Association Between Emission Parameters and Material-phase Concentrations of Phthalate Plasticizers and their Alternatives

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Abstract

Plasticizers are frequently used in building materials and consumer products and many are semi-volatile organic compounds (SVOCs). Understanding the emission rate of plasticizers in indoor environments is critical for subsequent exposure and health risk assessments. While concerns have been increasing regarding the use of phthalate plasticizers in products and the emission of phthalates has been characterized in previous studies, the emission characteristics of compounds that are now being used as alternatives for phthalates remain poorly understood. In this work, we measured key parameters governing the emission of several phthalates and also their most recent emerging alternatives. Measurements include the gas-phase concentration in equilibrium with the material, \( y_0 \), and the vapor pressure, \( p^* \), using polyvinyl chloride (PVC) sheets with relatively high, but accurately known levels of the material-phase concentration, \( C_0 \), of the target plasticizers. We found that the PVC sheets containing different plasticizers show varying levels of \( y_0 \) (0.05 – 184 µg m\(^{-3}\)) despite having the same material-phase concentrations \( (C_0 = 32.9\%) \). We further examined the influence of high material-phase concentrations on \( y_0 \) and found that the measured concentrations of \( y_0 \) of diisononyl phthalate (DINP) (i.e., 0.12, 0.13, and 0.13 µg m\(^{-3}\)) for three PVC sheets were almost the same despite having significantly different material-phase levels (i.e., 39%, 33%, and 26% w/w, respectively). The deviation from the previously reported linear relationship between \( y_0 \) and \( C_0 \) can be attributed to the assumption that the material with plasticizers is a ‘dilute solution’ at high material-phase concentrations, which likely becomes invalid at these high levels. Preliminary results also show that the plasticizers are ideally mixed in the polymer and that their simultaneous presence does not affect the \( y_0 \) of individual compounds, even at relatively high material-phase concentrations.

Keywords: Plasticizer, Emission, PVC, Phthalate alternatives.
1 INTRODUCTION

Plasticizers, many of which are semi-volatile organic compounds (SVOCs) as defined by the United States Environmental Protection Agency (US EPA), are commonly used in a wide range of building materials and consumer products. Since they are not chemically bonded to the polymer matrix, they can be slowly emitted from the source products into the indoor air (Lucattini et al., 2018). Due to their relatively low vapor pressure, gas-phase SVOCs may accumulate in indoor aerosol because of gas-particle partitioning (Liu et al., 2010) and SVOCs may further sorb to a variety of indoor surfaces such as windows, dishes, clothing, and furniture (Bi et al., 2015). Those surfaces may serve as strong reservoirs of SVOCs and substantially increase their residence time in indoor environments for months or years even after the sources are removed (Xu and Little, 2006). Exposure to potentially harmful plasticizers may create significant health risks such as asthma, endocrine-disrupting effects, or even cancer (Latini et al., 2006; Bornehag and Nanberg, 2010; Fajersztajn et al., 2013; Kay et al., 2014; Ait Bamai et al., 2016) due to their extended presence in indoor environments. In particular, phthalate plasticizers have been associated with negative health impacts, resulting in the ban or restriction of several phthalates, for example, di(2-ethylhexyl) phthalate (DEHP), in the US, Canada, Europe, and Australia (Eichler et al., 2019). These restrictions lead to increased use of phthalate alternatives, many of which have poorly understood emission characteristics and indoor partitioning behavior. The plasticizers diisononyl phthalate (DINP), diisodecyl phthalate (DIDP), and bis(2-propylheptyl) phthalate (DPHP) are
commonly used and therefore included in this work, although they do not meet the US EPA criteria for defining SVOCs, as their boiling points at ambient pressure are above 400°C (US EPA). However, it is crucial to understand the emission of these emerging plasticizers from indoor source materials and their transport in indoor environments to assess potential risks.

Xu and Little (2006) demonstrated that the emission rate of SVOCs is a function of the critical parameter, $y_0$, which is the gas-phase concentration in equilibrium with the source material. Since then, chamber studies have been developed to measure $y_0$ values of a range of SVOCs, mostly phthalate plasticizers, in different source materials such as building materials and consumer products (Liang and Xu, 2014; Wu et al., 2016a; Cao et al., 2017; Wang et al., 2023). Of those source materials, polyvinyl chloride (PVC) flooring has been frequently tested due to its common use in indoor environments and often high plasticizer concentrations. Liang and Xu (2014) found a linear relationship between the material-phase concentration of DEHP in PVC materials, $C_0$, and $y_0$ for $C_0 \leq 13\%$. Liu and Zhang (2016) suggested a polymer-solvent interaction for characterizing SVOC emissions and showed that $C_0$ is correlated with the ratio of $y_0$ and the vapor pressure of the SVOC, $p^*$. Eichler et al. (2018) summarized previous measurement results and demonstrated that the assumption of an ideal solution is invalid and that instead Henry’s law can be applied to associate $C_0$ with a constant activity coefficient (i.e., $y_0/p^*$). This observation was also confirmed by Liang et al. (2018) for a broader range of SVOCs and materials. More recently, a modeling
study indicated that the activity coefficients may change with $C_0$ and that they may differ significantly depending on the plasticizer class (Addington et al., 2020). However, the modeling results were not validated experimentally and all previous measurements were limited to materials with relatively low $C_0$ (less than 30% by weight). It is still unknown if the Henry’s law-based linear relationship holds for higher material-phase plasticizer concentrations and for emerging phthalate alternatives that are now more frequently used in PVC flooring due to the bans and restrictions of some historically used phthalate plasticizers.

Additionally, the vapor pressures of several plasticizers typically used indoors are only loosely constrained. Vapor pressure measurements vary by orders of magnitude. For example, DEHP vapor pressure data are found to vary by two orders of magnitude as reported in the literature (Wu et al., 2016b). Since many plasticizers investigated in this study are relatively new on the market, it is necessary to measure their vapor pressure to enable the development of reliable predictive relationships and to reduce reported uncertainties of $p^*$ in the literature. Additionally, the vapor pressure is a critical parameter that drives chemical behavior and can be used to predict the partitioning of SVOCs in the indoor environment (Liang et al., 2019; Eichler et al., 2021).

Therefore, there is a critical need to improve the understanding of the correlation between $y_0$ and $C_0$ and to better manage uncertainties of vapor pressure measurements of emerging phthalate alternatives. To address these knowledge gaps, the objectives of this study are to 1) measure and
report $y_0$ and $p^*$ of phthalates and their emerging alternatives present in a variety of vinyl sheets with accurately known material-phase concentrations and 2) investigate the change of $y_0$ with varying levels of $C_0$ for the same plasticizer and with the simultaneous presence of multiple plasticizers.

2 METHODS

2.1 Chemicals

Details of phthalates and their alternatives used in this study are summarized in Table 1. Deuterium-labeled DEHP (D$_4$-DEHP) was used as an internal standard and was obtained from AccuStandard. Methanol (anhydrous, purity >99%, Sigma-Aldrich) was used for cleaning glassware and preparing solutions. Dichloromethane (purity >99.5%, VWR) was used for extractions. The solvents were analyzed regularly to monitor for potential contamination.

<table>
<thead>
<tr>
<th>Chemical name</th>
<th>Abbreviation</th>
<th>CAS No.</th>
<th>MW (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetyl tri-n-butyl citrate</td>
<td>ATBC</td>
<td>77-90-7</td>
<td>402.5</td>
</tr>
<tr>
<td>Fatty acids, soybean-oil, epoxidized, 3-methylbutyl esters</td>
<td>EIAS</td>
<td>1394959-45-5</td>
<td>Unspecified*</td>
</tr>
<tr>
<td>Dibutyl terephthalate</td>
<td>DBT</td>
<td>1962-75-0</td>
<td>278.3</td>
</tr>
<tr>
<td>Bis(2-ethylhexyl) terephthalate</td>
<td>DEHT</td>
<td>6422-86-2</td>
<td>390.6</td>
</tr>
<tr>
<td>Diisodecyl phthalate</td>
<td>DIDP</td>
<td>26761-40-0, 68515-49-1</td>
<td>446.7</td>
</tr>
<tr>
<td>1,2-Cyclohexanedicarboxylic acid, dinonyl ester, branched and linear</td>
<td>DINCH</td>
<td>474919-59-0, 166412-78-8</td>
<td>424.6</td>
</tr>
<tr>
<td>Diisononyl phthalate</td>
<td>DINP</td>
<td>28553-12-0,</td>
<td>418.6</td>
</tr>
</tbody>
</table>
2.2 Source materials

We used 14 PVC sheets with predetermined, gravimetrically-verified material-phase concentrations of plasticizers that were prepared and provided by the European Plasticisers, a sector group of the European Chemical Industry Council (Cefic). Details regarding the composition of each source material sheet are summarized in Table 2. The PVC sheets were intentionally selected so that sheets #1-9 had the same plasticizer material-phase concentrations to allow direct comparison of $y_0$ independently of the material-phase concentration. Additional PVC sheets with varying material-phase concentrations of DINP (i.e., sheets #10-12) were chosen to investigate the influence of varying material-phase concentrations on $y_0$. Finally, the simultaneous presence of multiple plasticizers in the same material and their joint effects on $y_0$ were studied by using PVC sheets containing a mixture of different plasticizers yet having the same total material-phase concentration (i.e., sheets #13-15). The source material sheets were each cut into two round pieces with a diameter of 11 cm for the $y_0$ chamber experiments.

2.3 $y_0$ measurements

<table>
<thead>
<tr>
<th>Plasticizer Name</th>
<th>CAS Number</th>
<th>Molecular Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bis(2-ethylhexyl) adipate</td>
<td>DEHA</td>
<td>370.6</td>
</tr>
<tr>
<td>Bis(2-propylheptyl) phthalate</td>
<td>DPHP</td>
<td>446.7</td>
</tr>
<tr>
<td>3-(pentanoyloxy)-2,2-bis[(pentanoyloxy)methyl]propyl pentanoate/ pentaerythritol tetravalerate</td>
<td>PETV</td>
<td>472.6</td>
</tr>
</tbody>
</table>

*: The compound is a mixture of chemical species without a pre-determined molecular weight.
A previously-developed micro chamber method was used to measure \( y_0 \) of the phthalates and phthalate alternatives in the PVC source materials (Wang et al., 2023). While a detailed description can be found in Wang et al. (2023), we briefly summarize the method here. An aluminum micro chamber with a ‘sandwich-like’ configuration was used. The chamber consists of two round aluminum plates, one at the bottom and one at the top of the chamber, with an aluminum ring in between. Source material sheets are placed in between the plates and the ring to maximize the emission area and minimize the area available for wall loss inside the chamber. Clean air was supplied to the chamber at 300 ml min\(^{-1}\) via the inlet on one side of the ring and gas-phase samples were collected using Tenax TA sorbent tubes at 75 ml min\(^{-1}\) using a sampling port located on the ring at an angle of about 135° to the inlet. Prior to the sampling, sorbent tubes were cleaned by conditioning them at 320°C for 30 minutes while purging them with nitrogen. Before each experiment, the metal surfaces of the micro chamber were rinsed multiple times with methanol. Blank air samples were collected before experiments to make sure that no contamination remained in the chamber.

2.4 \( p^* \) measurement

We used a partial saturator tube method that was previously described by Wu et al. (2016b) to measure the vapor pressure of the phthalates and phthalate alternatives included in this study. In brief, we coated the inner surface of a 30 cm stainless steel tube with the target SVOC as a pure
liquid and supplied clean air at the inlet of the partial saturator tube. The air then becomes saturated or near-saturated with the SVOC while flowing through the tube. Samples of the SVOC in the gas phase can be collected at the partial saturator tube outlet with Tenax TA sorbent tubes. Based on the measured gas-phase concentration, the vapor pressure can then be calculated (Wu et al., 2016b).

2.5 Chemical analysis

The sorbent tubes were thermally desorbed in a thermal desorber (Turbomatrix 100 TD) and target SVOCs were analyzed by a gas chromatography-flame ionization detection (GC-FID) system (Agilent 6890). For DINP and DINCH, which cannot be accurately quantified via the GC-FID system, a GC-MS system (Thermo Scientific DSQII) coupled with a Markes TD-100 thermal desorber was used for analysis. The sorbent tubes were desorbed for 30 mins at 300°C with a helium flow rate of 50 ml min⁻¹, and a cold trap temperature of 5°C. Flash heating of the cold trap to 320°C transferred the analyte through the valves at 250°C and through the transfer line at 255°C to the GC. The temperature cycle of the GC-FID, using a 0.53 mm × 30 m RXT-5 column (Restek Inc.), was as follows: The temperature was held at 50°C for 1 min, ramped at 10°C min⁻¹ until reaching 280°C, then ramped at 20°C min⁻¹ to reach 320°C, and finally held at 320°C for 5 min. The oven temperature of the GC-MS with a 0.25 mm × 30 m RXT-5 column (Restek Inc.) was held at 50°C for 1 min, ramped at 35°C min⁻¹ to 320°C, and held at 320°C for 10 min.
Multi-point calibration curves for each analyte were developed for both the GC-MS and GC-FID methods by injecting five levels of diluted liquid standards of analytes into the sorbent tube covering the concentration ranges in the samples. Before GC-MS analysis, 1 µL of D₄-DEHP solution (20 µg/mL) in methanol was injected into each Tenax TA sorbent tube as an internal standard. For GC-FID analysis, the sorbent tubes were desorbed directly without using an internal standard. All tubes were analyzed in two successive runs to ensure complete desorption of the plasticizers from the tubes and the GC-MS or -FID system. The second run showed concentrations below the detection limit in all cases.

3 RESULTS AND DISCUSSION

As shown in Table 2, \( y_0 \) levels of plasticizers including DPHP, DIDP, PETV, EIAS, and DBT were measured and reported for the first time alongside their vapor pressures in this study. We

<table>
<thead>
<tr>
<th>PVC sheets</th>
<th>Plasticizer</th>
<th>( C_0 )(^\text{(%}, \text{w/w}) )</th>
<th>( y_0 ) (( \mu \text{g m}^{-3} ))</th>
<th>( p^* ) (( \mu \text{g m}^{-3} ))</th>
<th>( y_0/p^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Standard deviation</td>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>1</td>
<td>DINCH</td>
<td>33</td>
<td>1.36</td>
<td>0.34</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>DPHP</td>
<td>33</td>
<td>0.11</td>
<td>0.04</td>
<td>0.062</td>
</tr>
<tr>
<td>3</td>
<td>DIDP</td>
<td>33</td>
<td>0.05</td>
<td>0.01</td>
<td>0.074</td>
</tr>
<tr>
<td>4</td>
<td>ATBC</td>
<td>33</td>
<td>5.16</td>
<td>0.26</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>DEHA</td>
<td>33</td>
<td>14.4</td>
<td>0.90</td>
<td>1444</td>
</tr>
<tr>
<td>6</td>
<td>PETV</td>
<td>33</td>
<td>0.07</td>
<td>0.01</td>
<td>0.156</td>
</tr>
<tr>
<td>7</td>
<td>EIAS</td>
<td>33</td>
<td>1.47</td>
<td>0.38</td>
<td>2.29</td>
</tr>
<tr>
<td>8</td>
<td>DEHT</td>
<td>33</td>
<td>0.14</td>
<td>0.02</td>
<td>0.24</td>
</tr>
<tr>
<td>9</td>
<td>DINP(^i)</td>
<td>33</td>
<td>0.11</td>
<td>0.02</td>
<td>0.40</td>
</tr>
</tbody>
</table>
found that the PVC sheets containing different plasticizers show varying levels of $y_0$ ($0.05 - 184 \mu g \, m^{-3}$) despite having the same material-phase concentrations ($C_0 = 32.9\%$). According to Eichler et al. (2018), $y_0$ values of SVOCs are a function of their vapor pressures and the material-phase concentration. If the material-phase concentrations are the same, which is the case for PVC sheets # 1-9, 11, and 13 in Table 2, the ratio between $y_0$ and $p^*$ ($y_0/p^*$) should be similar between SVOCs. This conclusion roughly agrees with our measurements of $y_0/p^*$ for DINCH, DIDP, ATBC, PETV, EIAS, DEHT, DINP, and DBT, which are 0.85, 0.72, 0.52, 0.46, 0.64, 0.57, 0.33, and 0.34, respectively. However, DEHA and DPHP have substantially lower and higher results for $y_0/p^*$, which are 0.01 and 1.80, respectively. The lower $y_0/p^*$ of DEHA is probably due to its orders of magnitude higher vapor pressure, which makes it the most volatile compound on the list. In contrast, the reason for the higher $y_0/p^*$ of DPHP, although not substantial, is unknown. Since DPHP is the least volatile compound in this study, it is possible that its low volatility can result in slight deviations from the mean $y_0/p^*$ (0.57) of other analytes. However, we note that the material-phase concentrations of most PVC sheets, 32.9\%, are higher than all previous

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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>DINP&lt;sup&gt;2&lt;/sup&gt;</td>
<td>39</td>
<td>0.12</td>
<td>0.02</td>
<td>0.40</td>
<td>0.02</td>
</tr>
<tr>
<td>11</td>
<td>DINP&lt;sup&gt;2&lt;/sup&gt;</td>
<td>33</td>
<td>0.13</td>
<td>0.01</td>
<td>0.40</td>
<td>0.02</td>
</tr>
<tr>
<td>12</td>
<td>DINP&lt;sup&gt;2&lt;/sup&gt;</td>
<td>26</td>
<td>0.13</td>
<td>0.01</td>
<td>0.40</td>
<td>0.02</td>
</tr>
<tr>
<td>13</td>
<td>DBT</td>
<td>33</td>
<td>184</td>
<td>7.79</td>
<td>547</td>
<td>19.8</td>
</tr>
<tr>
<td>14</td>
<td>DEHT</td>
<td>26</td>
<td>0.11</td>
<td>0.01</td>
<td>0.24</td>
<td>0.20</td>
</tr>
<tr>
<td>15</td>
<td>DBT</td>
<td>6.6</td>
<td>32.0</td>
<td>3.56</td>
<td>547</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>DINCH</td>
<td>26</td>
<td>1.22</td>
<td>0.19</td>
<td>1.6</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>DBT</td>
<td>6.6</td>
<td>35.6</td>
<td>1.52</td>
<td>547</td>
<td>19.8</td>
</tr>
</tbody>
</table>

<sup>1</sup> CAS number: 28855-12-0
<sup>2</sup> CAS number: 68515-48-0

10
measurements summarized by Eichler et al. (2018). Whether the linear relationship between $y_0$ and $C_0$ for a given SVOC holds at very high material-phase concentrations has not been investigated in the past.

To probe this dependency at high material-phase concentrations, we selected three PVC sheets that contained different levels of DINP, ranging from 26% to 39%, in the materials manufactured by the same vendor (i.e., PVC sheets #10-12). As shown in Fig. 1a, the measured gas-phase concentrations of DINP in the micro chamber are similar even though the DINP material-phase concentrations in the three materials differ significantly. The negligible influence of the material-phase concentrations on the chamber gas-phase concentrations, which is directly used for calculating $y_0$ in Fig. 1b, indicates that the linear relationship, reported and summarized by Eichler et al. (2018), may no longer exist after the material-phase concentration exceeds 25%-30% w/w for DINP. While this study has limited data to quantify this threshold for all target plasticizers, this deviation from the Henry's law-based relationship can be attributed to the high material-phase concentrations in our experiment, which were not accounted for in previously developed linear correlations assuming a dilute solution (i.e., the mass fraction of plasticizers is substantially lower than the total mass of the material). The findings agree with a previous modeling study suggesting that the activity coefficient ($y_0/p^*$) for phthalates and terephthalates may plateau when $C_0$ is higher than 30% (Addington et al., 2020). These results may further
contribute to explaining the discrepancy of \( y_0/p^* \) for DEHA and DPHP since their volatility differences can cause them to deviate from Henry’s law dependency at lower material-phase concentrations. The finding raises an important and urgent need for accurate measurements of material-phase concentrations of plasticizers in materials and products on the consumer market.

The measurements of SVOCs in source materials have been limited to a narrow range of products (i.e., vinyl flooring, polyurethane foam, crib mattresses, backpacks, toys, and vehicle cabin materials) for a limited number of SVOCs (Liang and Xu, 2014; Xie et al., 2015; Cao et al., 2017; Pei et al., 2017; Yang et al., 2019; Plaisance et al., 2022). Note that the measurement accuracy of plasticizer material-phase concentrations in polymers may also vary significantly and depends on the choice of extraction method such as accelerated solvent extraction, ultrasonic assisted extraction, Soxhlet extraction, and solvent dissolution (Vandenburg et al., 1997; Gimeno et al., 2014; Nhlapo et al., 2018). Therefore, it is important to perform strict quality control of the extraction procedures when adapting for more efficient methods, particularly for less soluble plasticizers with low volatility. The uncertainty caused by material-phase extractions, which may result in discrepancies from manufacture-added concentrations, further increases the need to investigate a broader range of materials and to use optimized methods to measure \( C_0 \), \( y_0 \), and \( p^* \).
Fig. 1. The influence of material-phase concentrations on a) the gas-phase concentrations of DINP in the chamber and b) $y_0$ of DINP.

We further investigated the impact of the simultaneous presence of plasticizers on $y_0$ by using three PVC sheets containing an equal amount of total plasticizers yet different individual concentrations. DBT was present as the only plasticizer in PVC sheet #13 (containing 33% w/w DBT) and also in combination with either DEHT in PVC sheet #14 (containing 26% and 6.6% w/w of DEHT and DBT, respectively) or DINCH in PVC sheet #15 (containing 26% and 6.6% w/w of DINCH and DBT, respectively). As shown in Fig. 2, the gas-phase concentrations of DBT in the chamber are relatively similar even in the presence of either DEHT or DINCH. The results suggest that the plasticizers are ideally-mixed in the polymer and their simultaneous presence, even at relatively high material-phase concentrations, does not affect the $y_0$ of individual compounds. The conclusion can be further strengthened by calculating the steady-state
gas-phase concentrations of DBT at 6.6% and 33%, which are 35 µg m⁻³ and 180 µg m⁻³, respectively. The ratio of these two gas-phase concentrations is 0.19, which agrees with the ratio of their respective material-phase concentrations, 0.20 (i.e., 6.6%/33%). We acknowledge that more comprehensive studies for a broader range of compounds and materials are needed to solidify this conclusion. However, such efforts will require specially prepared source materials and consequently need stronger ties between industry and academic institutions.

![Figure 2](image)

**Fig 2.** The effects of the simultaneous presence of SVOCs on $y_0$, shown here on the example of DBT in the presence of either DEHT or DINCH.

4 CONCLUSIONS

In this study, we reported for the first time the gas-phase concentration in equilibrium with the material, $y_0$, and the vapor pressure, $p^*$, of a wide range of plasticizers that are now being used as alternatives for traditional phthalates such as BBzP and DEHP, for a variety of PVC sheets with a
known and verified material-phase concentration, $C_0$. We found that the PVC sheets containing different plasticizers show varying levels of $y_0$ (0.05 – 184 µg m$^{-3}$) despite having the same material-phase concentrations ($C_0 = 32.9\%$). The reported data have strong practical implications for predicting the emission and concentrations of plasticizers in indoor environments and assessing the subsequent impacts on aerosol formation and human health. As pointed out in a previous work (Xu and Hubal, 2009), $y_0$ is the most critical parameter for estimating SVOC emission rates and understanding human exposure. Additionally, the vapor pressures of emerging plasticizers measured in this study can contribute to more accurate predictions of gas-particle partitioning and enhance the accuracy in the estimation of aerosol formation in indoor environments.

We also investigated the relationship of three critical parameters at high material-phase plasticizer concentrations. The measured concentrations of $y_0$ of DINP (i.e., 0.12, 0.13, and 0.13 µg m$^{-3}$) for three PVC sheets were almost the same despite having significantly different material-phase levels, 39%, 33%, and 26% w/w, respectively. We found that the previously reported, Henry’s law-based linear relationship between $C_0$ and $y_0$ may no longer exist after the material-phase concentration exceeds a certain threshold (e.g., about 30% w/w for DINP). This deviation from Henry's law can be attributed to the invalid assumption at high material-phase concentrations that the material with plasticizers is a ‘dilute solution’. Preliminary results showed that the
plasticizers are ideally-mixed in the polymer and their simultaneous presence, even at relatively high material-phase concentrations, does not affect the $y_0$ of individual compounds.

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DISCLAIMER

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

CB wrote the manuscript and contributed to the experimental work, data analysis and interpretation. CMAE contributed to the experimental work, data interpretation, and manuscript writing. CW conducted the experimental work, performed data analysis and interpretation, and contributed to the manuscript. JCL contributed to all aspects of the research and manuscript preparation and devised and supported the research.
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