o/w} < 5$. For ITX and EHA (log $K_{o/w} > 5$), M values vary significantly among different simulants, and they were always higher for ITX, which has a lower MW.

Diffusion coefficients were calculated according to a mathematical modeling based on Fick's second law. At 5 °C the lowest D was 2.5×10^{-12} cm/s for ITX and the highest was 2.6×10^{-9} cm/s for benzophenone. At 25 °C the lowest D was 5.9×10^{-11} cm/s for ITX and the highest was 3.6×10^{-9} cm/s for Irgacure 651 and Irgacure 184, and at 40 °C the lowest D was 1.0×10^{-10} cm/s for ITX and the highest was 9.1×10^{-9} cm/s for Irgacure 651.

There are no relevant differences among D values calculated for different food simulants, except ITX, at 5 °C. In this case a relationship between the EtOH content in the simulant and the diffusion coefficient was found, which might be due to the swelling effect of the polymer when in contact with a food simulant with high ethanol content.

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