Water Solubility, Vapor Pressure, and Activity Coefficients of Terpenes and Terpenoids

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Water solubilities, activity coefficients, and vapor pressures of some terpenes and terpenoids were determined from two sets of experiments. The first involved liquid−liquid contacting until saturation of an aqueous layer, which gave solubility and activity coefficient at infinite dilution γ^{∞}. The second set involved stripping a solute from a nonsaturated aqueous solution by an air stream. This last experiment gave the product $\gamma^{\infty}P°$ from which vapor pressure $P°$ was deduced. Reliability of the results was established from predicted $P°$ values, and data for 12 compounds are now available. Data obtained at 25 °C showed low solubilities (0.037−0.22 mmol/L) and high activity coefficients (10^5−10^6) for terpenes, whereas oxygenated monoterpenes exhibited solubilities 20 orders of magnitude higher, in the range of 2−20 mmol/L and 10^3−10^4 for activity coefficients. Vapor pressures ranged from 100 to 550 Pa for terpenes and from 1 to 130 Pa for terpenoids. Attempts to estimate water solubility showed that recent equations in the literature are unable to predict this property with an accuracy better than 140%.

Introduction

Monoterpenes are widespread natural unsaturated hydrocarbons derived from isoprene units through different stereoregulated processes (Misra et al., 1996). They can be acyclic, monocyclic, or bicyclic. They occur as mostly complex hydrocarbons, or as oxygenated derivatives, such as alcohols, aldehydes, ketones, and carboxylic acids, named terpenoids. Many of these terpenoids are considered as GRAS and are used as food additives and as fragances (Werf et al., 1996).

Several monoterpenes such as α or *β*-pinene, limonene, and *β*-myrcene can be used as precursors in biotransformations to produce terpenoids such as borneol, carvone, and α-terpineol. Development of these processes needs knowledge of solubilities, activity coefficients, and vapor pressures of different terpenes and terpenoids.

Data on solubility and vapor pressure of terpenes are scarce and often inconsistent (Weidenhamer et al., 1993; Schmid et al., 1992; Terrance and LeMaguer, 1980; Massaldi and King, 1973).

In this work, two suitable independent methods are developed for determining water solubility, activity coefficients, and vapor pressure of terpenes and terpenoids. Reliability of the results is assessed by comparison of vapor pressure results with well-established prediction techniques and measurements. Solubility results are compared with recent prediction methods.

Materials and Methods

Materials. Eleven monoterpenes were chosen for this study. They comprised four hydrocarbons ((−)-α-pinene, (−)-*β*-pinene, *R*-(+)-limonene, myrcene), five monoalcohols ((1*S*)-*endo*-(−)-borneol, (−)-carveol, (+)-α-terpineol, (±)-linalool, (1*R*)-*endo*-(+)-fenchyl alcohol), two oxides ((+)-limonene oxide and (−)-α-pinene oxide), and one ketone ((+)-carvone). All the monoterpenes were used as received and stored at +4 °C except for (1*S*)-*endo*-(−)-borneol and (−)-carveol, which were stored at room temperature. Purities and other information for these compounds are given in Table 1. Impurities were determined by the manufacturers by gas chromatography. This meant contaminants had different retention times from the compound of interest, which could thus easily be identified on the chromatograms. It was therefore considered that these foreign compounds could not induce errors in the measurements.

Water Solubility Determination. Principle. The water solubility of the terpenes was determined by measuring solute content in a saturated aqueous solution at a given temperature. This saturated solution was obtained using a two-liquid-phase contact method (Turner et al., 1996).

Experimental. (a) Procedure. Saturated aqueous solutions were prepared by adding an excess of each compound to 200 mL of distilled water in a conical flask (250 mL) sealed first with a rubber cap coated with aluminum foil, because of the tendency of some terpenes such as *d*-limonene to adsorb onto the rubber (Massaldi and King, 1973). The flask was then sealed with another layer of aluminum foil pressed tightly around the top and placed in a water bath stirred at 320 rpm and thermostated at 25 °C until a constant solute concentration was obtained, which took from 24 to 100 h, depending on the test compound.

This treatment gave a mixture of an organic phase and a heterogeneous aqueous layer containing small suspended droplets of test compound. This emulsion could be treated in two ways, settling or centrifugation. The use of both techniques has been reported in the literature (Weidenhamer et al., 1993; Schmid et al., 1992), and so they were tested and compared according to Figure 1.

For the settling approach, the conical flask was allowed to stand for 2−3 h. A 10-mL sample of the clear aqueous phase obtained was then removed and its solute content was determined (see below Analytical Method). For solid solutes, samples were filtered through a membrane (0.2 μm) before analysis.

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Table 1. Sources and Properties of Selected Monoterpenes

compound	source	purity	molecular formula	molecular mass (g/mol)	specific gravity
hydrocarbons					
R-(+)-limonene	fluka	99%	$C_{10}H_{16}$	136.24	0.843
(−)-α-pinene	fluka	99%	$C_{10}H_{16}$	136.24	0.853
(−)-*β*-pinene	fluka	99%	$C_{10}H_{16}$	136.24	0.871
myrcene	fluka	>90%	$C_{10}H_{16}$	136.24	0.793
alcohols					
(1*R*)-endo-(+)-fenchyl, alcohol	Aldrich	97%	$C_{10}H_{18}O$	154.25	
(−)-carveol	Aldrich	99%	$C_{10}H_{16}O$	152.24	1.496
(1*S*)-endo-(−)-borneol	Aldrich	99%	$C_{10}H_{18}O$	154.25	
(±)-linalool	Fluka	~97%	$C_{10}H_{18}O$	154.25	0.861
(+)-α-terpineol	Fluka	~99%	$C_{10}H_{18}O$	154.25	0.935
oxides					
(+)-limonene oxide (cis and trans mixture)	Aldrich	97%	$C_{10}H_{16}O$	152.24	0.929
(−)-α-pinene oxide	Aldrich	97%	$C_{10}H_{16}O$	152.24	0.964
ketone					
(+)-carvone	Fluka	>99%	$C_{10}H_{14}O$	150.22	0.960

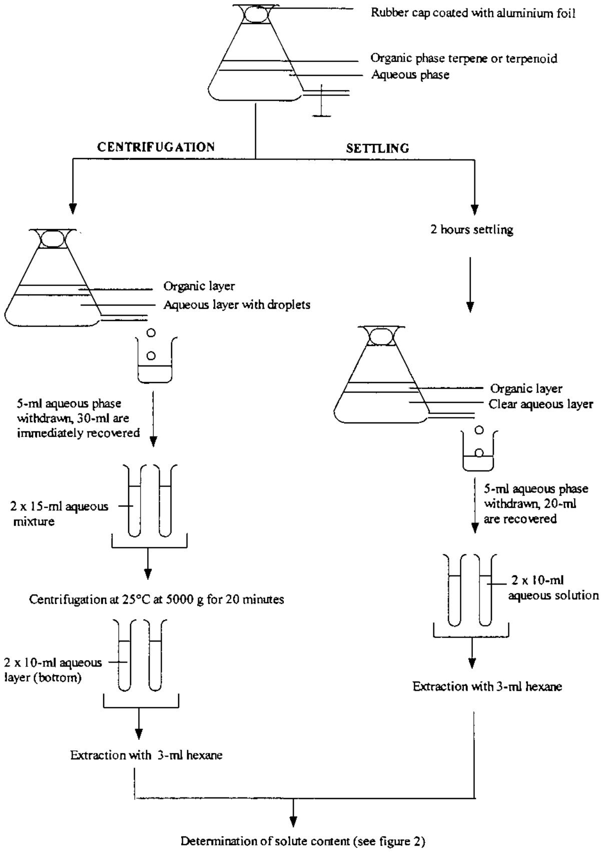

Figure 1. Protocols used for determination of water solubility.

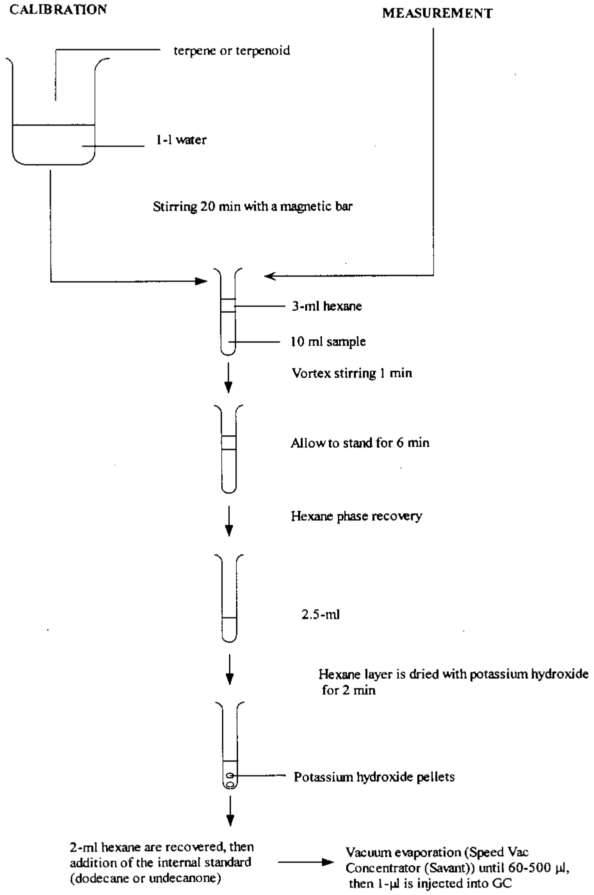

Figure 2. Sample analysis protocol.

Alternatively, 30 mL of aqueous emulsion was immediately withdrawn from the flask and centrifuged at 5000*g* for 20 min. The more dense aqueous layer obtained was then carefully recovered, and its solute content was measured (see below Analytical Method). To prevent contamination by organic drops, a gentle blowing action was applied as the pipet tip passed through the organic layer (Terrance and LeMaguer, 1980) and it was wiped to remove the organic phase clinging to the outer surface of the pipet.

(b) Analytical Method. Monoterpene quantification was performed by liquid−liquid extraction and gas chromatography (Figure 2). Liquid samples (10 mL) were transferred to test tubes containing hexane in the volume ratio 3:10. They were sealed with rubber caps and agitated using a vortex mixer for 1 min. After phase separation, the solvent extract from each tube (2.5 mL) was dried with potassium hydroxide pellets for 2 min. Then 2 mL of dried hexane was transferred to tubes containing the internal standard, 100 *µ*L of dodecane at 375 mg/L in hexane for nearly all terpenes and terpenoids, or 2-undecanone at 412 mg/L in hexane for (−)-carveol, (+)-α-terpineol, and (+)-limonene oxide. The solutions were then evaporated down under reduced pressure using a Speed Vac concentrator (Savant) to 60−500 *µ*L. Each evaporation was carried on both samples and four standard solutions in hexane (see below). These standard solutions were used to plot the calibration curve for the run.

One microliter of each concentrated solution was injected into a gas chromatograph using split (1/100) or splitless injection. The solvent extract was stored at −20 °C; it was stable for at least 3 days in these conditions.

A Hewlett-Packard 5890 series II (HP Co., Palo Alto, CA) gas chromatograph equipped with a flame ionization detector and a split/splitless injection system was used; it was fitted with a Supelco SPB-5 (Supelco Inc., Bellefonte, PA) capillary column of internal diameter 0.32 mm, length 30 m, and film thickness 0.25 μm. The carrier gas was nitrogen; the injector and detector temperatures were 220 °C and 250 °C, respectively. The following oven temperature program was used: 100−120 °C for 5 min, then 20 °C/min to 200 °C for 5 min. Hewlett-Packard HP 3365 series II Chemstation software was used for data acquisition and processing.

Calibration curves for each compound were performed from a set of serial dilutions of a homogeneous aqueous terpene solution treated as in Figure 2. A stock aqueous solution with a solute concentration slightly less than its solubility was prepared, and each sampling for further dilutions with water was carried out with stirring. The resulting aqueous standards were then extracted with hexane, and the organic layers were concentrated in the same run as samples to be analyzed (see above and Figure 2). This procedure always gave straight lines passing through the origin and was used for both settling and stripping experiments. When centrifugation was used to separate excess solute from an aqueous solution, a centrifugation step (5000*g*, 20 min) was applied to the above aqueous stock solution before serial dilution and extraction procedures.

Determination of $\gamma^{\infty}P°$ by Stripping Experiments. (a) Basis of Method. In an aerated stirred reactor (see below), *C*, the molar solute concentration in a liquid phase, was allowed to partition between *y* mole fraction of solute in the gas phase and *x* mole fraction of solute in the liquid phase at a fixed temperature. A material balance on the solute gives eq 1

$$\frac{-G°y}{V} = \frac{\mathrm{d}C}{\mathrm{d}t} \tag{1}$$

where $G°$ is the molar output aeration rate and *V* the volume of liquid in the reactor. This equation assumes solute accumulation in the gas phase above the liquid is negligible (Duhem and Vidal, 1978). If the solvent can be considered as nonvolatile, which is reasonable with water (Duhem and Vidal, 1978), and if *y* is small, then $G°$ can be considered as *G*, the input aeration rate. Furthermore, if the gas and liquid phases are at thermodynamic equilibrium, we can write

$$y = \gamma\frac{P°}{P_T}x \tag{2}$$

where $P°$ is the solute vapor pressure at the system temperature and P_T is the total pressure in the system (atmospheric pressure). If the solution is dilute we have

$$\gamma = \gamma^{\infty} = \text{constant} \tag{3}$$

and

$$x \cong C/C_{H_2O} \tag{4}$$

where γ^{∞} is the activity coefficient at infinite dilution of solute in liquid phase and C_{H_2O} is the water concentration (55.55 mol/L). Equations 1 to 4 are combined to give after integration the following relation

$$\ln\frac{C_0}{C} = \frac{G\gamma^{\infty}P°}{VP_TC_{H_2O}}t \tag{5}$$

Plotting ln C_0/C against time gives a straight line with slope α, from which $\gamma^{\infty}P°$ was deduced.

Assuming the saturated solution obtained from two-liquid-phase contacting (see above) can be considered as dilute (*x* (mole fraction) < 0.01), γ can be calculated as follows

$$\gamma = \gamma^{\infty} = C_{H_2O}/S \tag{6}$$

where *S* is the solute molar solubility in water.

It was then possible to determine vapor pressure by combining these two independent experiments. Knowledge of $\gamma^{\infty}P°$ and solubility *S* allows the calculation of vapor pressure using the following equation:

$$P° = \frac{\alpha VP_TS}{G} \tag{7}$$

(b) Experimental. (i) Materials. The materials and the chromatograph were the same as those used for solubility measurements.

(ii) Measurement Conditions. Stripping experiments were performed in a Biostat MD (B.Braun Biotech International, Melsungen, Germany) bioreactor with a jacketed vessel of total volume 7.5 L (height 38 cm, diameter 16 cm) having an internal concave bottom section. It was fitted with a stirrer shaft with three six-blade impellers 4 cm in diameter. The temperature was regulated at (25 ± 0.1) °C by means of a PID controller, the input air flow at 0.3 standard volume of gas per volume of liquid and per min by a mass flow controller (Bronkhorst, Ruurlo, The Netherlands), and the stirring speed was 1000 rpm. The volume of aqueous solution was 3 L (height of standing liquid 15.5 cm) and a probe (dissolved oxygen) port was kept opened on the top plate. No condenser was used.

(iii) Procedure. The initial solute concentration in the reactor was lower than its water solubility. After homogenization (1−12 h), aeration with dry air was started. Samples were periodically recovered and analyzed as previously described (Figure 2). Experiment durations were about 1 to 4 days depending on the volatility of the compounds studied.

Results and Discussion

Procedure for Extraction of an Aqueous Sample. The solute concentration of an aqueous solution has was determined by GLC analysis of a hexane extract, obtained after vortexing of the biphasic system. It is necessary, with this method, to ensure the contacting procedure allows the two phases to reach equilibrium by the end of the extraction process.

This state was rapidly reached, 10 s vortexing being sufficient to obtain a constant maximal solute concentration in the organic layer, as shown in Figure 3 for carvone. However, to ensure equilibrium is always reached, a mixing time of 1 min was used throughout this work (see Materials and Methods).

Solubility Measurement. (a) Validation of the Water Solubility Measurement Protocol. The experimental procedure for determining water solubility involves separation of the excess solute from the aqueous solution. This can be performed either by settling or centrifugation (Figure 1).

The settling duration must be long enough to ensure droplets remaining suspended in the aqueous phase are separated. This is generally achieved after about 1 h of standing, as shown in Figure 4 for carvone. For safety, a

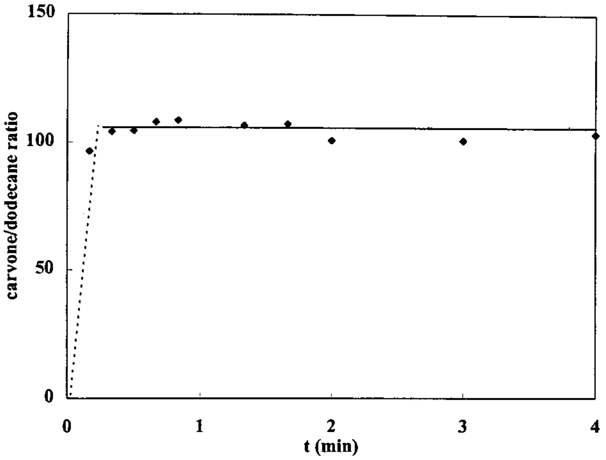

Figure 3. Influence of vortexing time on carvone extraction by hexane. Initial carvone concentration in water 1.2 g/L, 10 mL of aqueous phase extracted with 3 mL of hexane.

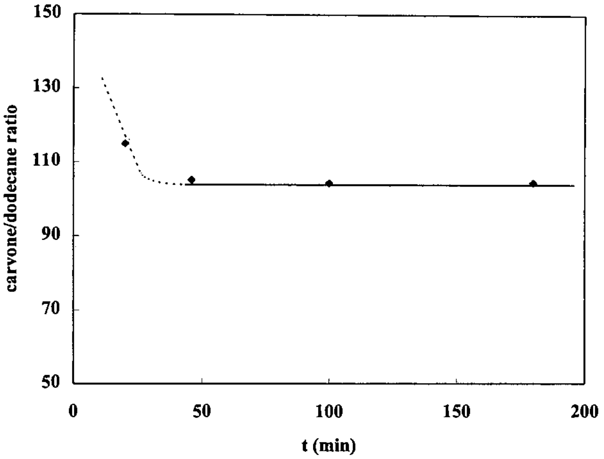

Figure 4. Influence of settling duration at 25 °C on carvone recovery in the bottom aqueous layer. Results obtained after shaking an excess solute (5 g) in 250 mL of water in an Erlenmeyer as described in Materials and Methods.

Table 2. Comparison of Solubility Results Achieved According to the Experimental Procedure Used to Separate Excess Solute from the Aqueous Solution. Case of Carvone

method	carvone concentration/(mmol/L)
settling	8.80 ± 0.22
centrifugation	
calibration as for settling	7.22 ± 0.18
stock solution for calibration centrifuged	8.77 ± 0.22

settling time of 2−3 h was used in the following (see Materials and Methods).

Water solubility of carvone at 25 °C is given in the AQUASOL dATAbASE (Myrdal et al., 1995). The value of 8.71 mmol/L, also reported by Terrance and LeMaguer (1980), can be considered as true and has been used as a reference to check the experimental procedure used in this work. Results obtained (Table 2) clearly show close agreement with the published data, with both settling and centrifugation, provided the stock aqueous solution used for calibration is also centrifuged before dilution. If this operation is omitted, centrifuged samples give underestimated values (Table 2). The reasons for this are unclear, but it might result from loss of some compound on the tube walls during centrifugation. This effect may be a potential source of error in solubility determinations, and so the settling approach is preferred for this purpose, although it is more time-consuming.

(b) Solubility and Activity Coefficient Results. Solubility data and activity coefficients at infinite dilution γ^∞ for terpenes and terpenoids in aqueous solution at 25 °C are given in Table 3.

Solubility of monoterpenes ranges very widely, from values as low as 0.037 mmol/L to 19 mmol/L as reported by Weidenhamer et al. (1993). The four monoterpenes had the lowest solubilities (less than 0.3 mmol/L), and the functionalized compounds the highest. Alcohols ((−)-carveol, (±)-linalool, α-terpineol) were more soluble than the similar ketone ((+)-carvone) in the monocyclic skeletons.

The solubility values determined are compared with literature data in Table 4. Very sharp differences can be seen among the various sets of data. However, Schmid et al. (1992) use the centrifugation technique, which can give underestimated results if the calibration procedure does not use centrifuged solutions. The authors give no information about their protocol. Also, Weidenhamer et al. (1993) use the settling approach, but carried out at room temperature. These comparisons demonstrate the usefulness of this study.

Determination of Vapor Pressure by Stripping. (a) Validation of the Stripping Procedure. The main assumption in eq 5 is that liquid−vapor equilibrium is actually attained during stripping experiments. Calculations carried out by Li et al. (1993) on the benzene−water system stripped by helium led them to the conclusion that equilibrium is reached with a path length of 15 cm, with bubble diameters less than 1 mm. These conditions are always met in our experiments (see Materials and Methods); furthermore, our stripping apparatus allows stirring of the liquid, which increases the transfer rates. Hence, equilibrium should normally be reached in this work.

One way to ensure this is to carry out the process using a well-known compound with a large limiting activity coefficient, in the range of those expected for terpenes and terpenoids. The choice of such a solute remains a difficult task, because for high-γ^∞ compounds there are not many accurate γ^∞ data available and agreement among literature values is poor (Li et al., 1993). However, many data exist for γ^∞ of benzene in water, and it can be considered that the true value at 25 °C is near 2475 (Li et al., 1993; Duhem and Vidal, 1978; Tucker et al., 1981). Also, the vapor pressure of benzene is reported to be 12 625 Pa (Duhem and Vidal, 1978).

As expected from eq 5, plotting ln C_0/C against time actually gives a straight line passing through the origin (Figure 5). The slope of this line is equal to (0.079 ± 0.003) min^{-1}, corresponding to a limiting activity coefficient of 2.5×10^3. This value is in very close agreement with the above accepted one, and it can be considered that assumptions in eq 5 are satisfied by the stripping design used.

(b) Determination of $\gamma^\infty P^\circ$ and Vapor Pressure P°. Figure 6 gives an example of concentration decrease in the liquid phase during a stripping experiment carried out with α-pinene. This curve is, just as with benzene, of exponential shape, and plotting the natural logarithm of C_0/C versus time also gives a straight line. Vapor pressures at 25 °C obtained with this approach are summarized in Table 3.

Only few experimental values for terpene and terpenoid vapor pressures at 25 °C can be found in the literature, and they are often inconsistent (Table 5). However, evaluated data for α-pinene are available at temperatures ranging from −6 °C to 13.25 °C (Linder, 1931; from TRC SOURCE, 1997). Assuming vapor pressure varies with

Table 3. Terpenes and Terpenoids Solubility Measured in Water at 25°C, Activity Coefficient at Infinite Dilution $\gamma_{i}\infty$ and Vapor Pressures P° Obtained. the Confidence Interval Is Given at 95% Level. ND: Not Determined.

compound	solubility (mmol/l)	$\gamma_{i}\infty$/(dimensionless)	$\gamma^{\infty}P°$/(Pa)	$P°$/(Pa)
R-(+)-limonene	0.150 ± 0.015	$3.7 \times 10^5 \pm 3.7 \times 10^4$	$7.88 \times 10^7 \pm 7.88 \times 10^6$	213 ± 29
(−)-α-pinene	0.037 ± 0.004	$1.5 \times 10^6 \pm 1.5 \times 10^5$	$7.94 \times 10^8 \pm 7.94 \times 10^7$	529 ± 73
(−)-*β*-pinene	0.081 ± 0.006	$6.86 \times 10^5 \pm 5.14 \times 10^4$	ND^b	ND
myrcene	0.22 ± 0.02	$2.52 \times 10^5 \pm 2.52 \times 10^4$	$6.33 \times 10^7 \pm 6.33 \times 10^6$	251 ± 35
1*S*-*endo*-(−)-borneol	3.00 ± 0.24	$1.85 \times 10^4 \pm 1.48 \times 10^3$	$1.24 \times 10^5 \pm 2.90 \times 10^4$	6.7 ± 1.3
endo-(+)-fenchyl alcohol	5.37 ± 0.32	$1.03 \times 10^4 \pm 0.62 \times 10^3$	$1.55 \times 10^5 \pm 2.17 \times 10^3$	15 ± 3
(−)-α-pinene oxide	2.55 ± 0.48	$2.18 \times 10^4 \pm 4.14 \times 10^3$	$2.38 \times 10^6 \pm 4.51 \times 10^5$	109 ± 20
(+)-limonene oxide	4.61 ± 0.16	$1.20 \times 10^4 \pm 0.42 \times 10^3$	$9.96 \times 10^5 \pm 4.97 \times 10^4$	83 ± 5
β-ionone	0.88 ± 0.08	$6.31 \times 10^4 \pm 5.68 \times 10^3$	$4.54 \times 10^4 \pm 6.81 \times 10^3$	7.2 ± 1.2
(−)-carveol	19 ± 2	$2.92 \times 10^3 \pm 2.92 \times 10^2$	ND	ND
(±)-linalool	10.11 ± 0.61	$5.49 \times 10^3 \pm 0.33 \times 10^2$	ND	ND
α-terpineol	12.25 ± 1.10	$4.53 \times 10^3 \pm 0.41 \times 10^2$	ND	ND
(+)-carvone	8.80 ± 0.22	$6.31 \times 10^3 \pm 0.16 \times 10^2$	ND	ND

Table 4. Comparison of Solubility Data at 25 °C for Some Terpenes and Terpenoids

compound	solubility/(mmol/L)
limonene	0.095,^{a} 0.045,^{b} 0.10,^{d} 0.15^e
myrcene	<0.073,^{a} 0.043,^{b} 0.22^e
α-pinene	0.16,^{a} 0.026,^{b} 0.037^e
β-pinene	0.24,^{a} 0.049,^{b} 0.081^e
carvone	3.97,^{a} 8.71,^{c} 8.80^e
carveol	7.32,^{a} 19^e
borneol	1.78,^{a} 3^e

[a] Weindenhamer et al. (1993). [b] Schmid et al. (1992). [c] Myrdal et al. (1995). [d] Massaldi and King (1973). [e] This work (Table 3).

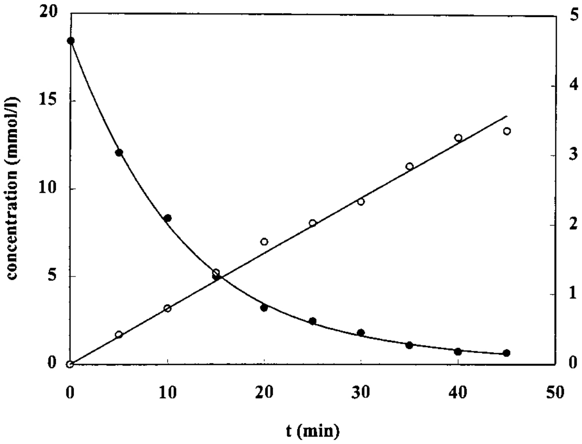

Figure 5. Time-course of benzene concentration (●) and ln C_0/C (○) during a stripping experiment by an air stream. Initial concentration, C_0 = 1.44 g/L, temperature = 25 °C, aeration rate, 0.9 L/min, volume of liquid = 3 L, stirring speed = 1000 rpm, *P* = 96 kPa.

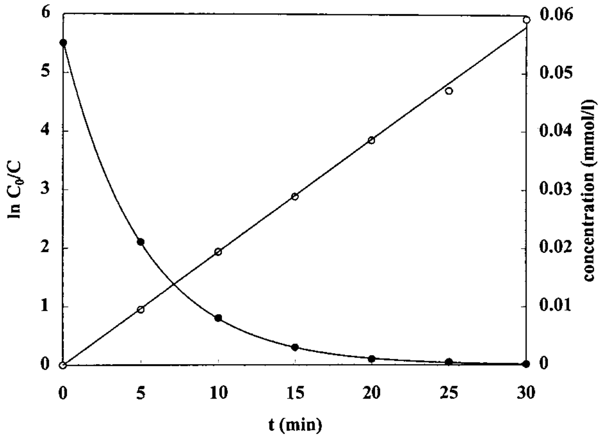

Figure 6. Typical time course of limonene concentration (●) and ln C_0/C (○) during a stripping experiment by an air stream. Initial concentration, C_0 = 7.5 mg/L, temperature = 25 °C, aeration rate = 0.9 L/min, stirring speed = 1000 rpm, volume of liquid = 3 L, *P* = 98.6 kPa.

Table 5. Comparison of Available Vapor Pressures, in Pa, with Results in This Work

compound	experimental literature value	estimated value	this work^e
limonene	267,^{a} 187^b	223,^{c} 205^d	213
α-pinene	613^a	581,^{c} 465^d	529
myrcene	253^a	305^d	251

[a] Simon et al. (1995), values at 24 °C. [b] Massaldi and King (1973). [c] Estimated using the five parameters equation given by Daubert and Danner (1989). [d] Estimated using the ACD method (ACD/PVAP Web Service V.2.6, 1995). [e] Data from Table 3.

temperature according to the Clausius–Clapeyron equation, ln P^0 was plotted against the reciprocal of the temperature. This gave a straight line that extrapolated to the value at 25 °C obtained in this work (Figure 7).

Also, several estimation methods exist, generally based on the group contribution method (Grain, 1982). Among these, software developed by ACD (Advanced Chemistry Development, Inc, Toronto, Canada) gives results in close agreement with our experimental data; the slope of the straight line, obtained by plotting ACD values against experimental ones, is close to unity (Figure 8). These results demonstrate that terpene and terpenoid vapor pressures can be predicted from commercial software with an accuracy close to 20%, which can be considered an acceptable value, especially when this approach is used for engineering purposes (Banerjee, 1996).

Solubility Correlations. Solubility correlations (or predictions) involve two families of equations. The first gives results as activity coefficients, while the second calculates the solubility itself. The most widely accepted approach for activity coefficient prediction is the use of the UNIFAC (Uniquac functional group activity coefficients) model (Abrams and Prausnitz, 1975), which is a group contribution method. Several modifications of the original model have been proposed (Larsen et al., 1987; Gmehling et al., 1993). However, it has been shown that existing UNIFAC-type models perform poorly when applied to the prediction of infinite dilution activity coefficients in polar mixtures, especially in water containing ones (Voutsas and Tassios, 1996, 1997). Data in Figure 9 show that although a linear relation can be found between the logarithm of experimental and calculated values, γ^{∞} can be predicted by UNIFAC only with an average accuracy close to 220%.

The second kind of correlation, giving solubility, and also based on the group contribution method, involves the use of log *P*, i.e., the logarithm of octanol/water partition coefficient in an octanol–water standard system (Hansch

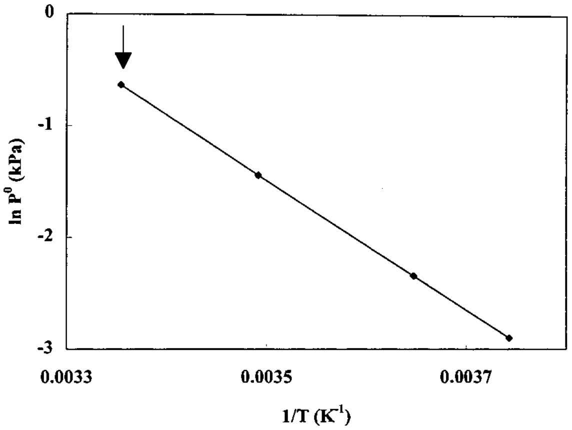

Figure 7. ln P^0 plotted against the reciprocal of temperature for α-pinene. The arrow indicates the value obtained in this work (Table 3); other data are from Linder (1931) (from TRC SOURCE, 1997).

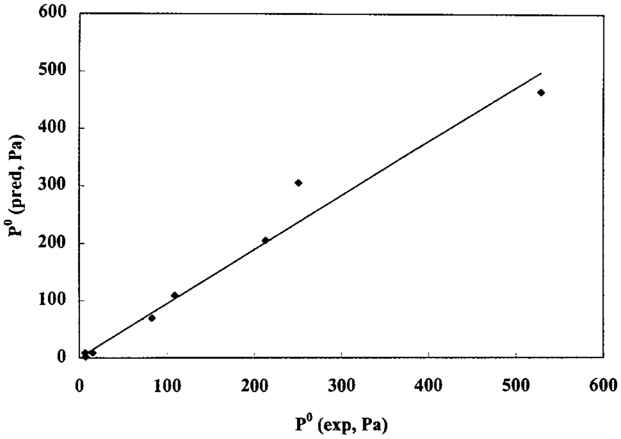

Figure 8. Comparison of our experimental vapor pressures to those calculated by ACD software. The slope of the straight line is (0.94 ± 0.12), the confidence interval being given at the 95% level.

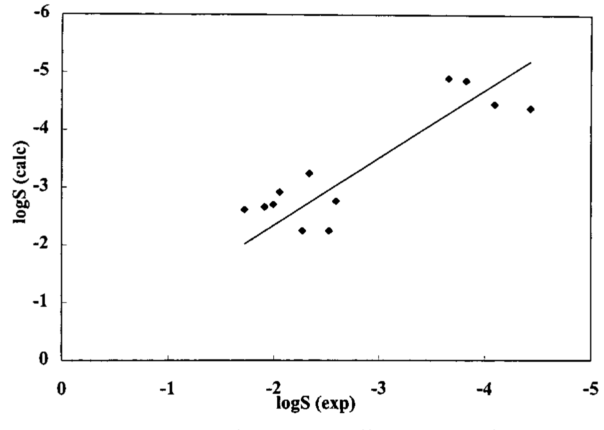

Figure 9. Comparison of activity coefficients at infinite dilution estimated with the UNIFAC−Larsen model to our experimental data. The slope of the straight line is (0.88 ± 0.08), the confidence interval being given at the 95% level.

and Leo, 1995). Some authors (Yalkowsky and Banerjee, 1992) claim that this approach is at present the most successful one. One of the most recent studies published in this area proposes the following regression-derived correlation (Meylan et al., 1996)

$$\log S = 0.796 - 0.854 \log P - 0.00728\, M_W + \sum \mathrm{fi} \qquad (8)$$

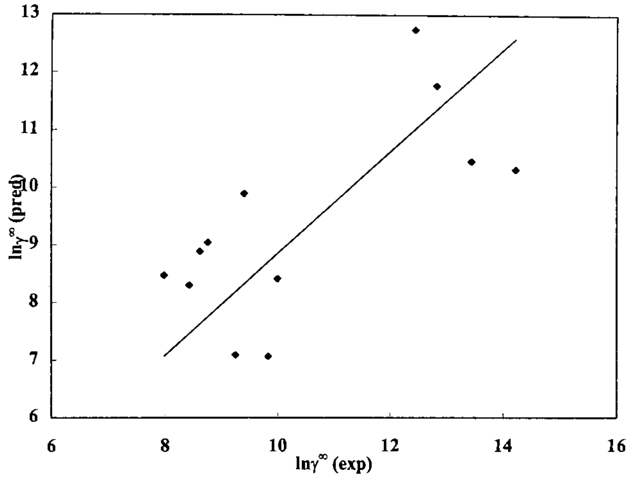

Figure 10. Calculated solubilities (mol/l) from equation proposed by Meylan et al. (1996) plotted against experimental values. The slope of the straight line is 1.17 ± 0.12, the confidence interval being given at the 95% level.

where S is the water solubility in mol/L, the term log P is calculated using the SRC (Syracuse Research Corporation, Syracuse, NY) computer program LOGKOW, M_W is the molecular weight of the solute (g/mol), and Σfi is the summation of correction factors.

Figure 10 shows the results obtained with compounds tested in this work. Although a straight line can be drawn between experimental and calculated values, terpene solubilities can be predicted only with an average accuracy near 140%.

Conclusion

Two independent experiments have been developed in this work. The first is a measurement of solubility, using a saturated aqueous solution. The solubility obtained allows the determination of activity coefficients at infinite dilution. This method is simple enough to allow determinations over a wide range of solubilities. The second procedure involves stripping the solute by a gas stream and gives the product $\gamma^\infty P°$. Results obtained by the two methods allow vapor pressure calculation. Vapor pressures obtained in this work are in close agreement with predicted values. We therefore conclude that vapor pressure of compounds belonging to the terpene family may be easily estimated with existing methods.

Data obtained show high volatilities for the terpenes, whereas functionalized compounds are less volatile. Such information is useful for biological treatment in aerated lagoons and for biotransformation processes using terpenes as substrates in pure aqueous phase, since low solubility will affect the biotransformation rates and high volatility will result in substrate and product losses.

A preliminary approach to solubility prediction reveals that the main equations available in the literature cannot reasonably be considered as being able to predict water solubility of terpenes and terpenoids. Additional work in this area is needed and is in progress.

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