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Double stimulus-responsive palladium catalysts for ethylene polymerization and copolymerization

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ABSTRACT

The external stimulus response strategy has been evolved rapidly in the field of olefin polymerization. In this work, we modularly synthesized three types of double stimulus responsive α-diimine palladium catalysts, combining redox regulation and other regulation together, such as light, Lewis acid and alkali cations. The catalytic activities and the molecular weight of polyethylene products can be regulated for 4 times in ethylene polymerization. These palladium complexes were also used for the copolymerization reaction of ethylene and polar monomers, such as methyl 10-undecylenate and methyl acrylate, effectively regulating the catalytic activities, the molecular weight and polar monomer incorporation of the prepared copolymers. The research on these dual-regulated palladium complexes makes full use of prepared catalysts and provides new inspirations for regulating olefin polymerization.

In recent years, the designs and synthesis of various transition metal catalysts have promoted the development of the olefin polymerization field [1–6], including the discoveries of new ligands and the improvements of literature-reported structures [7–9]. Recently, the emerging field of tuneable catalysis for olefin polymerization has attracted widespread attention in the academic community, the chemical reactivity of which can be selectively transformed between several different states via simple external stimulus [10–14]. The external stimulus often creates “on/off” behaviour or modulating the electronic and steric effects, affecting the polymerization process along with the properties of polymer products significantly [15–18].

There are some appealing external stimuluses employed to regulate transition metal catalyse olefin polymerization process, including photochemistry [19–21], acid/base [22–24], redox [25–30], supramolecular modulation [31,32], *etc*. For example, Chen *et al.* introduced the ferrocene units into the α-diimine palladium catalyst and utilized the stepwise redox of ferrocene units to modulate the catalyst properties during the polymerization and copolymerization of olefins (Scheme 1, **I**) [33]. Long and co-workers also applied the reductant (or photo reductant) to α-diimine nickel catalyst with acenaphthene backbone, successfully adjusting the microstructure of polyethylene (Scheme 1, **II**) [34,35]. In addition to redox-controlled olefin polymerization, Chen *et al.* also used external light stimulation to regulate the *trans-cis* isomeric behaviour of azobenzene unit to change the steric hindrance/electronic effect of the α-diimine catalyst, thereby regulating the activity of the catalyst and the topology of polyethylene products (Scheme 1, **III**) [36]. Further, the extra addition of Lewis acid/base can regulate the electron cloud density of the catalyst metal centre to control olefin polymerization. For example, Jordan *et al.* added Lewis acid ($B(C_6F_5)_3$) to the (phosphine-sulfonate) PdMe catalysts to enhance the chain growth and chain transfer rate of the catalyst in ethylene polymerization (Scheme 1, **IV**) [37]. And Do *et al.* investigated the positive role of secondary metal ions on metal-catalysed polymerization processes, which was conducive to increase in catalytic efficiency as well as enhancement in polymer molecular weight (Scheme 1, **V**) [38–40].

These fascinating stimulus-responsive categories have been applied to synthesize switchable catalysts using for olefin polymerization. However, there are few studies focused on the synergistic effect of two different external stimulus strategies utilized in one catalyst structure. Brookhart-type α-diimine palladium and nickel complexes was a pioneer in producing polyethylene [41,42]. Structurally, the symmetrical structure of α-diimine ligand is conducive to introducing two different functional groups. For instance, Chen's group designed α-diimine palladium systems with both azobenzene unit and urea functional group to realize the light-mediated self-assembly process of the catalysts, adjusting the polymerization

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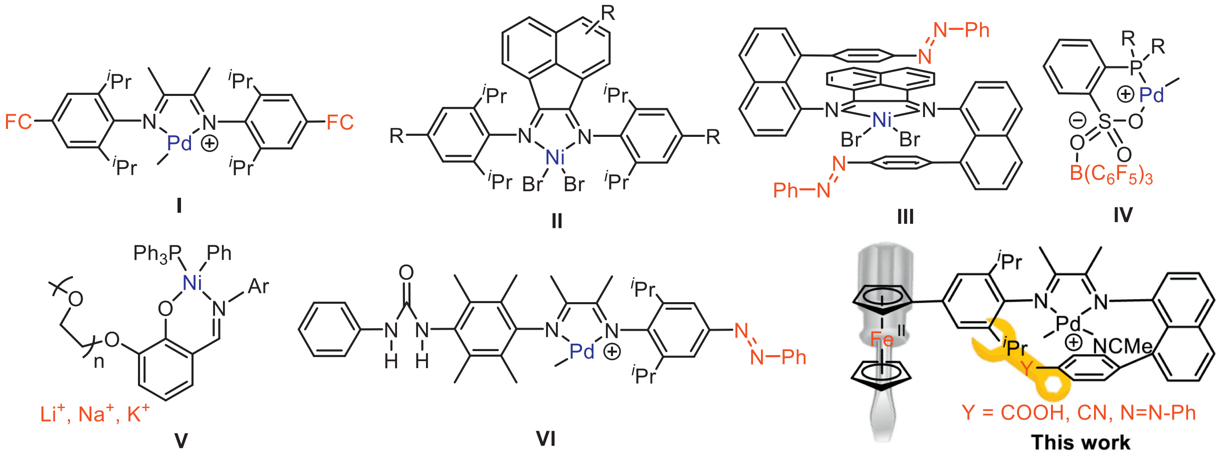

Scheme 1. A series of reported stimulus responsive transition metal catalysts for olefin polymerization.

activity and molecular weight distribution of polyethylene products (Scheme 1, **VI**) [31]. Inspired by these reports, we further developed dual-regulated α-diimine palladium systems. In this contribution, we introduced two units with different stimulus responses into one catalyst system to explore the synergy between different regulatory methods. And these different stimulus response units can be combined into the catalyst structure through simple chemical reactions.

2,6-Diisopropyl-4-ferroceneaniline [43] and 8-(4-(phenyldiazenyl)phenyl)naphthalen-1-amine [36] were prepared according to published procedures. 4-(8-Aminonaphthalen-1-yl)benzonitrile and 4-(8-aminonaphthalen-1-yl)benzoic acid were synthesized by Pd-catalyzed coupling reaction. Then three ligands (L1-L3) were prepared by two steps of condensation reactions in high yields (Fig. 1a). The ligands were characterized by ^{1}H NMR, ^{13}C NMR analyses and HRMS. The corresponding palladium complexes (Pd1-Cl, Pd2-Cl and Pd3-Cl) were obtained in 78%–85% yields from the reaction of the corresponding ligands with one equivalent of (COD)PdMeCl (COD = 1,5-cyclooctadiene) respectively. The palladium complexes were characterized by ^{1}H NMR, ^{13}C NMR and MALDI-TOF-MS and X-ray diffraction. In order to elevate the operability of polymerization processes, single-component cationic palladium species Pd1-Pd3 was generated by reacting corresponding Pd-Cl with one equivalent of sodium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate (NaBAF) in the presence of MeCN. The addition of 1 equiv. of AgBAF to Pd1-Pd3 led to the formation of Pd1$^+$-Pd3$^+$, which could be isolated and used in ethylene (co)polymerization subsequently. The changes in the redox potential of these palladium complexes before and after oxidation by AgBAF indicate changes in the oxidation valence state (Table S1 and Fig. S1 in Supporting information).

The single crystal of Pd1-Cl, Pd2-Cl and Pd3-Cl were shown in Figs. 1b-d. These palladium centers adopted spare-planar geometries, which are typical of reported α-diimine palladium complexes [44,45]. The most important structural feature of these complexes is that stimulus-responsive units Y lie on the axial position of the palladium centers. As such, light or additives (B(C$_6$F$_5$)$_3$ and alkali cations) may directly influence the chemical environment of metal center, thereby influence its properties during ethylene polymerization.

The complex Pd1 with ferrocene and azobenzene units showed moderate polymerization activity under dark condition at 20 °C (2.6 × 10^4 g mol^{-1} h^{-1}), offering polyethylene products with high branching density (96/1000C) and molecular weight (43.3 × 10^3 g/mol, Table 1, entry 1). When being stimulated by light (UV, 365 nm), the catalytic activity decreased slightly, while the molecular weight of the produced polyethylene increased to 52.3 × 10^3 g/mol (Table 1, entry 2). When being oxidized by AgBAF, the catalytic performance (activity and molecular weight) of Pd1$^+$ obviously decreased (Table 1, entry 3). However, on the basis of the oxidized catalyst Pd1$^+$, the introduction of UV light stimulation increased the molecular weight of the polymer (Table 1, entry 4). Above all, the complexes Pd1 showed adjustable catalytic performance in ethylene polymerization (Fig. 2a). Further research, the UV–vis absorption spectra (Fig. S2 in Supporting information) indicated fast and reversible *trans-cis* isomerization of Pd1 and Pd1$^+$ when exposed to ultraviolet light (λ = 365 nm or 420 nm). It was demonstrated that the photoinduced *trans-cis* isomerization of azobenzene unit enhanced the steric hindrance of the Pd center, which may lead to an increase in the molecular weight of polymer [36–46]. Meanwhile, the ^{1}H NMR studies of the palladium complex oxidized by AgBAF demonstrated the redox process (Fig. S3 in Supporting information).

In this work, B(C$_6$F$_5$)$_3$ was chosen to investigate the effect of Lewis acid in ethylene polymerization. It has been reported that B(C$_6$F$_5$)$_3$ can coordinate with -CN units and cause positive changes of catalysts [22-24,47]. Furthermore, significant chemical shift of Me-Pd was observed in the ^{1}H NMR spectra of palladium complex after adding B(C$_6$F$_5$)$_3$ (Fig. S4 in Supporting information). ^{19}F NMR (Figs. S5 and S6 in Supporting information) spectra also provided evidence for the coordination between B(C$_6$F$_5$)$_3$ and -CN units. Complexes Pd2-Cl and Pd2-Cl with B(C$_6$F$_5$)$_3$ were analyzed by infrared spectroscopy, indicating desired interaction was formed (Fig. S7 in Supporting information). The catalyst Pd2 showed similar activities with Pd1, and the addition of B(C$_6$F$_5$)$_3$ showed a positive effect on the molecular weight of polyethylene products (increasing to 35.0 × 10^3 g/mol), while the activities of polymerization slightly decreased (Table 1, entries 5 and 6). This may be due to the increased steric hindrance of palladium center after coordination with B(C$_6$F$_5$)$_3$. However, for the catalyst Pd2$^+$, there was no visible change in catalytic performance after the addition of B(C$_6$F$_5$)$_3$ (Table 1, entries 7 and 8).

It has been proved that the functional group of carboxylic acid can combine with different metal ions [48]. Herein, the catalyst Pd3-Na$^+$/Pd3-K$^+$ was generated from the reaction of Pd3 with 1.2 equiv. of NaH/HK in the presence of CH$_2$Cl$_2$ to synthesize the α-diimine palladium catalyst with both ferrocene unit and carboxylate functional group. The complexes Pd3 also showed tunable catalytic properties in ethylene polymerization (Fig. 2b). Specifically, Pd3 displayed a moderate activity in ethylene polymerization (1 × 10^5 g mol^{-1} h^{-1}, Table 1, entry 9), and the oxidized complex Pd3$^+$ showed a decrease in both activity and molecular weight

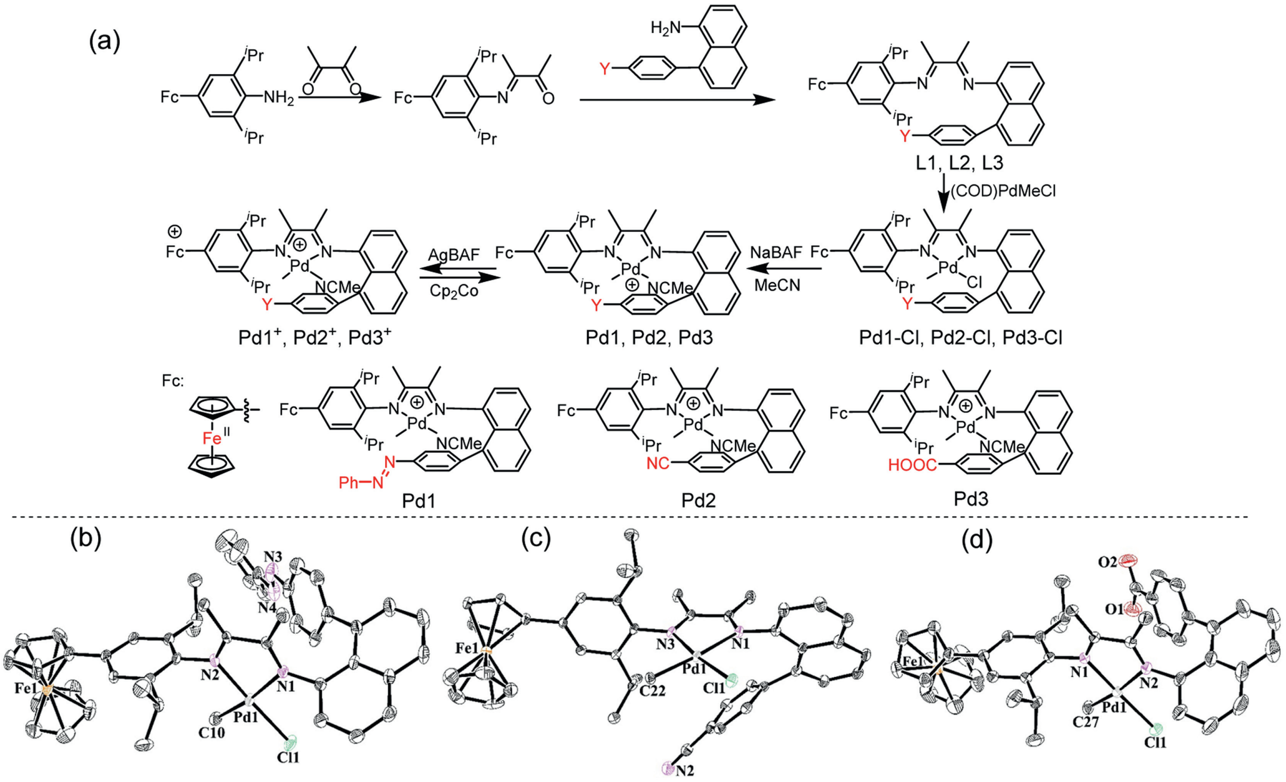

Fig. 1. (a) Synthesis of functionalized ligands and metal complexes. X-ray crystallographic structures of (b) Pd1-Cl (CCDC No. 2244431): Pd1-Cl1 2.2882(14), Pd1-C10 2.028(5), Pd1-N1 2.165(4), Pd1-N2 2.033(4), N1-Pd1-N2 77.14(16), C10-Pd1-Cl1 89.29(16); (c) Pd2-Cl (CCDC No. 2244432): Pd1-C22 2.038(5), Pd1-Cl1 2.2948(12), Pd1-N1 2.148(4), Pd1-N3 2.035(4), N1-Pd1-N3 77.80(14), C22-Pd1-Cl1 90.79(14); (d) Pd3-Cl (CCDC No. 2244433): Pd1-C27 2.018(7), Pd1-C11 2.2924(19), Pd1-N1 2.022(5), Pd1-N2 2.154(6), N1-Pd1-N2 77.20(2), C27-Pd1-Cl1 89.20(2).

Table 1
Ethylene polymerization in different conditions. [a]

Entry	Cat.	Yield (g) [b]	Activity ($\times 10^4$ g mol^{-1} h^{-1}) [b]	B [c]	M_n ($\times 10^3$ g/mol) [d]	PDI [d]	Light or $B(C_6F_5)_3$
1	Pd1	0.52	2.6	96	43.3	1.3	Dark
2	Pd1	0.33	1.7	94	52.3	1.2	UV
3	Pd1$^+$	0.35	1.8	97	16.2	1.6	Dark
4	Pd1$^+$	0.22	1.1	96	26.7	1.3	UV
5	Pd2	0.36	1.8	95	30.7	1.3	–
6	Pd2	0.30	1.5	94	35.0	1.3	2.5 equiv.
7	Pd2$^+$	0.28	1.4	98	6.2	1.4	–
8	Pd2$^+$	0.20	1.0	97	6.7	1.4	2.5 equiv.
9	Pd3	0.19	1.0	92	37.3	1.2	
10	Pd3$^+$	0.13	0.7	96	29.7	1.1	
11	Pd3-Na$^+$	0.27	1.4	91	50.7	1.2	
12	Pd3-K$^+$	0.30	1.5	95	52.9	1.5	
13	Pd3$^+$-Na$^+$	0.21	1.1	95	45.2	1.1	
14	Pd3$^+$-K$^+$	0.30	1.5	95	49.2	1.5	

[a] Polymerization conditions: 10 µmol Pd catalysts, 20 mL CH_2Cl_2, 2 h, 8 atm, 20 °C.
[b] Activity (10^4 g mol^{-1} h^{-1}) was determined from the mass of the polymer product and was the average of at least two runs.
[c] Branches per 1000 carbon atoms, determined by ^{1}H NMR analysis in CD_3Cl.
[d] M_n (10^3 g/mol) and PDI were determined by gel permeation chromatography (GPC) in THF at 40 °C.

(Table 1, entry 10). Unexpected, Pd3-Na$^+$ and Pd3-K$^+$ derived from Pd3 exhibited higher activities (up to 1.5×10^4 g mol^{-1} h^{-1}) and molecular weight (up to 52.9×10^3 g/mol) in ethylene polymerization (Table 1, entries 11 and 12). It was proved by density functional theory (DFT) calculation in the literature that the metal ion complexes to the O atom and forms a cation-π interaction with the electron-deficient aryl ring [49,50], which may improve the rigidity and stability of catalyst. Compared to Pd3$^+$, the polymerization activities and the molecular weight of polyethylene products catalyzed by Pd3$^+$-Na$^+$and Pd3$^+$-K$^+$ also increased (Table 1, entries 13 and 14). Similar phenomena can also be observed in the polymerization process of the above three dual controllable palladium catalysts at other temperatures (Table S2 in Supporting information).

Furthermore, these Pd complexes can also catalyze the copolymerization of ethylene with polar monomers to produce functionalized polyolefin. Firstly, complex Pd1 can catalyze the copolymerization of ethylene and methyl acrylate (MA) in moderate activity (9.3×10^3 g mol^{-1} h^{-1}), generating the copolymer with the high comonomer incorporation (2.1 mol%) and high molecular weight (13.2×10^3 g/mol, Table 2, entry 1). The molecular weight of the copolymer prepared under UV light increased to 16.9×10^3 g/mol, while the comonomer incorporation decreased to 1.1 mol% (Table 2, entry 2). Unfortunately, the copolymerization

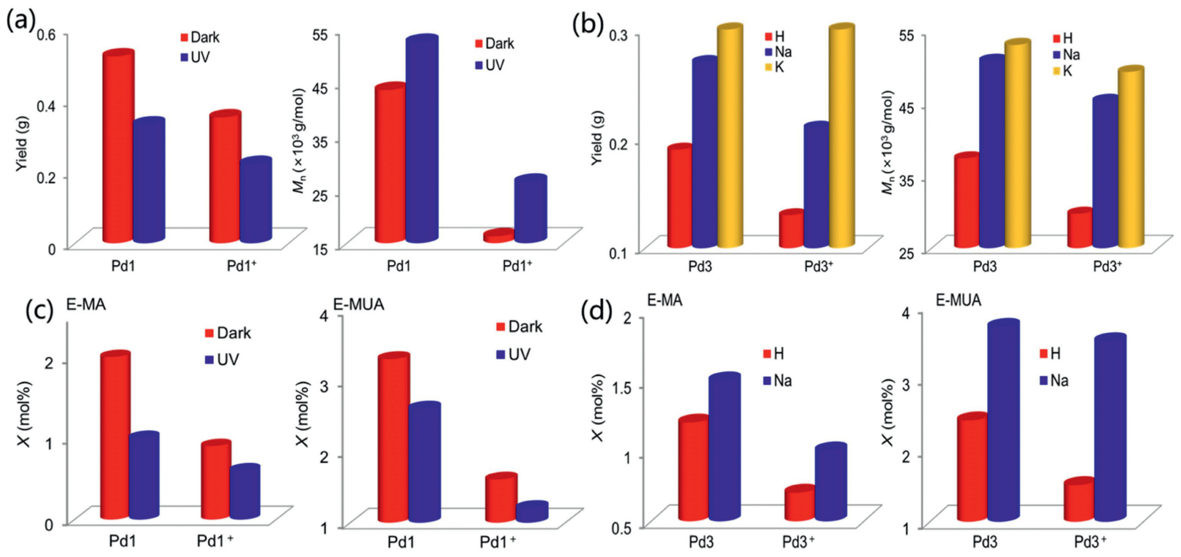

Fig. 2. Performance of Pd1 or $Pd1^+$ in (a) ethylene polymerization and (c) ethylene copolymerization. Performance of Pd3 or $Pd3^+$ in (b) ethylene polymerization and (d) ethylene copolymerization.

Table 2
Ethylene copolymerization with different polar monomers. [a]

Entry	Cat.	Monomers	c (mol/L)	Yield (g) [b]	Activity ($\times 10^3$ g mol^{-1} h^{-1}) [b]	X (mol%) [c]	M_n ($\times 10^3$ g/mol) [d]	PDI [d]	Light or $B(C_6F_5)_3$
1	Pd1	MA	2.5	0.37	9.3	2.1	13.2	1.6	Dark
2	Pd1	MA	2.5	0.25	6.3	1.1	16.9	1.4	UV
3	$Pd1^+$	MA	2.5	0.26	6.5	0.9	3.8	1.2	Dark
4	$Pd1^+$	MA	2.5	0.15	3.8	0.6	6.7	1.4	UV
5	Pd1	MUA	1	0.50	12.5	3.3	24.0	1.1	Dark
6	Pd1	MUA	1	0.32	8.0	2.6	30.6	1.1	UV
7	$Pd1^+$	MUA	1	0.30	7.5	1.6	13.6	1.5	Dark
8	$Pd1^+$	MUA	1	0.18	4.5	1.2	20.9	1.3	UV
9	Pd2	MA	2.5	0.35	8.8	1.1	12.3	1.4	–
10	Pd2	MA	2.5	0.27	6.8	0.9	16.4	1.3	2.5 equiv.
11	$Pd2^+$	MA	2.5	0.25	6.3	0.6	4.6	1.3	–
12	$Pd2^+$	MA	2.5	0.15	3.8	0.5	5.3	1.3	2.5 equiv.
13	Pd2	MUA	1	0.38	9.5	2.7	9.7	1.3	–
14	Pd2	MUA	1	0.18	4.5	2.4	9.9	1.4	2.5 equiv.
15	$Pd2^+$	MUA	1	0.25	6.3	2.4	4.1	1.2	–
16	$Pd2^+$	MUA	1	0.15	3.8	1.8	4.3	1.2	2.5 equiv.
17	Pd3	MA	2.5	0.21	5.3	1.2	13.3	1.4	
18	Pd3-Na^+	MA	2.5	0.36	9.0	1.5	19.7	1.2	
19	$Pd3^+$	MA	2.5	0.17	4.3	0.7	5.7	1.3	
20	$Pd3^+$-Na^+	MA	2.5	0.25	6.3	1.1	24.9	1.2	
21	Pd3	MUA	1	0.12	3.0	2.2	11.3	1.5	
22	Pd3-Na^+	MUA	1	0.19	4.8	3.6	19.0	1.3	
23	$Pd3^+$	MUA	1	0.08	2.0	1.5	6.1	1.4	
24	$Pd3^+$-Na^+	MUA	1	0.13	3.3	3.4	31.9	1.7	

[a] Polymerization conditions: 20 µmol Pd catalysts, total volume of CH_2Cl_2 and polar monomer = 20 mL, 20 °C, 2 h, 8 atm.
[b] Activity ($\times 10^3$ g mol^{-1} h^{-1}) was determined from the mass of the polymer product and was the average of at least two runs.
[c] Branches per 1000 carbon atoms, determined by ^1H NMR analysis in CD_3Cl.
[d] M_n ($\times 10^3$ g/mol) and PDI were determined by gel permeation chromatography (GPC) in THF at 40 °C.

performance (catalytic activity, molecular weight and comonomer incorporation) of the oxidized catalyst $Pd1^+$ deteriorated (Table 2, entries 3 and 4). Bio-renewable methyl 10-undecenoate (MUA) was mildly poisoning due to its long spacer between the functional group and the double bond [51]. Pd1 produced E-MUA copolymer with high comonomer incorporation (3.3 mol%) and high molecular weight (24.0×10^3 g/mol, Table 2, entry 5). With the control of UV light or oxidants, Pd1 regulated the copolymerization of ethylene and MUA similarly to that of ethylene and MA (Table 2, entries 6–8), which were shown in Fig. 2c directly.

Similarly, Pd2 can catalyze the copolymerization of ethylene with the comonomer MA and MUA in moderate activities up to 10.0×10^3 g mol^{-1} h^{-1}. The copolymers with moderate comonomer incorporation (up to 1.1 mol%) and high molecular weight (up to 12.3×10^3 g/mol, Table 2, entries 9 and 13) were produced. Adding $B(C_6F_5)_3$ to Pd2 resulted in decrease in the catalytic activities and comonomer in corporations, while the molecular weight of the copolymer increasing (Table 2, entries 10 and 14). Compared to Pd2, complex $Pd2^+$ led to decrease copolymerization performance (Table 2, entries 11 and 15). The addition of $B(C_6F_5)_3$ to the oxidized $Pd2^+$ hindered the trend of performance decline (Table 2, entries 12 and 16).

For Pd3, copolymerization of ethylene and polar monomers (MA or MUA) can also be regulated (Fig. 2d). The Pd3-Na^+obtained by adding alkali cations significantly improved the copolymerization performance of ethylene and polar monomers (MA or MUA, Table 2, entries 18 and 22), increasing copolymerization activity (up to 9.0×10^3 g mol^{-1} h^{-1}) and polar monomer incorporation

(3.6 mol%) as well as copolymer molecular weight (19.7×10^3 g/mol). This may be due to the cation-π interaction between metal ions and the electron-deficient aryl ring. The catalyst $Pd3^+$ was similar to $Pd1^+$ and $Pd2^+$, of which the copolymerization performance was reduced. When introducing sodium ions into catalyst $Pd3^+$, the copolymerization performance of $Pd3^+$-Na^+ was significantly improved (Table 2, entry 24).

In summary, we combined light regulation, Lewis acid regulation, or alkali cations regulation to oxidation regulation to synthesize three double stimulus responsive α-diimine palladium catalysts. These dual-regulated palladium catalysts can affect the ethylene polymerization process, regulating the molecular weight and branching density of polyethylene products. More importantly, these palladium complexes can catalyze the copolymerization of ethylene and polar monomers, such as methyl acrylate and methyl 10-undecenoate, and the comonomer incorporation can be regulated effectively. The research on these dual-regulated palladium complexes makes full use of prepared catalysts and provides new inspirations for regulating olefin polymerization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cclet.2024.109534.

References

[1] A. Nakamura, T.M.J. Anselment, J. Claverie, et al., Acc. Chem. Res. 46 (2013) 1438–1449.
[2] H.L. Mu, G.L. Zhou, X.Q. Hu, Z.B. Jian, Coord. Chem. Rev. 435 (2021) 213802.
[3] C.L. Chen, Nat. Rev. Chem. 2 (2018) 6–14.
[4] S.L.J. Luckham, K. Nozaki, Acc. Chem. Res. 54 (2021) 344–355.
[5] C. Tan, C.L. Chen, Angew. Chem. Int. Ed. 58 (2019) 7192–7200.
[6] C.W. Hong, Z.H. Wang, H. Jiang, et al., Chin. Chem. Lett. 34 (2023) 107918.
[7] S. Mecking, M. Schnitte, Acc. Chem. Res. 53 (2020) 2738–2752.
[8] H.L. Mu, L. Pan, D.P. Song, Y.S. Li, Chem. Rev. 115 (2015) 12091–12137.
[9] Q. Wang, Z. Zhang, C. Zou, C.L. Chen, Chin. Chem. Lett. 33 (2022) 4363–4366.
[10] A.M. Doerr, J.M. Burroughs, S.R. Gitter, et al., ACS Catal. 10 (2020) 14457–14515.
[11] A.J. Teator, D.N. Lastovickova, C.W. Bielawski, Chem. Rev. 116 (2016) 1969–1992.
[12] U. Lüning, Angew. Chem. Int. Ed. 51 (2012) 8163–8165.
[13] C.L. Chen, ACS Catal. 8 (2018) 5506–5514.
[14] H. Suo, Z. Zhang, R. Qu, Y. Gu, Y. Qin, Catalysts 13 (2023) 670.
[15] T.V. Tran, L.H. Do, Eur. Polym. J. 142 (2021) 110100.
[16] S. Deng, B.J. Jolly, J.R. Wilkes, et al., Nat. Rev. Methods Primers 3 (2023) 28.
[17] C. Tan, M. Chen, C.L. Chen, Trends Chem. 5 (2023) 147–159.
[18] F.A. Leibfarth, K.M. Mattson, B.P. Fors, H.A. Collins, C.J. Hawker, Angew. Chem. Int. Ed. 52 (2013) 199–210.
[19] J.M. Kaiser, J.M. Burroughs, B.K. Long, J. Am. Chem. Soc. 144 (2022) 21206–21212.
[20] Y.S. Liu, E. Harth, Angew. Chem. Int. Ed. 60 (2021) 24107–24115.
[21] L. Zhou, Y.J. Wu, K. Chen, et al., Org. Chem. Front. 10 (2023) 4854–4861.
[22] C. Tan, Q. Muhammad, W.M. Pang, C.L. Chen, Polym. Chem. 11 (2020) 411–416.
[23] M. Chen, W.P. Zou, Z.G. Cai, C.L. Chen, Polym. Chem. 6 (2015) 2669–2676.
[24] N.D. Contrella, R.F. Jordan, Organometallics 33 (2014) 7199–7208.
[25] M. Abubekerov, S.M. Shepard, P.L. Diaconescu, Eur. J. Inorg. Chem. 15 (2016) 2634–2640.
[26] R. Mundil, L.E. Wilson, D. Schaarschmidt, et al., Polymer 179 (2019) 121619.
[27] W.C. Anderson, S.H. Park, L.A. Brown, J.M. Kaiser, B.K. Long, Inorg. Chem. Front. 4 (2017) 1108–1112.
[28] J.M. Kaiser, B.K. Long, Coord. Chem. Rev. 372 (2018) 141–152.
[29] M. Chen, B.P. Yang, C.L. Chen, Angew. Chem. Int. Ed. 54 (2015) 15520–15524.
[30] J. Bernauer, J. Pölker, A. Jacobi von Wangelin, ChemCatChem 14 (2022) e202101182.
[31] G.H. Wang, D. Peng, Y. Sun, C.L. Chen, CCS Chem. 2 (2020) 2025–2034.
[32] J. Flapper, J.N.H. Reek, Angew. Chem. Int. Ed. 46 (2007) 8590–8592.
[33] M.H. Zhao, C.L. Chen, ACS Catal. 7 (2017) 7490–7494.
[34] W.C. Anderson Jr, J.L. Rhinehart, A.G. Tennyson, B.K. Long, J. Am. Chem. Soc. 138 (2016) 774–777.
[35] J.M. Kaiser, W.C. Anderson, B.K. Long, Polym. Chem. 9 (2018) 1567–1570.
[36] D. Peng, C.L. Chen, Angew. Chem. Int. Ed. 60 (2021) 22195–22200.
[37] Z.G. Cai, Z.L. Shen, X.Y. Zhou, R.F. Jordan, ACS Catal. 2 (2012) 1187–1195.
[38] Z.Z. Cai, D.W. Xiao, L.H. Do, J. Am. Chem. Soc. 137 (2015) 15501–15510.
[39] Z.Z. Cai, L.H. Do, Organometallics 36 (2017) 4691–4698.
[40] T.V. Tran, E. Lee, Y.H. Nguyen, H.D. Nguyen, L.H. Do, J. Am. Chem. Soc. 144 (2022) 17129–17139.
[41] L.H. Guo, S.Y. Dai, X.L. Sui, C.L. Chen, ACS Catal. 6 (2016) 428.
[42] F.Z. Wang, C.L. Chen, Polym. Chem. 10 (2019) 2354–2369.
[43] U. Siemeling, B. Neumann, H.G. Stammler, O. Kuhnert, Polyhedron 18 (1999) 1815–1819.
[44] S.Y. Dai, C.L. Chen, Angew. Chem. Int. Ed. 55 (2016) 13281.
[45] Y.X. Zhang, Z.B. Jian, Macromolecules 54 (2021) 3191–3196.
[46] J.S. Yang, X.Q. Hu, Z.B. Jian, Chin. J. Chem. 40 (2022) 2919–2926.
[47] P. Zhang, M.H. Zhao, W.M. Pang, C.L. Chen, Sci. Chin. Chem. 62 (2019) 475–478.
[48] C. Tan, C. Zou, C.L. Chen, J. Am. Chem. Soc. 144 (2022) 2245–2254.
[49] X.Y. Zhang, G.O. Jones, J.L. Hedrick, R.M. Waymouth, Nat. Chem. 8 (2016) 1047–1053.
[50] D.A. Dougherty, Science 271 (1996) 163–168.
[51] L.M. de Espinosa, M.A. Meier, Eur. Polym. J. 47 (2011) 837–852.