Malaysian Journal of Analytical Sciences (MJAS)
Published by Malaysian Analytical Sciences Society

MEASUREMENT OF SOLVENT PROPERTIES USING KAMLET-TAFT APPROACH FOR APPLICATION IN SYNTHESIS

(Pengukuran Sifat Pelarut Menggunakan Pendekatan Kamlet-Taft untuk Penggunaan dalam Sintesis)

Tariqul Islam[1], A. B. M. Helal Uddin[1], Sahena Ferdosh[2], Md. Zaidul Islam Sarker[1,3]*

[1]*Faculty of Pharmacy*
[2]*Faculty of Science*
International Islamic University Malaysia, 25200 Kuantan, Pahang, Malaysia
[3]*Food Science Program,*
Northern Marianas College, 501250, Saipan MP 96950, USA

Program Leader of Food Science Program, Cooperative Research, Education and Extension Services,

**Corresponding author: mdzaidul.sarker@marianas.edu*

Received: 31 August 2021; Accepted: 11 January 2022; Published: xx February 2022

Abstract

Solvents are an unavoidable part of pharmaceutical and chemical manufacturing/synthesis, most of them are toxic or hazardous. The study on toxic solvent replacement is ongoing over the world. Researchers are trying to overcome the hazardous issues that can be possible using the mixture of hydrogen bond donor (HBD) and hydrogen bond acceptor (HBA) solvent as a safe/recommended solvent mixture. This study presented the possibility for the replacement/limitation of dipolar aprotic solvent in drug synthesis by solvent-pair mixture where the Kamlet-Taft (KT) parameter worked as a tool to alternate the uses of such types of toxic solvents. It has been simplified here among the many methods and equations of the KT approach. The polarity (π*), basicity (β), and acidity (α) of 10 pure solvents and 16 solvent-pair mixtures were measured spectroscopically, utilizing well-suited dyes or indicators. The highest absorption wavenumber value of indicators in the solution was selected and the simplified KT equations were used to determine the solvent properties (π*, β, α). Solvent mixtures were classified as per the solvent selection guideline of GSK2016 and CHEM21. Four pure solvents (tetrahydrofuran, dimethylformamide, dimethylsulfoxide, and acetone) exhibited low KT acidity, high KT basicity, and high KT polarity. Eight aqueous solvent mixtures (water-acetone, water-ethanol, water-isopropyl alcohol, water-dimethylsulfoxide, water-dimethylformamide, water-tetrahydrofuran), and two non-aqueous solvent mixtures (ethanol-dimethylformamide, ethanol-dimethylsulfoxide) showed low KT acidity and high KT basicity. Solvent classification by composite score showed that four solvent mixtures were as recommended and 5 mixtures were near to recommended solvent among 16 solvent mixtures. KT parameter was a simplified approach to determine which mixture can bind with active pharmaceutical ingredients (API) that is indicated by KT solvatochromic properties and solvent classification.

presents

using works

Keywords: Kamlet-Taft parameters, hazardous solvent, solvent-pair mixture, dipolar aprotic solvent, drug synthesis

Abstrak

Pelarut adalah bahagian yang tidak dapat dielakkan dalam pembuatan/sintesis farmaseutikal dan kimia, kebanyakannya beracun atau berbahaya. Kajian mengenai penggantian pelarut toksik sedang dijalankan di seluruh dunia. Penyelidik berusaha mengatasi masalah berbahaya yang mungkin dilakukan dengan menggunakan campuran pelarut penderma ikatan hidrogen (HBD) dan pelarut

ikatan hidrogen (HBA) sebagai campuran pelarut yang selamat/disyorkan. Kajian ini menunjukkan kemungkinan penggantian/pembatasan pelarut aprotik dipolar dalam sintesis ubat dengan campuran pasangan pelarut di mana parameter Kamlet-Taft (KT) berfungsi sebagai alat untuk mengganti penggunaan jenis pelarut toksik tersebut. Ini telah dipermudahkan di sini antara banyak kaedah dan persamaan pendekatan KT. Kekutuban (π*), asas (β), dan keasidan (α) daripada 10 pelarut tulen dan 16 campuran pasangan pelarut telah diukur dengan menggunakan spektroskopi, berdasarkan pewarna atau indikator yang sesuai. Nilai penyerapan gelombang tertinggi dari indikator dalam larutan dipilih dan persamaan KT digunakan untuk menentukan sifat pelarut (π*, β, α). Campuran pelarut dikelaskan mengikut garis panduan pemilihan pelarut GSK 2016 dan CHEM21. Empat pelarut tulen (tetrahidrofuran, dimetilformamida, dimetilsulfoksida, dan aseton) menunjukkan keasidan KT rendah, asas KT tinggi, dan kekutuban KT tinggi. Lapan campuran pelarut berasaskan air (air-aseton, air-etanol, air-isopropil alkohol, air-dimetilsulfoksida, air-dimetilformamida, air-tetrahidrofuran), dan dua campuran pelarut tidak berasaskan air (etanol-dimetilformamida, etanol-dimetilsulfoksida) menunjukkan keasidan KT rendah dan asas KT yang tinggi. Penggolongan terhadap 16 campuran pelarut berdasarkan skor komposit menunjukkan empat campuran pelarut adalah seperti yang disyorkan dan 5 campuran pelarut hampir dengan yang disyorkan. Parameter KT adalah pendekatan yang dipermudah untuk menentukan campuran mana yang dapat mengikat dengan bahan aktif farmaseutikal (API) yang ditunjukkan oleh sifat solvatochromic KT dan klasifikasi pelarut.

Kata kunci: parameter Kamlet-Taft, pelarut berbahaya, campuran pasangan pelarut, pelarut aprotik dipolar, sintesis ubat

Introduction

In 1976, Kamlet and Taft introduced a model to measure the solvatochromic properties, known as Kamlet-Taft parameters [1]. In 1997, Marcus brought some modifications in the measurement of KT parameters [2]. Various equations and indicators were used to calculate the KT parameters (KT acidity, KT basicity, and KT polarity) so that the appropriate result is obtained by averaging [3]. The most used indicators were N, N-dimethyl-4-nitroaniline, 4-nitro anisole, and N,N-dimethyl-3-nitro aniline for π* value; 4-nitroaniline, 4-nitrophenol, 4-aminoacetophenone and (tetramethyl ethylenediamine)(acetylacetonato)copper(II) perchlorate for β value; Cis-bis-(1,10-phenan throline)dicyanoiron(II), 2,6-dichloro-4-(2,4,6-triphenyl-1-pyridinio) phenolate, and 2,6-diphenyl-4-(2, 4, 6-tripheny-1-pyridinio) phenoxide/ phenolate for α value. The indicators were utilized in KT measurement because their UV variations are higher than the UV-Vis cutoff (310 nm) of the cyclic ketone [4]. In analysis, many specific equations are used to calculate the KT parameters that were prepared based on the indicators [2,5], and the concentration of the indicator greatly affects the result [6].

Solvents are categorized into four major types; recommended, problematic, hazardous, and highly hazardous based on health, safety, environment, and global harmonized system (GHS) hazards statements [7]. Most used solvents are hazardous as per the recommendation of the international conference on harmonization (ICH), Pfizer, GSK, and Sanofi [8,9], as shown in Table 1. Recently, KT parameters have been used to investigate the replacement/limitation of hazardous solvents using solvent-pair mixtures in synthetic chemistry. Most of the HBD-HBA solvent mixtures exhibit as solvent of recommended and problematic category [7,10,11], they can be applied in API [4,11] and non-API chemical [5,12,13] synthesis. The maximum use of safe solvents can minimize the health risks and negative impacts on the environment, which can be the most effective way to limit the use of hazardous solvents [14-17]. However, many methods; KT solvatochromic parameters using COSMO-RS [18], KT parameters using solvate ionic liquids [19] were more complex. Taking into consideration the advancement of the KT parameters in synthetic chemistry, the measurement technique has been simplified for determining the solvatochromic parameters. The 16 solvent-pair mixtures and 10 pure solvents were analyzed to determine the probability of application in replacing dipolar aprotic solvents (dimethylformamide, dimethylacetamide, N-methyl-2-pyrrolidone, pyridine etc.).

Table 1. Recommendation from Pfizer, GSK, Sanofi, and ICH regarding the use of the following solvents

Most Used Organic Solvents	**Concern in Use (Comment)** [8,9]			
	Pfizer	**GSK**	**Sanofi**	**ICH**
Dimethylformamide (DMF)	Undesirable	Major issues	Substitution requested	To be limited
Dimethylacetamide (DMAC)	Undesirable	Major issues	Substitution requested	To be limited
N-methyl-2-pyrrolidone(NMP)	Undesirable	Major issues	Substitution requested	To be limited
Dichloromethane (DCM)	Undesirable	Major issues	Substitution advisable	To be limited
Chloroform	Undesirable	Major issues	No comment	To be limited
1,4-Dioxane	Undesirable	Major issues	Substitution requested	To be limited
Pyridine	Undesirable	No comment	Substitution advisable	To be limited
Diisopropyl ether (IPE)	Undesirable	Major issues	Substitution advisable	Unknown

Please put here the both references no.

Materials and Methods

Materials

Analytical reagent (AR) grade methanol (MeOH 99.9%), acetone (Ace 99.8%), tetrahydrofuran (THF 99.8%), dimethyl sulfoxide (DMSO 99.9%), and calcium chloride anhydrous (99.9%) were received from Merck KGaA, Germany. Ethanol (EtOH 99.8%) was purchased from HmbG chemicals, Malaysia. HPLC grade acetonitrile (ACN 99.99%), AR grade dichloromethane (DCM 99.9%) were purchased from QREC (Asia), Malaysia. AR grade dimethylformamide (DMF 99.99%), and isopropyl alcohol (iPrOH 99.99%) were received from Fisher Scientific, UK. Three solvatochromic indicators were purchased: N, N-dimethyl-4-nitroaniline 98% as indicator 1 from Alfa Aesar through Permula chemicals, Malaysia; 4-nitro aniline 99% (Indicator 2) and Reichardt's dye 90% or 2,6-diphenyl-4-(2,4,6-triphenyl-1-pyridinio) phenolate 90% as indicator 3 from Sigma-Aldrich. To avoid humidity contamination or light degradation, the samples and indicators were weighted cautiously. A microbalance (Brand: Mettler Toledo; model: AX-205) was used to prepare the samples by mass with an uncertainty of ±1×10-4 g.

Analytical condition of KT parameters

Organic solvents were dried to free residual water before analysis using calcium chloride anhydrous. Indicator concentration in the solvent was from 0.03 mM to 0.05 mM (for indicator 1 & 2) and 0.1 mM (for indicator 3). The indicator and solvent were mixed properly before analysis to limit a variety of UV absorption to 0.5-1.2. The desired UV spectra of the solution were determined at a resolution of 0.2 nm using a double beam UV-Vis spectrophotometer (Shimadzu, UV-1800). Every UV-Vis spectrum was performed in triplicate. During the UV analysis, the temperature has been controlled at 25±0.1 °C using a temperature controller (Shimadzu, TCC-240A).

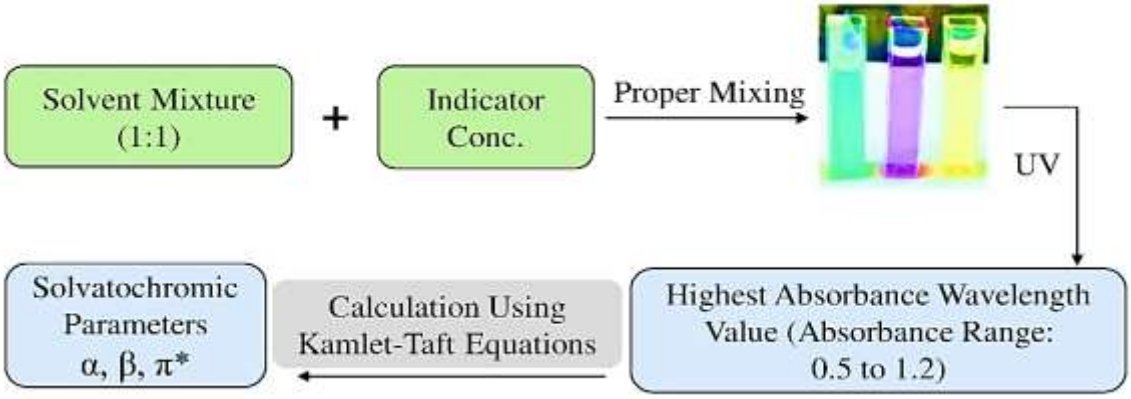

Figure 1. Measurement overview of solvatochromic parameters (π*, β, α) using the KT theory

Measurement equation of KT parameters

Three solvatochromic parameters i.e., KT polarity, KT basicity, and KT acidity were measured according to the original approach of KT theory using three equations (equation S1 to equation S3) [3,4]. The absorption wavenumber (V_{max}) from the highest wavelength value of the analytical sample was converted into KiloKaiser unit (1KK = 1000 cm^{-1}) to calculate the equations (1-3).

Statistical analysis

Experimental results were expressed as mean (n = 3) with uncertainty values and the data was analyzed using ANOVA and Dunnett's t-test in SPSS (version 20). *P values of 0.05 or less were regarded as significant.

Results and Discussion

The values of the measured wavenumbers (Vmax) and the obtained KT parameters have been expressed in Table 2 and Table 3. The absorbance range was established among the samples confined within 0.5 to 1.2. A total of ten pure solvents were analyzed to determine π*, β, and α. At the same time, sixteen mixed (HBD-HBA) solvents were also analyzed, involving eight aqueous and eight non-aqueous solvent pairs. In pure solvents, EtOH, MeOH, H_2O, iPrOH showed a high KT acidity and low KT polarity, whereas, DCM, ACN showed a low KT basicity. On the other hand, Ace, ACN, DMSO, DMF, and THF showed low acidity. In other words, the recommended solvents showed a high KT acidity, low KT basicity, and low KT polarity. In contrast, maximum problematic and hazardous solvents showed low KT acidity, high KT basicity, and high KT polarity except for DCM, iPrOH, and MeOH. Almost similar findings have been reported in the literature [20, 21].

Among the 16 mixed solvents, only four solvent mixtures i.e., H_2O-EtOH, H_2O-iPrOH, H_2O-DMSO, EtOH-DMSO were exhibited as recommended solvents, and the other 12 solvent mixtures were demonstrated as problematic in which 5 solvent mixtures (H_2O-Ace, EtOH-Ace, MeOH-Ace, H_2O-CAN, EtOH-CAN) showed as near to recommended solvent, as shown in Table 4. Eight aqueous (H_2O-MeOH, H_2O-Ace, H_2O-EtOH, H_2O-CAN, H_2O-iPrOH, H_2O-DMSO, H_2O-DMF, H_2O-THF) and two non-aqueous solvent mixtures (EtOH-DMF, EtOH-DMSO) showed a low KT acidity, low KT basicity, and high KT polarity. On the contrary, other non-aqueous solvent mixtures (EtOH-CAN, EtOH-Ace, EtOH-THF, MeOH-Ace, MeOH-DMF, MeOH-THF) showed a high KT acidity, low KT polarity, and low KT basicity, tabulated (Table 3). Similar results were found in the literature and previous work [6,11,12]. The solvent ranking was required for the application of mixed solvents that was prepared based on the GSK2016 and Innovative Medicines Initiative CHEM21 (IMI-CHEM21) solvent selection guideline [22]. The ranking of mixed solvents was ascertained from the minimum value of the GSK health and safety scores of HBA solvent using the equation (S4) [22].

Prat et al. and Byrne et al. stated that the commonly used solvents in drug synthesis and processing are hazardous, such as DMF, DMSO, NMP, DMAC, and pyridine, which are from dipolar aprotic solvents (HBA). IMI-CHEM21, GSK, Pfizer, ICH guidelines suggested that those solvents should be substituted/limited with safe solvents due to their toxic activities [7-9]. American Chemical Society (ACS) and Green Chemistry Institute (GCI) were investigating to replace such solvents in synthetic chemistry [23]. Duereh et al. stated that API has both HBD and HBA sites and dipolar aprotic (HBA) solvents have low KT acidity, high KT basicity, and high KT polarity. HBA solvents could easily create a strong chemical binding with the HBD site of API for these chemical properties [5].

Duereh et al. studied with 52 solvent mixtures and they reported that combinations of HBD-HBA allow the binding with API because solvent mixtures show low KT acidity, high KT basicity, and high KT polarity properties. For that, the solvent mixture can be used for the replacement of dipolar aprotic solvent. Although strong binding with API depends on physicochemical properties of solvent mixture. All mixtures who exhibited low KT acidity and high KT basicity, they are also capable to bind with the HBD site of API, can be selected for drug synthesis [4, 11, 13]. The solvent ranking was prepared to know which mixture is hazardous or problematic and which is recommended before being applied in synthesis. However, pure recommended solvents typically showed high acidity that is not capable to bind with the API. Therefore, when the solvent-pair mixtures show low KT acidity ($\alpha \approx 0$), high KT basicity ($\beta > 0.6$), and high KT polarity ($\pi^* > 0.6$), they offer a strong binding with the API [3, 11].

Indicator 1: Polarity (π^*) = $(28.10 - V_{max1}) / 3.52$ (1)

Indicator 2: Basicity (β) = $(0.984V_{max1} + 3.49 - V_{max2}) / 2.759$ (2)

Indicator 3: Acidity (α) = $(1.318V_{max1} - 47.7 + V_{max3}) / 5.47$ (3)

Composite score = $\sqrt{}$ (Safety score x Health score) (4)

Table 2 The properties of pure solvents from the wavenumber average (V_{max}) using the original approach of KT equations

Solvent	*V_{max} (Mean±SD)	*Polarity (π^*) (Mean)	*V_{max} (Mean±SD)	*Basicity (β) (Mean)	*V_{max} (Mean±SD)	*Acidity (α) (Mean)
EtOH	25.92±0.06	0.62	25.80±0.03	0.70	25.80±0.02	0.82
MeOH	25.64±0.02	0.70	25.66±0.05	0.64	25.66±0.02	1.00
Ace	25.66±0.04	0.69	25.59±0.03	0.49	25.59±0.02	0.24
CAN	25.41±0.02	0.76	25.39±0.03	0.33	25.39±0.01	0.38
i-PrOH	25.94±0.02	0.61	25.91±0.07	0.56	25.91±0.01	0.60
DMSO	24.55±0.02	1.01	24.57±0.05	0.69	24.57±0.01	0.10
DMF	25.07±0.02	0.86	25.07±0.02	0.71	25.07±0.01	0.09
THF	26.05±0.05	0.58	25.95±0.05	0.48	25.95±0.11	0.00
DCM	25.48±0.03	0.74	25.43±0.04	0.00	25.43±0.06	0.04
H_2O	23.68±0.02	1.26	23.64±0.03	0.16	23.64±0.14	1.27

Key: *P values (P<0.05) were regarded as significant. Uncertainty value of $\pi^* = 8\times10^{-3}$, $\beta = 6\times10^{-3}$, and $\alpha = 8\times10^{-3}$

Need to put the space before and after of "±"

i.e., 1.35 ± 2.15

"±" need to add before of value i.e., = ± 8×10....

Table 3. The properties of mixed solvents from the wavenumber average (V_{max}) using the original approach of KT equations

HBD-HBA Mixture	*V_{max} (Mean±SD)	*Polarity (π) (Mean)	*V_{max} (Mean±SD)	*Basicity (β) (Mean)	*V_{max} (Mean±SD)	*Acidity (α) (Mean)
Aqueous solvent mixture						
H_2O-MeOH	24.14±0.02	1.12	24.14±0.05	0.40	24.14±0.03	0.82
H_2O-Ace	24.39±0.03	1.05	24.39±0.03	0.48	24.39±0.01	0.68
H_2O-EtOH	24.31±0.02	1.08	24.31±0.03	0.48	24.31±0.01	0.67
H_2O-CAN	24.51±0.02	1.02	24.51±0.04	0.41	24.51±0.01	0.82
H_2O-iPrOH	24.62±0.02	0.99	24.62±0.03	0.57	24.62±0.01	0.65
H_2O-DMSO	23.88±0.02	1.20	23.88±0.02	0.43	23.88±0.03	0.58
H_2O-DMF	24.08±0.01	1.14	24.08±0.02	0.48	24.08±0.03	0.62
H_2O-THF	24.98±0.02	0.89	24.98±0.02	0.60	24.98±0.01	0.64
Non-aqueous solvent mixture						
EtOH-CAN	25.46±0.02	0.75	25.46±0.05	0.51	25.46±0.001	0.82
EtOH-Ace	25.64±0.02	0.70	25.64±0.03	0.59	25.64±0.01	0.76
EtOH-DMF	25.36±0.02	0.78	25.36±0.04	0.65	25.36±0.02	0.67
EtOH-DMSO	25.17±0.02	0.83	25.17±0.04	0.74	25.17±0.01	0.60
EtOH-THF	25.81±0.02	0.65	25.81±0.02	0.64	25.81±0.02	0.70
MeOH-Ace	25.54±0.02	0.73	25.54±0.03	0.56	25.54±0.02	0.88
MeOH-DMF	25.32±0.02	0.79	25.32±0.02	0.63	25.32±0.02	0.81
MeOH-THF	25.71±0.05	0.68	25.71±0.03	0.61	25.71±0.02	0.84

Key: *P values (P<0.05) were regarded as significant. Uncertainty value of $\pi^* = 7\times10^{-3}$, $\beta = 8\times10^{-3}$, and $\alpha = 3\times10^{-3}$

"±" need to add before of value i.e., = ± 7×10....

Table 4. Ranking of the solvent-pair mixture from the minimum values of GSK health and safety score [22]

Solvent-pair (HBD-HBA)	GSK Scores of HBA Solvent				Composite Score (Rank)
	Safety	Health	Environmental	Waste	
H_2O-EtOH	7.7	8.9	6.7	4.2	8.3
H_2O-iPrOH	6.9	7.7	7.5	4.4	7.3
H_2O-DMSO	6.7	7.9	6.9	4.6	7.3
EtOH-DMSO	6.7	7.9	6.9	4.6	7.3
H_2O-Ace	6	7.7	7.7	3.3	6.8
EtOH-Ace	6	7.7	7.7	3.3	6.8
MeOH-Ace	6	7.7	7.7	3.3	6.8
H_2O-ACN	7.7	5.9	8.9	2.8	6.7
EtOH-ACN	7.7	5.9	8.9	2.8	6.7
H_2O-MeOH	7.1	4.9	8.4	4.0	5.9

Table 4 (cont'd). Ranking of the solvent-pair mixture from the minimum values of GSK health and safety score [22]

Solvent-pair (HBD-HBA)	GSK Scores of HBA Solvent				Composite Score (Rank)
	Safety	Health	Environmental	Waste	
H_2O-THF	4.9	5.9	5.2	3.5	5.4
EtOH-THF	4.9	5.9	5.2	3.5	5.4
MeOH-THF	4.9	5.9	5.2	3.5	5.4
H_2O-DMF	9	2.4	6.3	4.6	4.6
EtOH-DMF	9	2.4	6.3	4.6	4.6
MeOH-DMF	9	2.4	6.3	4.6	4.6

Keys: Recommended solvent-pairs (green highlight) = score 7-10, problematic solvent-pairs (yellow highlight) = score 4-7, hazardous solvent-pairs (red highlight) = score 0-4 are score ranges adopted from IMI-CHEM21 [7]

Conclusion

The Kamlet-Taft analytical approach was simple and efficient to measure the KT acidity, basicity, and polarity of solvents or solvent mixtures. However, the proper mixing and temperature control of the solvent and indicator was the prerequisite to get the correct result in KT analysis. The ranking of HBD-HBA combinations facilitated to find out a suitable solvent mixture to substitute hazardous solvents in drug synthesis. The highest yield was found when the solvent creates a strong interaction with the HBD site of API. It is possible if the solvent mixture carries low KT acidity and high KT basicity. The maximum use of this methodology could bring a revolutionary change in synthetic chemistry.

Acknowledgement

The authors are thankful to the Fundamental Research Grant Scheme of the Ministry of Education, Malaysia (GRANT NO: FRGS19-002-0610) and International Islamic University Malaysia for their support.

References

1. Kamlet, M. J., and Taft, R. W. (1976). The solvatochromic comparison method. I. The beta-scale of solvent hydrogen-bond acceptor (HBA) basicity. *Journal of the American chemical Society*, 98(2): 377-383.
2. Labban, A. S. and Marcus, Y. (1997). Solvatochromic parameters of ethanolamines. *Journal of the Chemical Society, Faraday Transactions*, 93(1): 77-79.
3. Islam, T., Sarker, M. Z. I., Uddin, A. H., Yunus, K. B., Prasad, R., Mia, M. A. R. and Ferdosh, S. (2020). Kamlet Taft parameters: A tool to alternate the usage of hazardous solvent in pharmaceutical and chemical manufacturing/synthesis-A gateway towards green technology. *Analytical Chemistry Letters*, 10 (5): 550-561.
4. Duereh, A., Guo, H., Honma, T., Hiraga, Y., Sato, Y., Lee Smith Jr, R. and Inomata, H. (2018). Solvent polarity of cyclic ketone (cyclopentanone, cyclohexanone): Alcohol (methanol, ethanol) renewable mixed-solvent systems for applications in pharmaceutical and chemical processing. *Industrial & Engineering Chemistry Research*, 57(22): 7331-7344.
5. Duereh, A., Sato, Y., Smith Jr, R. L., and Inomata, H. (2016). Analysis of the cybotactic region of two renewable lactone–water mixed-solvent systems that exhibit synergistic Kamlet–Taft basicity. *The Journal of Physical Chemistry B*, 120(19): 4467-4481.
6. Marcus, Y. (1994). The use of chemical probes for the characterization of solvent mixtures. Part 2. Aqueous mixtures. *Journal of the Chemical Society, Perkin Transactions 2*(8): 1751-1758.

7. Prat, D., Wells, A., Hayler, J., Sneddon, H., McElroy, C. R., Abou-Shehada, S. and Dunn, P. J. (2015). CHEM21 selection guide of classical-and less classical-solvents. *Green Chemistry*, 18(1): 288-296.
8. European Medicines Agency (2019), ICH guideline Q3C (R6) on impurities: guideline for residual solvents, step 5. https://www.ema.europa.eu/en/ich-q3c-r6-residual-solvents [Access online 08 October 2021].
9. Byrne, F. P., Jin, S., Paggiola, G., Petchey, T. H., Clark, J. H., Farmer, T. J., Hunt, A. J., McElroy, C. R. and Sherwood, J. (2016). Tools and techniques for solvent selection: green solvent selection guides. *Sustainable Chemical Processes*, 4(1): 1-24.
10. Prat, D., Hayler, J. and Wells, A. (2014). A survey of solvent selection guides. *Green Chemistry*, 16(10): 4546-4551.
11. Duereh, A., Sato, Y., Smith Jr, R. L. and Inomata, H. (2017). Methodology for replacing dipolar aprotic solvents used in API processing with safe hydrogen-bond donor and acceptor solvent-pair mixtures. *Organic Process Research & Development*, 21(1): 114-124.
12. Duereh, A., Sato, Y., Smith Jr, R. L. and Inomata, H. (2015). Spectroscopic analysis of binary mixed-solvent-polyimide precursor systems with the preferential solvation model for determining solute-centric Kamlet–Taft solvatochromic parameters. *The Journal of Physical Chemistry B*, 119(46): 14738-14749.
13. Duereh, A., Sato, Y., Smith Jr, R. L. and Inomata, H. (2015). Replacement of hazardous chemicals used in engineering plastics with safe and renewable hydrogen-bond donor and acceptor solvent-pair mixtures. *ACS Sustainable Chemistry & Engineering*, 3(8): 1881-1889.
14. Capello, C., Fischer, U. and Hungerbühler, K. (2007). What is a green solvent? A comprehensive framework for the environmental assessment of solvents. *Green Chemistry*, 9(9): 927-934.
15. Clark, J. H., and Tavener, S. J. (2007). Alternative solvents: shades of green. *Organic Process Research & Development*, 11(1): 149-155.
16. Jessop, P. G. (2011). Searching for green solvents. *Green Chemistry*, 13(6): 1391-1398.
17. Ashcroft, C. P., Dunn, P. J., Hayler, J. D. and Wells, A. S. (2015). Survey of solvent usage in papers published in organic process research & development 1997–2012. *Organic Process Research & Development*, 19(7): 740-747.
18. Sherwood, J., Granelli, J., McElroy, C. R. and Clark, J. H. (2019). A method of calculating the Kamlet–Abboud–Taft solvatochromic parameters using COSMO-RS. *Molecules*, 24(12): 2209.
19. Dolan, D. A., Sherman, D. A., Atkin, R., and Warr, G. G. (2016). Kamlet–taft solvation parameters of solvate ionic liquids. *ChemPhysChem*, 17(19): 3096-3101.
20. Marcus, Y. (1998). The properties of solvents. John Wiley & Sons, England: pp. 256
21. Marcus, Y. (1993). The properties of organic liquids that are relevant to their use as solvating solvents. *Chemical Society Reviews*, 22(6): 409-416.
22. Alder, C. M., Hayler, J. D., Henderson, R. K., Redman, A. M., Shukla, L., Shuster, L. E. and Sneddon, H. F. (2016). Updating and further expanding GSK's solvent sustainability guide. *Green Chemistry*, 18 (13): 3879-3890.
23. Hellsten, S., Qu, H. and Louhi-Kultanen, M. (2011). Screening of binary solvent mixtures and solvate formation of indomethacin. *Chemical Engineering & Technology*, 34(10): 1667-1674.