

¹ Graphical Abstract

² **Computational study of the glycolytic degradation of poly(ethylene tereph-**
³ **thalate catalyzed by N^1,N^2 -bis(2-aminobenzyl)-1,2-diaminoethane zinc(II)**

⁴ Pablo E. Alanis González, Isabel del Carmen Saenz Tavera, Victor Manuel Rosas
⁵ García

6 Highlights

7 **Computational study of the glycolytic degradation of poly(ethylene tereph-**
8 **thalate catalyzed by N^1,N^2 -bis(2-aminobenzyl)-1,2-diaminoethane zinc(II)**

9 Pablo E. Alanis González, Isabel del Carmen Saenz Tavera, Victor Manuel Rosas
10 García

11 • Research highlight 1

12 • Research highlight 2

13 Computational study of the glycolytic degradation of
14 poly(ethylene terephthalate catalyzed by
15 N^1,N^2 -bis(2-aminobenzyl)-1,2-diaminoethane zinc(II)

16 Pablo E. Alanis González^{a,*}, Isabel del Carmen Saenz Tavera^a, Victor Manuel
17 Rosas García^a

^a*Facultad de Ciencias Químicas, Universidad Autónoma de Nuevo León, Av. Universidad s/n,
Cd. Universitaria, San Nicolás de los Garza, 66455, Nuevo León, México*

18 **Abstract**

A possible reaction mechanism of the glycolytic degradation of poly(ethylene terephthalate) (PET) catalyzed with N^1,N^2 -bis(2-aminobenzyl)-1,2-diaminoethane zinc(II) (ABEN) was determined using KS-DFT using the meta-NGA global-hybrid functional, MN15 [1] up to def2-SVP/def2-TZVP level of theory making use of an energy-weighted climbing image nudged elastic band (EW-CI-NEB) algorithm [2] to determine the minimum energy path (MEP) and then optimizing the converged climbing image (CI) using eigenvector-following partitioned rational function optimization (EF P-RFO) to obtain the transition state (TS). The non-covalent interactions were obtained using an averaged independent gradient model (aIGM) algorithm [3]

19 *Keywords:*

20 KS-DFT, Polymer degradation, Catalysis

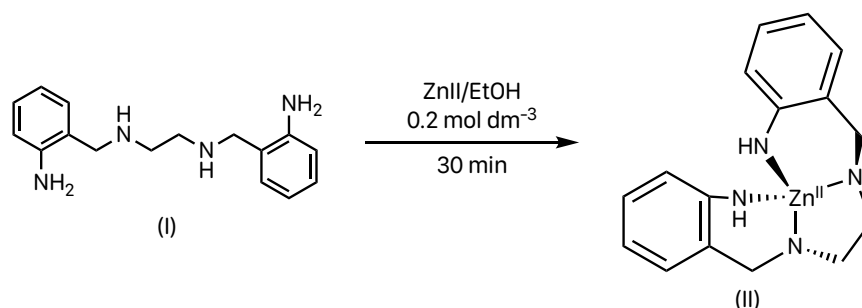
21 *PACS:* 82.20.Pm, 82.35.-x, 82.65.Jn

*Corresponding author

Email address: pabloalanis1998@gmail.com (Pablo E. Alanis González)

1. Introduction

By 2015, the annual global production of plastics surpassed 367 million tonnes; 55 % of all plastic waste was discarded, 25.5 % incinerated and just 19.5 % was recycled [4]. Poly(ethylene terephthalate) (PET) is one of the most widely traded polymer there is on the market. It's mainly used in the fabrication of bottles, packages and fibers. The widespread usage of this plastic is due to its properties, like an excellent tensile strength, chemical resistance, clarity, processability and a reasonable thermal stability, It is also very cheap to produce [5, 6]. Albeit all its properties, PET is also becoming a global problem, since a lot of it is not recycled at all. It is becoming a waste problem. Even though PET by itself is not harmful to humans and by itself does not impose an environmental damage, because of its substantial presence in bodies of water and its high resistance to biological and atmospheric agents, PET is classified as a nocive material [7] Chemical recycling of PET has become an important topic since this is the most sustainable way of recycling plastic, and produces *de novo* the starting materials of the synthesis of PET. There is an extensive amount of literature on the topic of chemical degradation of PET, processes such as methanolysis, hydrolysis and glycolysis have been thoroughly studied [8–10]. The most sustainable reaction of degradation of PET is the glycolysis since this reaction produces Bis(2-hydroxyethyl) terephthalate (BHET), one of the precursors of PET itself. PET glycolysis, nevertheless is not a very effective process if no catalyst is used. Plenty of studies have been made on the reaction of the degradation of PET via catalyzed glycolysis. Some transition metals such as zinc lead to a good yield in this type of reactions with the benefit that zinc is not a very toxic metal. For the chemical recycling of PET, numerous protocols involving hydrolysis, methanolysis and glycolysis among many others [8–10]



Scheme 1: Reported synthesis of ABEN [13].

have been reported. The uncatalyzed glycolysis of PET is not an effective process; transition metal (TM) salts have been determined to aid in this reaction. The oldest report of the catalyzed glycolytic degradation of PET was reported by Vaidya and Nadkarni [11] in which they carried the reaction using different metal acetates as catalysts. Then it was determined that Zn^{II} has a great in comparison to other TM (Mn^{II}, Co^{II} and Pb^{II}) activity as a catalyst in the glycolysis of PET [12]. Alongside the numerous zinc catalysts studied to date, a novel zinc catalyst, *N*¹,*N*²-bis(2-aminobenzyl)-1,2-diaminoethane zinc(II) (ABEN) [13] has shown to have a great catalytic activity in the glycolytic degradation of PET yielding around 78 % of BHET[14]. The main purpose of this article is to evaluate the possible reaction mechanism involved in this catalyzed glycolytic depolymerization of PET with ABEN and determine the covalent or non-covalent interactions involved.[15, 16]

2. Experimental

The starting configurations for EG and ABEN where proposed and optimized using XTB [?] with the force field GFN2-xTB [?]. The starting configuration for DBHET was proposed using crystallographic data [?], then reoptimized us-

ing r^2 SCAN-3cdef2/SVP. The final point energies were obtained all obtained using ω -B97X-D4/def2-SVP and def2-TZVPP on just the oxygen, nitrogen, and zinc atoms. The optimized structures were then merged onto the same Cartesian coordinates and then re-optimized in r^2 SCAN-3cdef2/SVP. Then, a multidimensional relaxed surface scan was performed keeping constrained, and varying the bond distances in 20 steps to obtain the products of the reactions depicted in . The optimized product and the starting geometry of the relaxed surface scan were the input for an Energy-Weighted Climbing image Nudged Elastic Band (EW-CI-NEB) [2] algorithm to find the path of minimum energy connecting both ends, followed by a P-RFO optimization to find a TS performed onto the climbing image (CI).

In order to determine covalent and non-covalent interactions regions between the molecules, an analysis based on Hirshfeld partition of molecular density (IGMH) algorithm within multiwfn was performed [?] onto the optimized reactant. To minimize computation time, aIGM was performed with the MEP obtained by NEB-TS.

With JANPA [?], CLPOs and bond orders for the reactants, products and transition states were obtained.

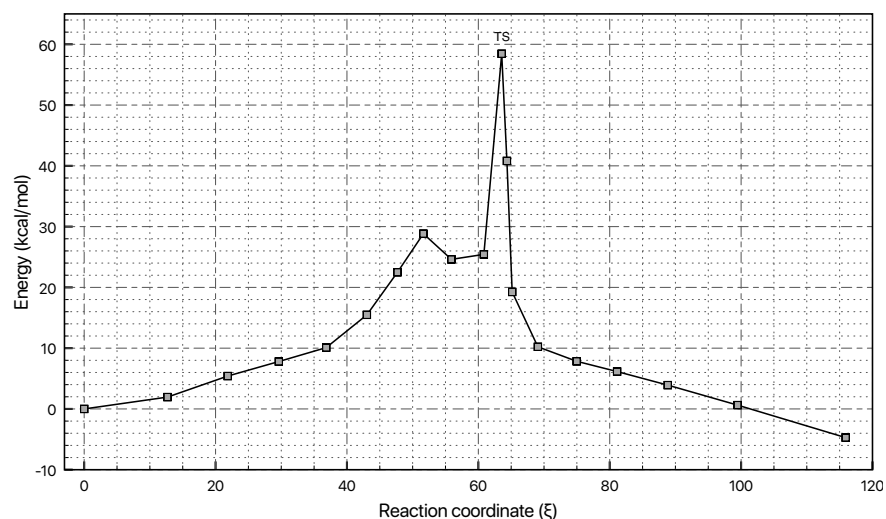


Figure 1: Minimum energy path obtained by NEB-TS on the uncatalyzed system.

3. Results

4. Discussion

5. Conclusion

References

- [1] H. S. Yu, X. He, S. L. Li, D. G. Truhlar, MN15: A Kohn–Sham global-hybrid exchange–correlation density functional with broad accuracy for multi-reference and single-reference systems and noncovalent interactions, Chem. Sci. 7 (2016) 5032–5051. doi:10/gj6rqn.
- [2] V. Ásgeirsson, B. O. Birgisson, R. Bjornsson, U. Becker, F. Neese, C. Riplinger, H. Jónsson, Nudged elastic band method for molecular reactions using energy-weighted springs combined with eigenvector following, J. Chem. Theory Comput. 17 (2021) 4929–4945. doi:10/gnm7x.

- 93 [3] C. Lefebvre, H. Khartabil, J.-C. Boisson, J. Contreras-García, J.-P. Piquemal,
94 E. Hénon, The Independent Gradient Model: A New Approach for Probing
95 Strong and Weak Interactions in Molecules from Wave Function Calcula-
96 tions, *ChemPhysChem* 19 (2018) 724–735. doi:10/gpng7f.
- 97 [4] R. Geyer, J. R. Jambeck, K. L. Law, Production, use, and fate of all plastics
98 ever made, *Sci. Adv.* 3 (2017) e1700782. doi:10/b9sp.
- 99 [5] R. J. Caldicott, The basics of stretch blow molding PET containers, *Plast.*
100 *Eng.* 55 (1999) 35–39.
- 101 [6] R. C. Thompson, S. H. Swan, C. J. Moore, F. S. vom Saal, Our plastic age,
102 *Philosophical Transactions of the Royal Society B: Biological Sciences* 364
103 (2009) 1973–1976. doi:10/dqvcxx.
- 104 [7] D. Paszun, T. Spychaj, Chemical recycling of poly(ethylene terephthalate),
105 *Ind. Eng. Chem. Res.* 36 (1997) 1373–1383. doi:10/b2t5nm.
- 106 [8] J. R. Campanelli, M. R. Kamal, D. G. Cooper, A kinetic study of the hy-
107 drolytic degradation of polyethylene terephthalate at high temperatures, *J.*
108 *Appl. Polym. Sci.* 48 (1993) 443–451. doi:10/ch9q4p.
- 109 [9] J. R. Campanelli, M. R. Kamal, D. G. Cooper, Kinetics of glycolysis of
110 poly(ethylene terephthalate) melts, *J. Appl. Polym. Sci.* 54 (1994) 1731–
111 1740. doi:10/bhq8n4.
- 112 [10] J. R. Campanelli, D. G. Cooper, M. R. Kamal, Catalyzed hydrolysis of
113 polyethylene terephthalate melts, *J. Appl. Polym. Sci.* 53 (1994) 985–991.
114 doi:10/fcgbkg.

- 115 [11] U. R. Vaidya, V. M. Nadkarni, Polyester polyols for polyurethanes from pet
116 waste: Kinetics of polycondensation, *J. Appl. Polym. Sci.* 35 (1988) 775–
117 785. doi:10/fkszjj.
- 118 [12] M. Ghaemy, K. Mossaddegh, Depolymerisation of poly(ethylene tereph-
119 thalate) fibre wastes using ethylene glycol, *Polym. Degrad. Stab.* 90 (2005)
120 570–576. doi:10/fhmv7.
- 121 [13] P. Elizondo-Martínez, B. Nájera-Martínez, N. Pérez-Rodríguez, L. Hinojosa-
122 Reyes, I. Gómez Del Río, Polyaza macroligands as potential agents for heavy
123 metal removal from wastewater, *J. Serb. Chem. Soc.* 78 (2013) 591–602.
124 doi:10/gjqg6j.
- 125 [14] A. Ovalle-Sánchez, P. Elizondo-Martínez, N. Pérez-Rodríguez,
126 E. Hernández-Fernández, M. G. Sánchez-Anguiano, Degradation of
127 poly(ethyleneterephthalate) waste to obtain oligomers using a zinc complex
128 as catalyst, *J. Chil. Chem. Soc.* 62 (2017) 3741–3745. doi:10/gjqg6r.
- 129 [15] M. Y. Abdelaal, T. R. Sobahi, M. S. I. Makki, Chemical degradation of
130 poly(ethylene terephthalate), *International Journal of Polymeric Materials*
131 57 (2008) 73–80. doi:10/b55x8v.
- 132 [16] M. M. A. Nikje, F. Nazari, Microwave-assisted depolymerization of
133 poly(ethylene terephthalate) [PET] at atmospheric pressure, *Adv. Polym.*
134 *Tech.* 25 (2006) 242–246. doi:10/c62nvj.