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Influence of solvent on the stability and reactivity of imidacloprid: theoretical study

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ABSTRACT

Pesticides are drained into water bodies. Water contamination by pesticide residues has increased dramatically with the continued excessive agricultural demand for pesticides. These have become a major threat to the environment and the ecosystem. The present account elucidates the influence of solvent on the stability and reactivity of imidacloprid. This one is an active agrochemical molecule widely used for its insecticidal activity. The goal is to understand the behavior of this molecule in different environments (aquatic, plant, animal, or in the air). The approach consists in describing the medium by a dielectric constant. The structure was optimized at density-functional theory level. The system energies were carried out with the M06-2X exchange-correlation potential, 6-311++G(d,p) basis, and C-PCM cavity (dielectric constant; ε = 2–80). Some global chemical descriptors such as electrophilicity (ω), chemical potential μ, and chemical hardness η are then calculated. NBO's plots were also described.

Keywords: Density-functional theory; Dielectric constant; Imidacloprid; Reactivity; Stability; Surfaces water

1. Introduction

Imidacloprid ($C_9H_{10}ClN_5O_2$, (E)-1-(6-chloro-3-pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine) [1] is the first generation of neonicotinoid insecticides, launched in 1991. It is one of the most effective insecticides for the control of sucking insect pests, including aphids, whiteflies, planthoppers, and thrips. However, the indiscriminate use of neonicotinoid-based insecticides has been blamed as the main cause of the disappearance of bees from the hive [2,3].

Surface water can be contaminated by pesticides through leaching phenomena from plants, soil, or surface runoff after the dissolution of pesticides in irrigation water and/or soil. They can also be transported by underground runoff. In different aquatic environments, pesticides can be deposited in the sediments temporarily or permanently. They can also volatilize or degrade [2,4–7]. Pesticides can also be found in wastewater [8,9].

Understanding the reactivity and the partition between different media of a chemical species goes through the study of its solubility in different solvents. It's also essential and crucial for the designing of the crystallization process. Many factors can influence the solubility; they can increase or decrease the solubility of a chemical species. These factors include the choice of solvent, temperature, other solutes present, pH, pressure, and the presence of hydrogen bonds [10]. However, the solubility data of imidacloprid published in the literature yet are relatively few.

In the present work, we are interested in the study of the influence of the solvent (described by its dielectric constant; ε = 2–80) on the stability of the structure of imidacloprid and its reactivity.

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2. Computational details

The biological activity of a bioactive molecule is closely related to its conformation [11]. That's why for the first time, we have calculated the structure of imidacloprid. Initially, we optimized and calculated the frequencies of the most stable conformation obtained by Moreira et al.: IMI1-V [12]. Improved structural and electronic imidacloprid data were obtained through computations performed with the density-functional theory (DFT) framework employing the 6-311++G(d,p) basis set and the M06-2X [13] exchange-correlation potential. All calculations were performed using the Gaussian09 program [14].

Consider now the calculated structure of imidacloprid in solution (at variable dielectric constant). The interest in the structure of bioactive molecules in non-aqueous solvents derives essentially from the fact that the biological activity of a chemical compound often depends on its lipophilicity. This property is usually estimated in terms of water/n-octanol or water/cyclohexane partition coefficients. Here, solvent is described by its dielectric constant; ε = 2–80 and the C-PCM model [15,16].

The natural orbitals of the bonds (NBO) calculations were carried out using the program NBO 3.1 [17,18] integrated into the Gaussian09 program.

3. Results and discussion

3.1. Structure

The computed structure is shown in Fig. 1.

3.2. Solvation energy

It is therefore interesting to study the evolution of the energy difference as a function of the dielectric constant medium. This point is illustrated in Fig. 2. The calculations in 6-311++G(d,p) with the exchange-correlation potential M06-2x were carried out using the structure calculated in the gaseous state and the same cavities in all settings. A standard factor for atomic radii of 1.2 was used. This method has given good results with other systems [19].

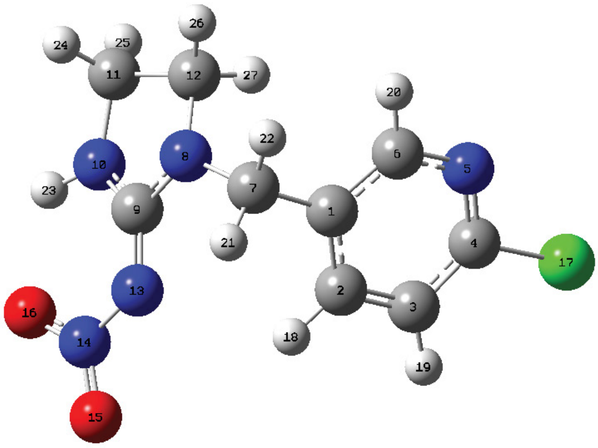

Fig. 1. DFT-optimized geometry for imidacloprid structure calculated in M06-2X/6-311++G(d,p).

The energy of solvation is calculated for the various dielectric constant values according to the relation:

$$E_{\text{Solvation}} = E_{\text{Solution}} - E_{\text{Gas}} \qquad (1)$$

where "E_{Solution}" is the system energy in solution (described here by the dielectric constant) and "E_{Gas}" is the system energy in the isolated state.

In Fig. 2, the greatest energy variations are observed below ε = 20. Beyond this value, the energy of solvation varies slightly to become almost constant from ε = 60. imidacloprid stabilizes at about 18 Kcal/mol during the transition from the isolated state to the hydrophobic state described by a dielectric constant equal to 2. For a ε value equal to 5, it stabilizes around 30 Kcal/mol. The passage of imidacloprid from a lipophilic medium (ε = 2) to an aqueous medium (ε = 80) stabilizes it energetically by approximately 21 Kcal/mol.

3.3. Frontier molecular orbitals highest occupied molecular orbital and lowest unoccupied molecular orbital

Fig. 4 shows the frontier molecular orbitals highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of our molecule in the different media studied. HOMO is the orbital that acts as an electron donor and LUMO is the orbital that largely acts as an electron receptor. The calculation of the energy Gap of frontier orbitals, which is the difference between the two [Gap = HOMO–LUMO], allows us to determine the chemical reactivity and the kinetic stability of the molecule. The calculated Gap's value in the isolated state (7,924 eV (Fig. 3)) remains in conformity with that obtained by Moreira et al. [12] (2.94 eV) for the IMI1-V conformation. This value evolves inversely with the value of the dielectric constant of the medium.

In molecular orbital topologies, the red lobes are positive and the green lobes are negative. The 3D diagrams show that the HOMO levels are located on the pyridine ring for the lowest epsilon values. It gradually shifts over the other cycle as this value increases. While LUMOs are distributed over the entire two cycles of imidacloprid at an isolated state, an almost total liberation of the pyridine ring is then observed for the various solvated states (Fig. 4).

3.4. Electrophilicity index

The global electrophilicity index ω [20] was calculated using the following expression:

$$\omega = \mu^2/2\eta \qquad (2)$$

The first quantity is chemical potential μ and the second is chemical hardness η. Approximately, $\mu = (\varepsilon_{\text{HOMO}} - \varepsilon_{\text{LUMO}})/2$ and $\eta = (\varepsilon_{\text{LUMO}} - \varepsilon_{\text{HOMO}})/2$ [21,22]. With $\varepsilon_{\text{HOMO}}$ and $\varepsilon_{\text{LUMO}}$, the one-electron energies of the HOMO and LUMO.

The curves of the evolution of the energy of solvation and the electrophilicity as a function of the dielectric constant of the medium represented in Figs. 2 and 5 show similar behaviors. A particularly pronounced change for the low values of the dielectric constant is observed in the two figures.

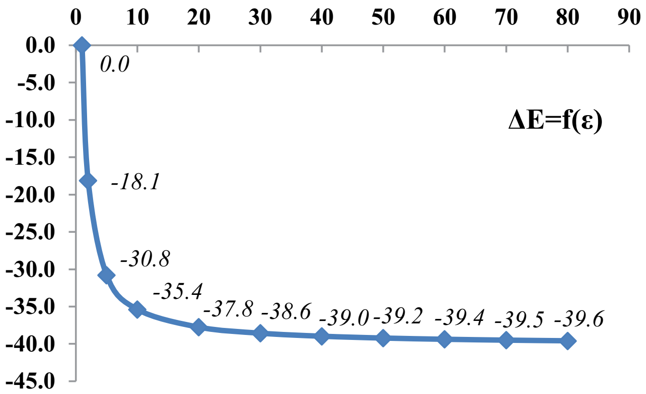

Fig. 2. Variation of the solvation energies with the dielectric constant (Energies in Kcal/mol).

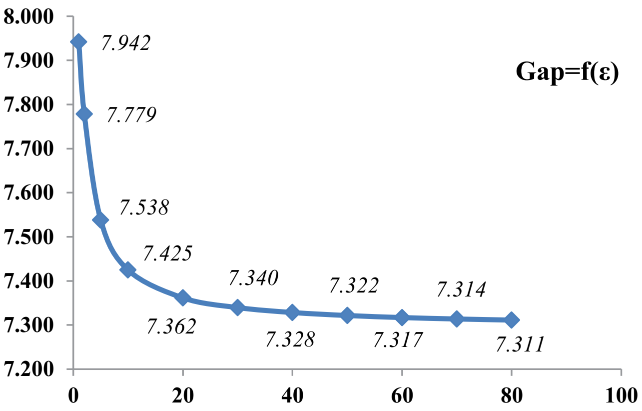

Fig. 3. Variation of the gap values (in eV) with the dielectric constant of the medium.

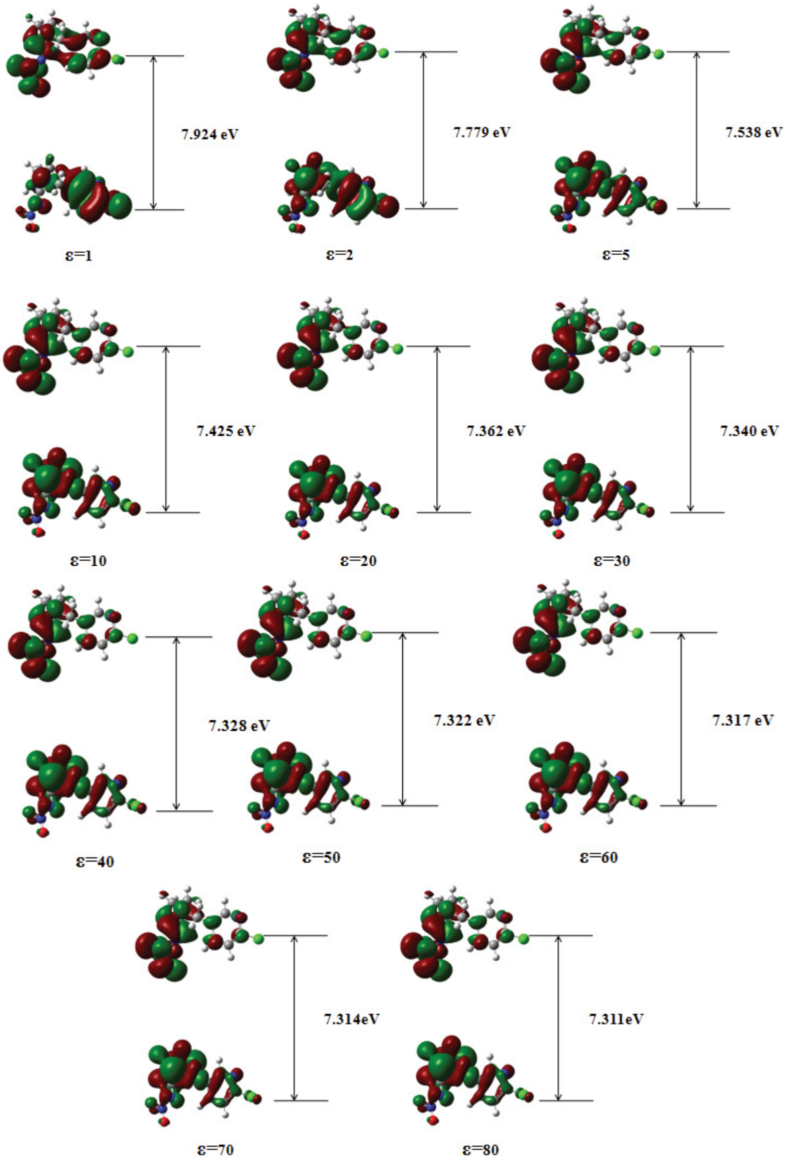

Fig. 4. The 3D diagrams of HOMOs and LUMOs calculated in M06-2x/6-311++G(d,p).

In Fig. 5, the value of chemical hardness η resulting from our calculations (3.971 eV) matches exactly that obtained by Moreira et al. [12] for the most stable conformation of imidacloprid obtained in a vacuum. The value of this parameter gradually decreases going from a vacuum to an aqueous medium. The lowest calculated value is 3,656 eV for imidacloprid in aqueous solution (ε = 80). García-Hernández et al. [23] calculate this parameter between 4.29 and 4.33 for a series of conformations of imidacloprid using the PBE0/6-311++G(d, p) method.

The values of the chemical potential μ vary between –4.434 for imidacloprid in aqueous solution and –4.799 eV for the isolated molecule.

3.5. Natural charges

The NBO charges for imidacloprid in a vacuum and C-PCM cavities are exhibited in Table 1. No significant differences were observed between both states (isolated and solvated). Analysis of the molecule natural charges suggests that N14 atom has the largest positive charge (0.65) and N10 atom is the most negative one (–0.64) for all studied media. This confirms the results obtained by Moreira et al. [12]. The most important differences in values observed for a change from vacuum to a aqueous solution are those related to atoms: N5 (Δq = 0.05), C7 (Δq = 0.06), O15 (Δq = 0.08) and H24, H25 and H26 (Δq = 0.04). The only nitrogen atom present in the pyridine ring is N5. The calculated value of its natural charge is –0.47 in a vacuum. Soliman [24] obtains it –0.4627 for the 2-chloropyridine and at –0.4627 for the 4-methylpyridine using the B3Lyp/6-311++G(d, p) method.

4. Conclusion

Imidacloprid is the most representative system of the new generation of insecticides. We have established a theoretical study of the analysis of chemical reactivity, based on the calculation of global chemical descriptors and frontier orbitals of this system in different environments (isolated system, non-polar and polar media). The different media are described by dielectric constant values. Our results show that the greatest variations in solvation energy are observed for non-polar media with an epsilon of less

Table 1
Natural (NBO) charges of the imidacloprid

		Dielectric constant values									
Atom	In vacuum	2	5	10	20	30	40	50	60	70	80
C1	–0.11	–0.11	–0.11	–0.09	–0.09	–0.09	–0.09	–0.09	–0.09	–0.09	–0.09
C2	–0.14	–0.15	–0.15	–0.15	–0.15	–0.15	–0.15	–0.15	–0.15	–0.15	–0.15
C3	–0.25	–0.26	–0.27	–0.27	–0.27	–0.27	–0.27	–0.27	–0.27	–0.27	–0.27
C4	0.20	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
N5	–0.47	–0.49	–0.50	–0.51	–0.51	–0.52	–0.52	–0.52	–0.52	–0.52	–0.52
C6	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
C7	–0.19	–0.22	–0.24	–0.24	–0.25	–0.25	–0.25	–0.25	–0.25	–0.25	–0.25
N8	–0.50	–0.50	–0.49	–0.49	–0.49	–0.49	–0.49	–0.49	–0.49	–0.49	–0.49
C9	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
N10	–0.64	–0.64	–0.63	–0.63	–0.63	–0.63	–0.63	–0.63	–0.63	–0.63	–0.63
C11	–0.18	–0.19	–0.20	–0.21	–0.21	–0.21	–0.21	–0.21	–0.21	–0.21	–0.21
C12	–0.18	–0.19	–0.20	–0.20	–0.21	–0.21	–0.21	–0.21	–0.21	–0.21	–0.21
N13	–0.48	–0.49	–0.50	–0.50	–0.50	–0.51	–0.51	–0.51	–0.51	–0.51	–0.51
N14	0.64	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.66	0.66
O15	–0.38	–0.41	–0.44	–0.45	–0.45	–0.46	–0.46	–0.46	–0.46	–0.46	–0.46
O16	–0.49	–0.50	–0.50	–0.50	–0.51	–0.51	–0.51	–0.51	–0.51	–0.51	–0.51
Cl17	0.01	0.00	–0.01	–0.01	–0.02	–0.02	–0.02	–0.02	–0.02	–0.02	–0.02
H18	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
H19	0.24	0.25	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
H20	0.19	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.23
H21	0.25	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
H22	0.21	0.24	0.26	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
H23	0.45	0.47	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
H24	0.19	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.23
H25	0.21	0.21	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.25
H26	0.21	0.21	0.24	0.24	0.24	0.25	0.25	0.25	0.25	0.25	0.25
H27	0.20	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

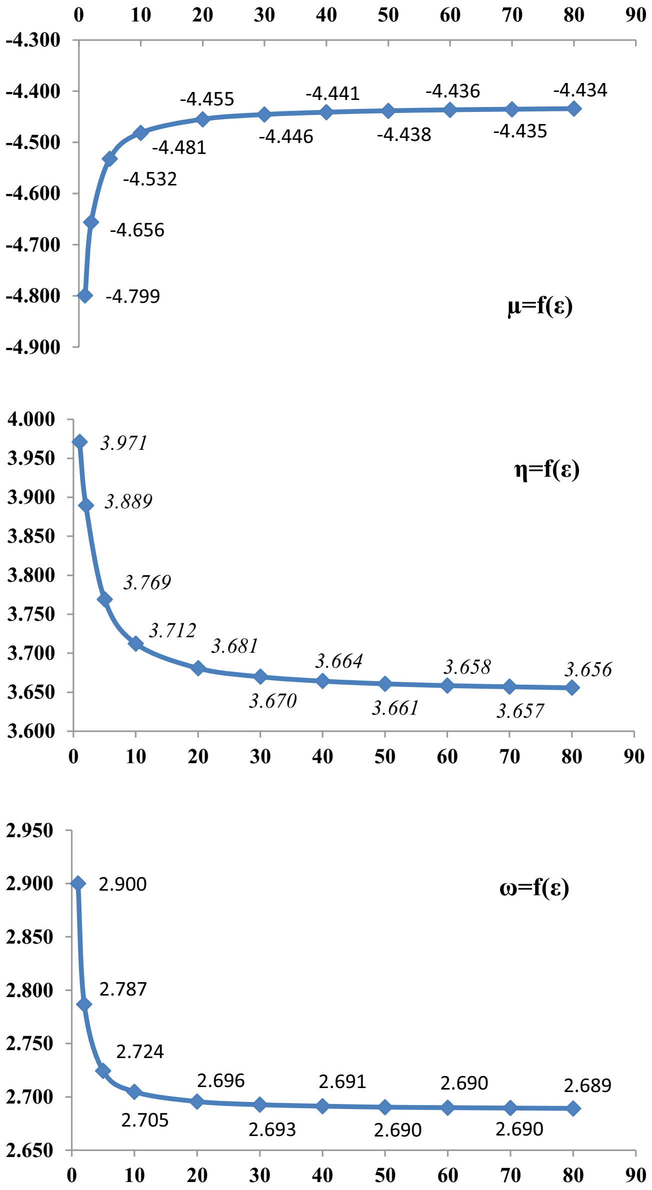

Fig. 5. Variation of chemical potential μ, chemical hardness η, and global electrophilicity index ω (in eV) with the dielectric constant of the medium.

than 20. The energy calculation shows that the passage of imidacloprid from a lipophilic medium to the aqueous medium stabilizes the studied pesticide considerably. On the other hand, the NBO calculations confirm those in the literature. The evolution of solvation energy and electrophily behave similarly concerning the media studied. Analysis of imidacloprid's natural charges suggests a positive charge for the N14 atom and another negative for the N10 atom in the studied media. While that of the N5 atom (the pyridine ring nitrogen) remains negative but less important than that of the N10 atom. It is rather of the same order as that of atoms N13 and N8. An important result that should not be overlooked is that of the HOMO and LUMO calculations. They show us that the behavior of the molecule and particularly that of the pyridine ring depends considerably on the dielectric constant.

References

[1] D. Chopra, T.P. Mohan, K.S. Rao, T.N. Guru, (2E)-1-[(6-Chloropyridin-3-yl)methyl]-N-nitroimidazolidin-2-imine (imidachloprid), Acta Crystallogr., Sect. E: Struct. Rep. Online, E60 (2004) o2415–o2417.

[2] C.A. Morrissey, P. Mineau, J.H. Devries, F. Sanchez-Bayo, M. Liess, M.C. Cavallaro, K. Liber, Neonicotinoid contamination of global surface waters and associated risk to aquatic invertebrates: a review, Environ. Int., 74 (2015) 291–303.

[3] ASSAf, Neonicotinoid Insecticides: Use and Effects in African Agriculture. A Review and Recommendations to Policymakers, Academy of Science of South Africa (ASSAf), 2021. Available at: http://hdl.handle.net/20.500.11911/178

[4] P. Bottoni, P. Grenni, L. Lucentini, A. Barra Caracciolo, Terbuthylazine and other triazines in Italian water resources, Microchem. J., 107 (2003) 136–142.

[5] E. Herrero-Hernández, M.S. Andrades, A. Álvarez-Martín, E. Pose-Juan, M.S. Rodríguez-Cruz, M.J. Sánchez-Martín, Occurrence of pesticides and some of their degradation products in waters in a Spanish wine region, J. Hydrol., 486 (2013) 234–245.

[6] M. Lamers, M. Anyusheva, N.T. La, V.V. Nguyen, T. Streck, Pesticide pollution in surface- and groundwater by paddy rice cultivation: a case study from Northern Vietnam, Clean – Soil, Air, Water, 39 (2011) 356–361.

[7] A. Székács, M. Mörtl, B. Darvas, Monitoring pesticide residues in surface and ground water in Hungary: surveys in 1990–2015, J. Chem., 2015 (2015) 717948, doi: 10.1155/2015/717948.

[8] A.R. Fernández-Alba, L. Hernando Guil, G. Díaz López, Y. Chisti, Toxicity of pesticides in wastewater: a comparative assessment of rapid bioassays, Anal. Chim. Acta, 426 (2001) 289–301.

[9] M. Köck-Schulmeyer, M. Villagrasa, M. López de Alda, R. Céspedes-Sánchez, F. Ventura, D. Barceló, Occurrence and behavior of pesticides in wastewater treatment plants and their environmental impact, Sci. Total Environ., 458–460 (2013) 466–476.

[10] A.F.M. Barton, Solubility parameters, Chem. Rev., 75 (1975) 731–753.

[11] R.J. Lewis, P. Camilleri, A.J. Kirby, C.A. Marby, A.A. Slawin, D.J. Williams, Structure–activity studies on amides inhibiting photosystem II, J. Chem. Soc., Perkin Trans. 2, (1991) 1625–1630.

[12] A.A.G. Moreira, P.D. Lima-Neto, E.W.S. Caetano, I.L. Barroso-Neto, V.N. Freire, Computational electronic structure of the bee killer insecticide imidacloprid, New J. Chem., 40 (2016) 10353–10362.

[13] Y. Zhao, D.G. Truhlar, The M06 suite of density functionals for main group thermochemistry, thermochemical kinetics, noncovalent interactions, excited states, and transition elements: two new functionals and systematic testing of four M06-class functionals and 12 other functionals, Theor. Chem. Acc., 120 (2008) 215–241.

[14] M. Frisch, G. Trucks, H. Schlegel, G. Scuseria, M. Robb, J. Cheeseman, G. Scalmani, V. Barone, B. Mennuci, G. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. Hratchian, A. Izmaylov, J. Bloino, G. Zheng, J. Sonnenberg, M. Hada, M. Ehra, K. Toyota, R. Fukude, J. Hasegawa, M. Ishida, T. Nakajima, K. Honda, O. Kitao, H. Nakai, T.J. Vreven, J. Montgomery, J. Peralta, F. Ogliaro, M. Bearpark, J. Heyd, E. Brothers, K. Kudin, J. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. Burant, S. Iyengar, J. Tomassi, M. Cossi, N. Rega, J. Millam, M. Klene, J. Knox, J. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, O. Yazyev, A. Austin, R. Cammi, C. Pomelli, J. Ochterski, R. Martin, K. Morokuma, V. Zakrzewski, G. Voth, P. Salvador, J. Dannenberg, S. Dapprich, A. Daniels, J. Foresman, J. Ortiz, J. Cioslowski, D. Fox, Gaussian 09, Gaussian Inc., Walligford, 2009.

[15] V. Barone, M. Cossi, Quantum calculation of molecular energies and energy gradients in solution by a conductor solvent model, J. Phys. Chem. A, 102 (1998) 1995–2001.

[16] M. Cossi, N. Rega, G. Scalmani, V. Barone, Energies, structures, and electronic properties of molecules in solution with the C-PCM solvation model, J. Comput. Chem., 24 (2003) 669–681.

[17] E.D. Glendening, Extension of Lewis Structure Concepts to Open-Shell and Excited-State Molecular Species, University of Wisconsin, 1987.

[18] E.D. Glendening, A.E. Reed, J.E. Carpenter, F. Weinhold, NBO, Version 3.1, Gaussian, (n.d.).

[19] N. Benbrahim, A. Rahmouni, M.F. Ruiz-López, A theoretical study of medium effects on the structure of the glycine analogue aminomethylphosphonic acid, Phys. Chem. Chem. Phys., 10 (2008) 5624–5632.

[20] R.G. Parr, L.v. Szentpály, S. Liu, Electrophilicity index, J. Am. Chem. Soc., 121 (1999) 1922–1924.

[21] R.G. Parr, R.G. Pearson, Absolute hardness: companion parameter to absolute electronegativity, J. Am. Chem. Soc., 105 (1983) 7512–7516.

[22] R.G. Pearson, Absolute electronegativity and hardness: application to inorganic chemistry, Inorg. Chem., 27 (1988) 734–740.

[23] E. García-Hernández, R. Flores-Moreno, Á. Vázquez-Mayagoitia, R. Vargas, J. Garza, Initial stage of the degradation of three common neonicotinoids: theoretical prediction of charge transfer sites, New J. Chem., 41 (2017) 965–974.

[24] S.M. Soliman, DFT study on the reactivity of mono-substituted pyridine ligands, Comput. Theor. Chem., 994 (2012) 105–111.