Theoretical Study of The Reaction of Ketene with Methanimine Using DFT Method

Haydar A. Mohammad-Salim
Department of Chemistry, Faculty of Science, University of Zakho, Duhok 42001, Kurdistan Region, Iraq

A B S T R A C T:

The Density Functional Theory (DFT) method was used to investigate the stepwise mechanism of the [2+2] cycloaddition (22CA) reaction of ketene with methanimine at the B3LYP/6-311++G(d,p) level of theory. Two modes of attack between reactants were investigated, yielding Azetidin-2-one from path1 and Azetidin-2-one from path2 as two possible products passing through two different transition states. The geometry of transition states and products was analysed. The study of stationary points and energetic parameters shows that the reaction mechanism is stepwise and that Azetidin-2-one P1 is thermodynamically and kinetically more favoured than Azetidin-3-one P2. The analysis of the frontier molecular HOMO and LUMO orbitals shows that the Azetidin-2-one P1 is more stable due to its higher energy gab. The global electronic flux from the strong nucleophilic ketene R1 to the methanimine R2 is predicted using conceptual density functional theory (CDFT) indices. Reactant’s electrophilic and nucleophilic Fukui functions were also investigated.

KEY WORDS: Stepwise mechanism; [2+2] cycloaddition; DFT; CDFT; Fukui Functions.
DOI: http://dx.doi.org/10.21271/ZJPAS.33.4.1
ZJPAS (2021), 33(4); 1-10 .

1. INTRODUCTION:

The chemistry of heterocycles has advanced dramatically in recent years,, and This family of molecules is the basis for the majority of compounds produced in the fields of industrial pharmaceutical chemistry (King et al., 2019; H. A. Mohammad-Salim & Abdallah, 2019b; Sowmya, Lakshmi Teja, Padmaja, Kamala Prasad, & Padmavathi, 2018). It's worth noting that heterocycles make up two-thirds of all compounds mentioned in the literature (Barber et al., 2018; Glasnov, 2018; Pawlowski, Stanek, & Stodulski, 2019). Therefore, it's understandable that heterocyclic compounds have become the focus of interest of a wide group of experimental and theoretical chemists.

One of the most effective synthetic strategies that requires the formation of different membered rings is cycloaddition reactions. These reactions occur when two unsaturated reactants interact. Among cycloaddition reactions, the 22CA reaction is one of the reactions used to build the four-membered ring and it is a structural unit in pharmaceutical compounds and natural occurring products (H. A. Mohammad-Salim & Abdallah, 2019a; H. A. Mohammad-Salim, Abdallah, Maiyelvaganan, Prakash, & Hochlaf, 2020; H. A. M. Salim, H. H. Abdallah, & P. Ramasami, 2018). The hetero-22CA reactions have been given attention by researchers due to their wide applications in the synthesis organic chemistry (Flores & Schmidt, 2019; Pang et al., 2018; H. M. Salim, H. H. Abdallah, & P. Ramasami, 2018). The four-membered heterocycles are the heterocyclic analogues of cyclobutane and are considered to be derived from cyclobutane by replacing a methylene group (-CH₂) with a heteroatom, usually, oxygen, sulfur or nitrogen.
The saturated heterocycles of four-membered containing oxygen, sulfur and nitrogen are called oxetane, thietane and azetidine, respectively. The small heterocycles with two heteroatoms, e.g. oxaphosphetanes and thioanalogues prepared from Witting reaction intermediate, also attract researchers due to their reactivity (Espinosa Ferao & Streubel, 2020; A. Kyri et al., 2018; A. W. Kyri et al., 2019).

In the previous two decades, computational chemistry has been an effective method for analyzing experimentally observed selectivity and reactivity results by creating a formal description of chemical reaction mechanisms (Krylov et al., 2018). Despite the number of modern uses of computational science in chemistry, the underlying theories of organic chemistry, since last 40 years, had not experienced major breakthrough. Domingo suggested the molecular electron density theory in 2016 to acknowledge the crucial role of electron density variations in molecular reactivity (Domingo, 2016; Ríos-Gutiérrez & Domingo, 2019). This theory has been successfully analyzing the experimental results of many cycloaddition reactions for the past four years (Domingo, Ríos-Gutiérrez, & Pérez, 2018; H. Mohammad-Salim, Hassan, Abdallah, & Oftadeh, 2020; H. A. Mohammad-Salim; H. A. Mohammad-Salim, Acharjee, & Abdallah, 2021; H. A. Mohammad-Salim, Basheer, Abdallah, Zeroual, & Jamil, 2021; Ríos-Gutiérrez & Domingo, 2019). Recently, this theory has been applied to analyse the experimental outcome of strain promoted and catalysed cycloaddition reactions and the observed chemio-, stereo- and regioselective synthesis of heterocyclic compounds (Abbiche et al., 2020; Acharjee, Mohammad-Salim, Chakraborty, Rao, & Ganesh; Domingo, Acharjee, & Mohammad-Salim, 2020; H. A. Mohammad-Salim, Acharjee, Domingo, & Abdallah, 2020).

Since four-membered heterocycles have industrial uses such as potential drugs, catalysts and dyesensitized solar cells (Fuentes de Arriba, Lenci, Sonawane, Formery, & Dixon, 2017; Mathew et al., 2014; Xu, Zhang, & Luo, 2014), the analysis of these compounds is of considerable interest. Preparation of nitrogen containing heterocyclic compounds have become a major point of interest among researchers due to its biological activities and success in the involvement of cancer treatment (Tokunova et al., 2001; Willenbring & Tantillo, 2008). Therefore, the primary goal of this investigation was to study the stepwise mechanism path of 22CA of ketene \( R_1 \) with methanimine \( R_2 \) (see Scheme 1) using theoretical methods in more details.

![Scheme 1. Mechanism of the 22CA reaction between ketene \( R_1 \) and methanimine \( R_2 \).](image-url)
2. COMPUTATIONAL METHODS

The Gaussian 16 package was used to do all calculations under the Linux operating system (Frisch et al., 2009). The B3LYP functional in DFT method has been shown to be a suitable method for studying 22CA reactions and is used in this study (R.G. Parr & Weitao, 1989; Saha et al., 2019; Svatanek, Pemberton, Mackey, Liu, & Houk, 2020). Throughout, B3LYP functional is used in conjunction with the 6-311++G(d,p) basis set (Ditchfield, Hehre, & Pople, 1971; Lee, Yang, & Parr, 1988). Geometry optimization on geometry convergence, electron density (SCF) convergence and integration grid were carried out in default settings.

The existence of one imaginary frequency was confirmed by frequency measurements at the optimized TSs, while in the case of the local minimum, the absence of imaginary frequency was confirmed. Intrinsic Reaction coordinate (IRC) calculations were performed using the Gonzales–Schlegel integration approach to validate the minimum energy reaction pathway linking the reactants and products through the defined TSs (Fukui, 1970; Gonzalez & Schlegel, 1991). The CDFT indices are computed using the equation discussed by Parr and co-workers (Robert G. Parr & Pearson, 1983; R.G. Parr & Weitao, 1994).

The electrophilic $f_k^+$ and nucleophilic $f_k^-$ Fukui functions (Domíngo, Pérez, & Sáez, 2013), which allow for the description of the nucleophilic and electrophilic centers of a reactants, were calculated via the examination of the Mulliken atomic spin density of the radical anion and the radical cation of ketene R1 and methanimine R2, from the optimized neutral geometries, using single-point energy calculations.

3. RESULTS AND DISCUSSION

Two regioisomeric paths, namely the path1 and path2 (see Scheme 1), for these 22CA reactions are feasible, due to non-symmetry of the reactants. The path1 reaction path is related with the formation of Azetidin-2-one (P1), while the path2 channel with the formation of Azetidin-3-one (P2), passing through different transition states.

The electronic energy profile for the 22CA reaction of R1 with R2 is shown in Figure 1. This figure shows the all possible transition states and intermediates associate with the reaction of ketene R1 with methanimine R2. The electronic energies (in kcal/mol) are relative to the energy of the two non-interacting reactants. Similarly, the relative energy for P2 is about 22 kcal/mol above the energy of P1. It’s worth to realize that the product P1 is a kinetic as well as thermodynamic product. It can be noted that there are two pathways of this reaction. One of them is to obtain IM1 intermediate passing through TS1C and the other is to form IM2 intermediate passing through TS1N. The results of electronic energy prefer the first pathway over the other. The electronic energy of IM2 intermediate is slightly above the most stable IM1 intermediate.

The IM1 and IM2 diradical intermediates are formed via TS1C and TS1N transition states, respectively. The activation energy is higher for the TS1N transition structure than the transition structure TS1C. Therefore, the path1 for obtaining P1 is expected to be the rate determining step. The next step of this reaction path corresponds to a rotation of the C-C and C-N bonds through the transition states TS2C and TS2N to form the product P1 and P2, respectively. The activation energy of this step is around 21 kcal/mol for TS2C and 30 kcal/mol for TS2N, respectively, such activation energies are obviously typical for the internal rotation of C-C and C-N single bond.

Table 1 lists the thermodynamic parameters for the 22CA reactions of R1 with R2 obtained in the gas phase with B3LYP/6-311++G(d,p) method. The first activation enthalpy for TS1C is 59.98 kcal/mol and for TS1N is 62.95 kcal/mol, while the second activation enthalpy for TS2C 61.89 kcal/mol while for TS2N is 67.85 kcal/mol. The values of Gibbs free energy for P1 is -14.60 kcal/mol, which refers to the spontaneous reaction. However, the Gibbs free energy for P2 is 7.61 kcal/mol that refers to the non-spontaneous reaction. The enthalpy of azetidin-2-one P1 azetidin-3-one P2 is negative, indicating the stability of both products. The observed data of thermodynamic parameters can be used to reach the conclusion that the product P1 is formed faster and has negative Gibbs free energy, thus P1 is preferred kinetically as well as thermodynamically.

ZANCO Journal of Pure and Applied Sciences 2021
Figure 1. Relative electronic energies (∆G) in kcal/mol of stationary points associated with the 22CA reaction of ketene with methanimine.

Table 1. Thermodynamic parameters for transition states, intermediates and products at B3LYP/6-311++G(d,p) level of theory in (kcal/mole) for ∆H and ∆G and in (cal/mol.K) for ∆S.

| Species | ∆H   | ∆G   |
|---------|------|------|
| TS1C    | 59.98 | 69.91 |
| IM1     | 41.55 | 51.56 |
Table 2 lists the HOMO and LUMO energies in eV computed at the B3LYP level of theory for reactants and products. As shown form the results in the table, the energy gap for $R_1$ is lower than the energy gap for $R_2$. It is worth to realize that the product $P_1$ has a wider energy gap than the product $P_2$, indicating the stability of this product.

**Table 2.** HOMO energies, LUMO energies and energy gap (in eV unit) for reactants and products at B3LYP/6-311++G(d,p) level of theory.

|       | HOMO  | LUMO  | Energy Gap |
|-------|-------|-------|------------|
| R1    | -7.20 | -0.82 | 5.61       |
| R2    | -6.86 | -1.75 | 6.69       |
| P1    | -6.70 | -1.54 | 6.84       |
| P2    | -6.83 | -1.75 | 5.73       |
Figure 2. The HOMO and LUMO of the P1 and P2 cycloadducts at B3LYP/6-311++G(d) level of theory. Their energies are given in Table 2.

The optimized geometries of all transition states at B3LYP/6-311++G(d,p) method are shown in Figure 3. The distances between C1 and C3, and C1 and N4 interacting centers at the transition states are: 2.15 Å at TS1C and 1.76 Å at TS1N. However, for the second part of the reaction, the distance between C1 and N4 is 1.68 Å at TS2C, while between C1 and C3 is 1.71 Å at TS2N. The C1-C3 and C1-N4 single bond distance was found to be 1.54 and 1.44 Å at the intermediates IM1 and IM2, respectively. Given that the formation of C-C and C-N single bonds starts at distances of 1.50-1.60 and 1.40-1.60 Å, respectively, these geometrical parameters mean that the formation of C-C and C-N single bonds has not yet started at either of the TSs.

Figure 3. B3LYP/6-311++G(d,p) optimised geometries of TSs and intermediates involved in the 22CA reactions of ketene R1 with methanimine R2. Bond lengths are given in Angstroms.

The reactivity in polar cycloaddition reactions can be examined using the global reactivity indices described within the conceptual DFT. The static global properties, namely, global nucleophilicity (N), chemical hardness (η), electronic chemical potential (μ) and global electrophilicity (ω) for the all reactants are listed in Table 3.

The electronic chemical potential (μ) of ketene R1 is -4.15 eV, which is higher than the R2 and this indicating that the global electronic flux will be from the R1 towards the electron-deficient R2. The power of electrophilicity for R1 and R2 is 1.54 eV and 1.37, which are moderate electrophiles, while R1 has a nucleophilicity power of 2.53 eV, which places it in the high nucleophilicity range with in the nucleophilicity and electrophilicity scale (Domingo, Aurell, Pérez, & Contreras, 2002). However, the power of nucleophilicity for R2 is 1.87 eV and it falls in the range of moderate nucleophile with in the nucleophilicity and electrophilicity scale (Domingo et al., 2002).
Table 3. The chemical hardness ($\eta$), electronic chemical potential ($\mu$), global electrophilicity ($\omega$) and global nucleophilicity (N) for all reactants in eV.

| Reactant | $\eta$ | $\mu$ | $\omega$ | N   |
|----------|--------|-------|--------|-----|
| R1       | 5.61   | -4.15 | 1.54   | 2.53|
| R2       | 6.68   | -4.27 | 1.37   | 1.87|

Table 4 lists the global and local properties of the reactants used in the 22CA reaction of R1 with R2. In reactant R1, the nucleophilic site is the C1 carbon (see Figure 4 for atom numbering), which has the highest Fukui function value for an electrophilic attack $f_k^-$. Consequently, the most favourable interaction will take place between the C1 center of reactant R1 and the C3 center of R2.

Figure 4. Schematic structures and atom numbering of reactants involved in [2+2] cycloaddition reaction.

A good explanation for the study of the regioselectivity in 22CA reactions can be computed by observing at those processes with a pronounced polar character, where the transition structure associated with the rate-determining step mostly involves the formation of one single bond between the most electrophilic and other nucleophilic sites in the 22CA pair of reactants.

Table 4. Static Global and Local properties of reactants involved in [2+2] cycloaddition reactions of R1 and R2.

| Reactants | site ($k$) | $f_k^-$ | $f_k^+$ |
|-----------|-----------|--------|--------|
| R1        | C1        | 0.54   | 0.33   |
|           | C2        | 0.06   | 0.16   |
| R2        | N4        | 0.11   | 0.18   |

To represent the charge transfer in a comparable manner, the molecular electrostatic potential (MESP) map of the transition states was obtained. Figure 5 shows the MESP maps for TS2C and TS2N transition states of two pathways path1 and path2, respectively. The red and blue colors, in the MESP map, indicate the region with higher and lower electron density, respectively. Thus, due to the electrostatic attractive forces between two interacting fragments, the formation of TS2C is more preferable to that of TS2N.
Figure 5. The molecular electrostatic potential (MEP) maps of the transition states TS2C and TS2N.

4. CONCLUSIONS

The B3LYP/6-311++G(d) method was used to study the [2+2] cycloaddition reaction of ketene with methanimine. Two modes of attack between reactants were studied, yielding Azetidin-2-one and Azetidin-3-one as two possible products passing through two different transition states. This reaction is taking place via a stepwise mechanism. It has been noted that, on comparing the energetic results and thermodynamics parameters, the reaction path leading to the formation of Azetidin-2-one are kinetically and thermodynamically more favorable than Azetidin-3-one. The analysis of the frontier molecular HOMO and LUMO orbitals indicates that the Azetidin-2-one (P1) are more stable due to its wider energy gap. The global electronic flux from the ketene R1 to the methanimine R2 is predicted, because of the high electronic chemical potential and strong nucleophilicity of the ketene R1 relative to the methanimine R2. The analysis of MESP maps for transition states indicates that the formation of TS2C is more preferable to that of TS2N. The regioselectivity of this cycloaddition is also proposed by electrophilic and nucleophilic Fukui functions.

REFERENCES

Abbiche, K., Mohammad-Salim, H., Salah, M., Mazoir, N., Zeroual, A., El Alaoui El Abdallaoui, H., . . . Hochlaf, M. 2020. Insights into the mechanism and regiochemistry of the 1,3-dipolar cycloaddition reaction between benzaldehyde and diazomethane. *Theoretical Chemistry Accounts*, 139(9), 148. doi: https://doi.org/10.1007/s00214-020-02662-4

Acharjee, N., Mohammad-Salim, H. A., Chakraborty, M., Rao, M. P., & Ganesh, M. 2021. Unveiling the high regioselectivity and stereoselectivity within the synthesis of spirooxindolenitropyrrolidine: A molecular electron density theory perspective. *Journal of Physical Organic Chemistry*, n/a(n/a), e4189. doi: https://doi.org/10.1002/poc.4189

Barber, J. S., Yamano, M. M., Ramirez, M., Darzi, E. R., Knapp, R. R., Liu, F., . . . Garg, N. K. 2018. Diels–Alder cycloadditions of strained azacyclic allenes. *Nature chemistry*, 10(9), 953.

Ditchfield, R., Hehre, W. J., & Pople, J. A. (1971). Self-Consistent Molecular-Orbital Methods. IX. An Extended Gaussian-Type Basis for Molecular-Orbital Studies of Organic Molecules. *Molecules*, 54(2), 724-728. doi:10.1063/1.1674902

Domingo, L. R. 2016. Molecular electron density theory: a modern view of reactivity in organic chemistry. *Molecules*, 21(10), 1319.

Domingo, L. R., Acharjee, N., & Mohammad-Salim, H. A. 2020. Understanding the Reactivity of Trimethylsilyldiazoolkanes Participating in [3+2] Cycloaddition Reactions towards Diethylfumarate with a Molecular Electron Density Theory Perspective. *Organics*, 1(1), 3-18.
Domingo, L. R., Aurell, M. J., Pérez, P., & Contreras, R. 2002. Quantitative characterization of the global electrophilicity power of common diene/dienophile pairs in Diels–Alder reactions. *Tetrahedron*, 58(22), 4417-4423. doi:https://doi.org/10.1016/S0040-4020(02)00410-6

Domingo, L. R., Pérez, P., & Sáez, J. A. 2013. Understanding the local reactivity in polar organic reactions through electrophilic and nucleophilic Parr functions. *RSC Advances*, 3(5), 1486-1494. doi:10.1039/C2RA22886F

Domingo, L. R., Ríos-Gutiérrez, M., & Pérez, P. 2018. A Molecular Electron Density Theory Study of the Reactivity and Selectivities in [3 + 2] Cycloaddition Reactions of C,N-Dialkyl Nitrones with Ethylene Derivatives. *The Journal of Organic Chemistry*, 83(4), 2182-2197. doi:10.1021/acs.joc.7b03093

Espinosa Ferao, A., & Streubel, R. 2020. 1, 2-Thiophosphoranes: The Quest for Wittig-Type Ring Cleavage, Rearrangement, and Sulfur Atom Transfer. *Inorganic Chemistry*, 59(5), 3110-3117.

Flores, D. M., & Schmidt, V. A. 2019. Intermolecular 2 + 2 Carbonyl–Olefincycloadditions Enabled by Cu(I)–Norbormene MLCT. *Journal of the American Chemical Society*, 141(22), 8741-8745. doi:10.1021/jacs.9b03775

Frisch, M. J., Trucks, G. W., Schlegel, H. B., Scuseria, G. E., Robb, M. A., Cheeseman, J. R., . . . Fox, D. J. 2009. Gaussian 09 B.01. Wallingford, CT.

Fuentes de Arriba, Á. L., Lenci, E., Sonawane, M., Formery, O., & Dixon, D. J. 2017. Iridium-Catalyzed Reductive Strecer Reaction for Late-Stage Amide and Lactam Cyanation. *Angewandte Chemie International Edition*, 56(13), 3655-3659. doi:10.1002/anie.201612367

Fukui, K. 1970. Formulation of the reaction coordinate. *The Journal of Physical Chemistry*, 74(23), 4161-4163. doi:10.1021/j100717a029

Glasnov, T. 2018. Photochemical Synthesis of Heterocycles: Merging Flow Processing and Metal-Catalyzed Visible Light Photoredox Transformations. In *Flow Chemistry for the Synthesis of Heterocycles* (pp. 103-132): Springer.

Gonzalez, C., & Schlegel, H. B. 1991. Improved algorithms for reaction path following: higher-order implicit algorithms. *The Journal of chemical physics*, 95(8), 5853-5860.

King, T. A., Stewart, H. L., Mortensen, K. T., North, A. J. P., Sore, H. F., & Spring, D. R. 2019. Cycloaddition Strategies for the Synthesis of Diverse Heterocyclic Spirocycles for Fragment-Based Drug Discovery. *European Journal of Organic Chemistry*, 2019(31-32), 5219-5229. doi:10.1002/ejoc.201900847

Krylov, A., Windus, T. L., Barnes, T., Marin-Rimoldi, E., Nash, J. A., Pritchard, B., . . . Head-Gordon, T. 2018. Perspective: Computational chemistry software and its advancement as illustrated through three grand challenge cases for molecular science.

The *Journal of Chemical Physics*, 149(18), 180901. doi:10.1063/1.5052551

Kyri, A., Gleim, F., Alcaraz, A. G., Schnakenburg, G., Ferao, A. E., & Streubel, R. 2018. “Low-coordinate” 1, 2-oxaphosphoranes—a new opportunity in coordination and main group chemistry. *Chemical Communications*, 54(52), 7123-7126.

Kyri, A. W., Gleim, F., Becker, D., Schnakenburg, G., Ferao, A. E., & Streubel, R. 2019. Synthesis of free and ligated 1, 2-thiaphosphoranes–expanding the pool of strained P-ligands. *Chemical Communications*, 55(11), 1615-1618.

Lee, C., Yang, W., & Parr, R. G. 1988. Development of the Colle-Salvetti correlation-energy formula into a functional of the electron density. *Physical Review B*, 37(2), 785-789. doi:10.1103/PhysRevB.37.785

Mathew, S., Yella, A., Gao, P., Humphry-Baker, R., Curchod, B. F., Ashari-Astani, N., . . . Grätzel, M. 2014. Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers. *Nature chemistry*, 6(3), 242.

Mohammad-Salim, H., Hassan, R., Abdallah, H. H., & Oftadeh, M. 2020. The Theoretical Study on the Mechanism of [3+ 2] Cycloaddition Reactions between α, β-unsaturated Selenolatedehyde with Nitrile and with Nitrile Oxide. *Journal of the Mexican Chemical Society*, 64(2).

Mohammad-Salim, H. A. 2021. Understanding the Reactivity of C-Cyclopropyl-N-MethylNitrone Participating in [3+ 2] Cycloaddition Reactions Towards Styrene with a Molecular Electron Density Theory Perspective. *Journal of the Mexican Chemical Society*, 65(1).

Mohammad-Salim, H. A., & Abdallah, H. H. 2019a. Theoretical Study for the [2+ 2] Cycloaddition Reaction Mechanism of Ketenes and their Derivatives. *Oriental Journal of Chemistry*, 35(5), 1550-1556.

Mohammad-Salim, H. A., & Abdallah, H. H. 2019b. Theoretical Study of the [4+ 2] Cycloaddition Reaction of Trifluoroethylene with Five-membered Chalcogens Heterocyclic Compounds. *AOR–THE SCIENTIFIC JOURNAL OF KOYA UNIVERSITY*, 7(2), 69-77.

Mohammad-Salim, H. A., Abdallah, H. H., Maiyelvaganan, K. R., Prakash, M., & Hochlaf, M. 2020. Mechanistic study of the [2+2] cycloaddition reaction of cyclohexenone and its derivatives with vinyl acetate. *Theoretical Chemistry Accounts*, 139(2), 19. doi:10.1007/s00214-019-2542-y

Mohammad-Salim, H. A., Acharjee, N., & Abdallah, H. H. 2021. Insights into the mechanism and regioselectivity of the [3 + 2] cycloaddition reactions of cyclic nitrone to nitrile functions with a molecular electron density theory perspective. *Theoretical Chemistry Accounts*, 140(1), 1. doi:10.1007/s00214-020-02703-y

Mohammad-Salim, H. A., Acharjee, N., Domingo, L. R., & Abdallah, H. H. 2020. A molecular electron density theory study for [3 + 2] cycloaddition reactions of

ZANCO Journal of Pure and Applied Sciences 2021
Mohammad-Salim, H. A., Basheer, H. A., Abdallah, H. H., Zeroual, A., & Jamil, L. A. 2021. A molecular electron density theory study for [3+2] cycloaddition reactions of N-benzylcyclohexyl nitrotrone with methyl-3-butenolate. New Journal of Chemistry, 45(1), 262-267. doi:10.1039/D0NJ04049E

Parr, R. G., & Weitao, Y. 1989. Density-Functional Theory of Atoms and Molecules: Oxford University Press.

Parr, R. G., & Weitao, Y. 1994. Density-Functional Theory of Atoms and Molecules: Oxford University Press.

Pawlowski, R., Stanek, F., & Stodulski, M. 2019. Recent Advances on Metal-Free, Visible-Light-Induced Catalysis for Assembling Nitrogen- and Oxygen-Based Heterocyclic Scaffolds. Molecules, 24(8). doi:10.3390/molecules24081533

Rios-Gutiérrez, M., & Domingo, L. R. 2019. Unravelling the Mysteries of the [3+2] Cycloaddition Reactions. European Journal of Organic Chemistry, 2019(2-3), 267-282. doi:10.1002/ejoc.201800916

Saha, R., Chatterjee, A., Mondal, S., Pal, P., Chakrabarty, K., & Das, G. K. 2019. Comparative DFT study on the platinum catalyzed [3+2] and [2+2] cycloaddition reactions between the derivatives of allene and alkene. Computational and Theoretical Chemistry, 1163, 112507.

Salim, H. A. M., Abdallah, H. H., & Ramasami, P. 2018. Stereoselectivity and Regioselectivity of the Cycloaddition Dimerization of allyl 3-(2-pyridyl) acrylate and allyl 3-(2-pyrryl) acrylate: DFT Calculations. Paper presented at the IOP Conference Series: Materials Science and Engineering.

Salim, H. M., Abdallah, H. H., & Ramasami, P. 2018. Mechanism and Thermodynamic Parameters of Patañó-Büchi Reaction of Benzene and Furan: DFT Study. Paper presented at the 2018 International Conference on Advanced Science and Engineering (ICOASE).

Sowmya, D. V., Lakshmi Teja, G., Padmaja, A., Kamala Prasad, V., & Padmavathi, V. 2018. Green approach for the synthesis of thiophenyl pyrazoles and isoxazoles by adopting 1,3-dipolar cycladdition methodology and their antimicrobial activity. European Journal of Medicinal Chemistry, 143, 891-898. doi:https://doi.org/10.1016/j.ejmech.2017.11.093

1-pyrrrole-1-oxide with dissubstituted acetylenes leading to bicyclic 4-isoxazolines. International Journal of Quantum Chemistry, n/a(n/a), e26503. doi:https://doi.org/10.1002/qua.26503

Mohammad-Salim, H. A., Basheer, H. A., Abdallah, H. H., Zeroual, A., & Jamil, L. A. 2021. A molecular electron density theory study for [3+2] cycloaddition reactions of N-benzylcyclohexyl nitrotrone with methyl-3-butenolate. New Journal of Chemistry, 45(1), 262-267. doi:10.1039/D0NJ04049E

Parr, R. G., & Pearson, R. G. 1983. Absolute hardness: companion parameter to absolute electronegativity. Journal of the American Chemical Society, 105(26), 7512-7516. doi:10.1021/ja00364a005

Parr, R. G., & Weitao, Y. 1989. Density-Functional Theory of Atoms and Molecules: Oxford University Press.

Parr, R. G., & Weitao, Y. 1994. Density-Functional Theory of Atoms and Molecules: Oxford University Press.

Pawlowski, R., Stanek, F., & Stodulski, M. 2019. Recent Advances on Metal-Free, Visible-Light-Induced Catalysis for Assembling Nitrogen- and Oxygen-Based Heterocyclic Scaffolds. Molecules, 24(8). doi:10.3390/molecules24081533

Rios-Gutiérrez, M., & Domingo, L. R. 2019. Unravelling the Mysteries of the [3+2] Cycloaddition Reactions. European Journal of Organic Chemistry, 2019(2-3), 267-282. doi:10.1002/ejoc.201800916

Saha, R., Chatterjee, A., Mondal, S., Pal, P., Chakrabarty, K., & Das, G. K. 2019. Comparative DFT study on the platinum catalyzed [3+2] and [2+2] cycloaddition reactions between the derivatives of allene and alkene. Computational and Theoretical Chemistry, 1163, 112507.

Salim, H. A. M., Abdallah, H. H., & Ramasami, P. 2018. Stereoselectivity and Regioselectivity of the Cycloaddition Dimerization of allyl 3-(2-pyridyl) acrylate and allyl 3-(2-pyrryl) acrylate: DFT Calculations. Paper presented at the IOP Conference Series: Materials Science and Engineering.

Salim, H. M., Abdallah, H. H., & Ramasami, P. 2018. Mechanism and Thermodynamic Parameters of Patañó-Büchi Reaction of Benzene and Furan: DFT Study. Paper presented at the 2018 International Conference on Advanced Science and Engineering (ICOASE).

Sowmya, D. V., Lakshmi Teja, G., Padmaja, A., Kamala Prasad, V., & Padmavathi, V. 2018. Green approach for the synthesis of thiophenyl pyrazoles and isoxazoles by adopting 1,3-dipolar cycladdition methodology and their antimicrobial activity. European Journal of Medicinal Chemistry, 143, 891-898. doi:https://doi.org/10.1016/j.ejmech.2017.11.093

Svatunek, D., Pemberton, R. P., Mackey, J. L., Liu, P., & Houk, K. 2020. Concerted [4+2] and Stepwise (2+2) Cycloadditions of Tetrafluoroethylene with Butadiene: DFT and DLPNO-UCSSD (T) Explorations. The Journal of Organic Chemistry, 85(5), 3858-3864.

Tokunova, É. F., Tyurina, L. A., Nikitin, N. A., Nikitina, I. L., Klen, E. É., Khaliullin, F. A., ... Kantor, E. A. 2001. Quantitative Structure - Activity Relationships for Microsomal Enzymatic System Modulants. Part I: Inhibitors. Pharmaceutical Chemistry Journal, 35(6), 322-327. doi:10.1023/A:1012345705162

Willebring, D., & Tantillo, D. J. 2008. Mechanistic possibilities for oxetane formation in the biosynthesis of Taxol’s D ring. Russian Journal of General Chemistry, 78(4), 723-731. doi:10.1134/S1070363208040336

Xu, C., Zhang, L., & Luo, S. 2014. Merging Aerobic Oxidation and Enamine Catalysis in the Asymmetric α-Amination of β-Ketocarboxyls Using N-Hydroxy carbamates as Nitrogen Sources. Angewandte Chemie International Edition, 53(16), 4149-4153. doi:10.1002/anie.201400776