Electronic Supporting Information (ESI) File

Ultra-Small Pt on Ce–Mn Binary Oxide Nanocomposite as a Robust Oxygen Reduction Reaction Catalyst with Enhanced Methanol Crossover Tolerance

Ammar Bin Yousaf[a]*, Asad Ali[b], Suryyia Manzoor[c], Bence Farkas[d], Peter Kasak[a]*

[a]Center for Advanced Materials, Qatar University, Doha 2713, Qatar

[b]School of Materials Science and Engineering, Hefei University of Technology, Hefei, 230009, P.R. China

[c]Institute of Chemical Sciences, Bahauddin Zakaria University, Multan 60800, Pakistan

[d]Institute of Laboratory Research on Geomaterials, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynka Dolina, Ilkovicova 6, 842 15 Bratislava, Slovakia.

* Corresponding Authors E-mails: ammar@mail.ustc.edu.cn / muhammad.ammar@qu.edu.qa / ammar.chemist18@gmail.com (A.B. Yousaf) and peter.kasak@qu.edu.qa (P. Kasak)

Table S1: ICP-MS data for Pt loading in the studied Pt_2/Ce-Mn-O, Pt_4/Ce-Mn-O and Pt_2/Ce-Mn-O electrocatalysts

Catalyst	**ICP-MS measurements**		
	Pt (mol)	**Pt (wt%)**	**Pt Nominal Loading**
Pt_2/Ce-Mn-O	2.247×10^{-6}	1.94	2

Pt_4/Ce-Mn-O	4.496×10^{-6}	3.70	4
Pt_6/Ce-Mn-O	6.743×10^{-6}	5.69	6

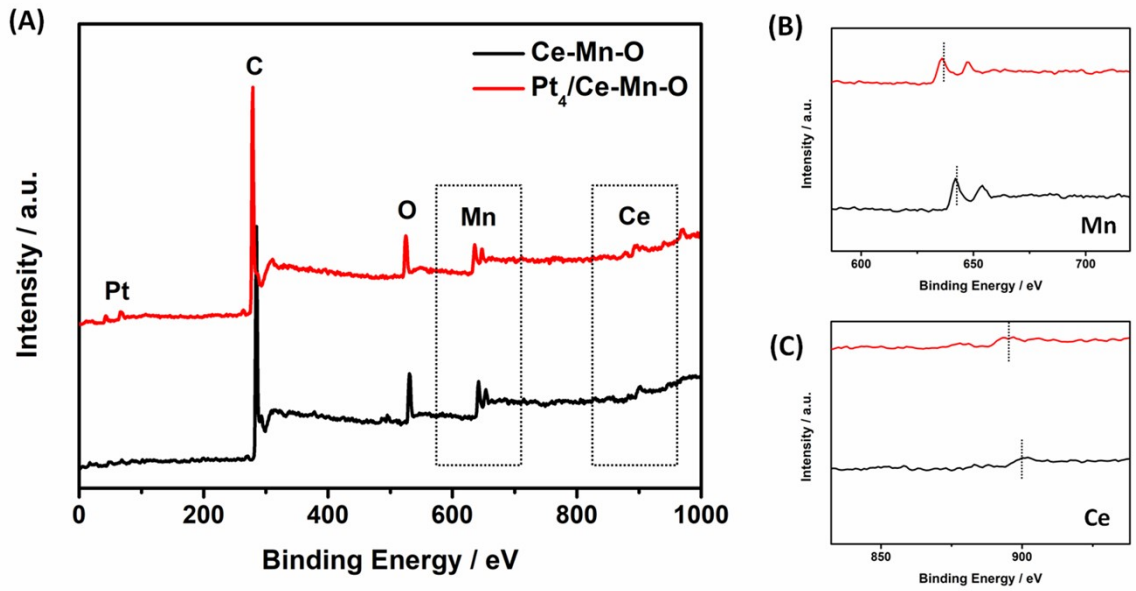

Fig. S1: (A) XPS survey spectrum for Ce-Mn-O and Pt_4/Ce-Mn-O catalysts, (B) selected area high resolution for Mn scan and (C) selected area high resolution for Ce scan, both showing negative shift in peaks after Pt loading on Ce-Mn-O

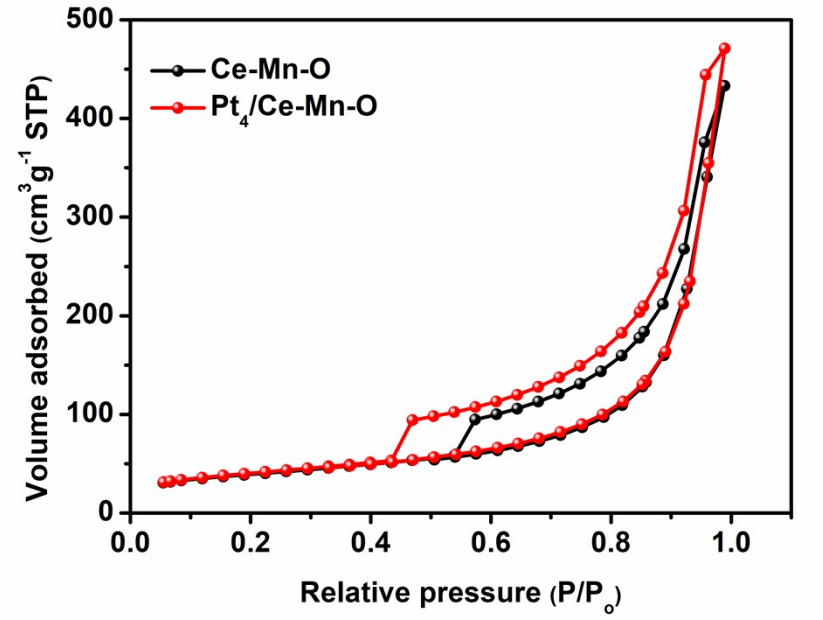

Fig. S2: Nitrogen adsorption-desorption isotherms of BET analysis for Ce-Mn-O and Pt_4/Ce-Mn-O nanocomposites catalysts.

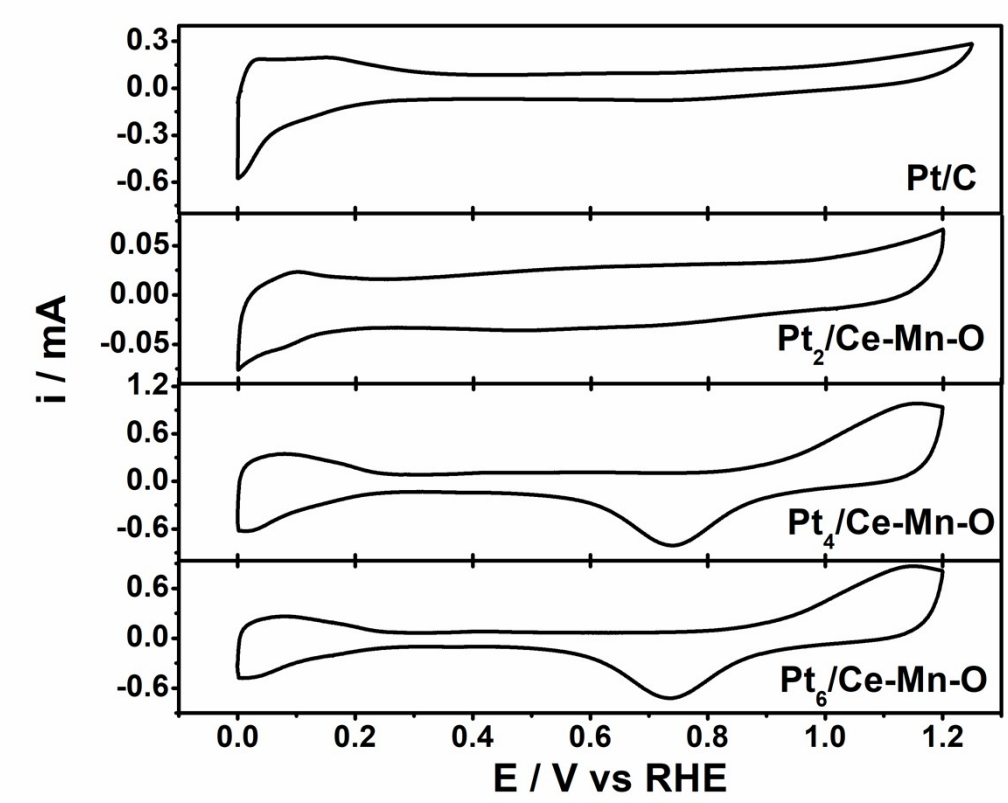

Figure S3: CVs for all the catalysts in 0.1 M KOH at scan rate of 50 mVs^{-1}, for the measurement of electrochemical active surface area (ECSA)

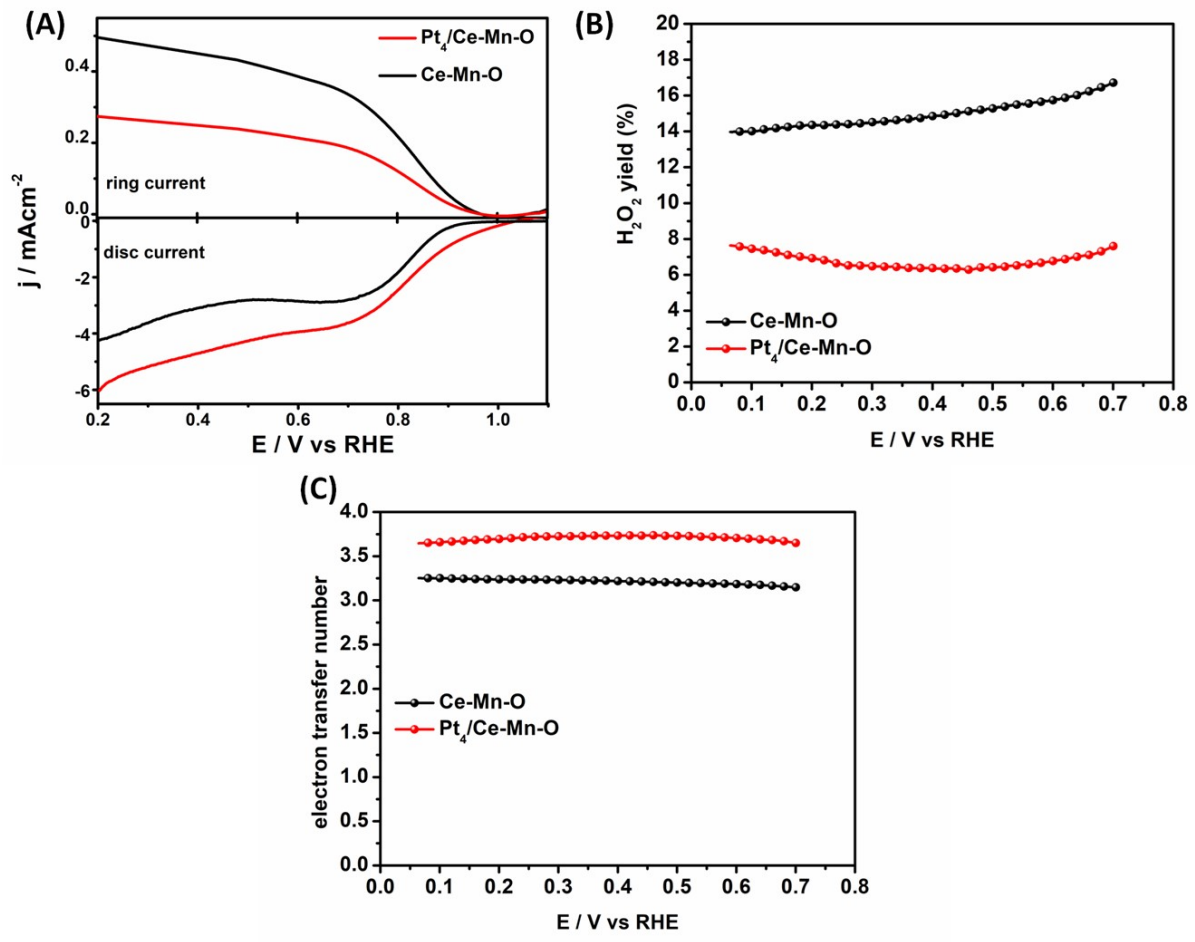

Fig. S4: (A) Rotating ring-disk electrode (RRDE) measurements for Ce-Mn-O and Pt_4/Ce-Mn-O catalysts with mentioned ring current and disc current polarization curves, **(B)** H_2O_2 percentage yield detected on a ring electrode and **(C)** calculated (*n* values) number of electron transfer from RRDE measurements

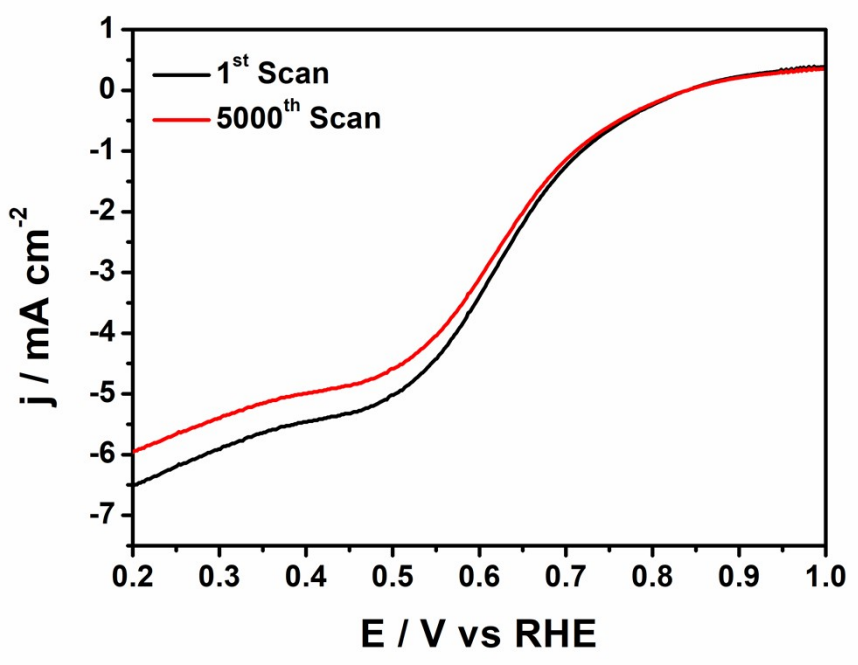

Fig. S5: Accelerated durability test (ADT) for ORR activity of Pt_4/Ce-Mn-O catalyst in an acidic medium of 0.1M $HClO_4$ with ORR polarization curves at 1600 rpm rotation rate for 1st (black line) and 5000th cycle (red line).

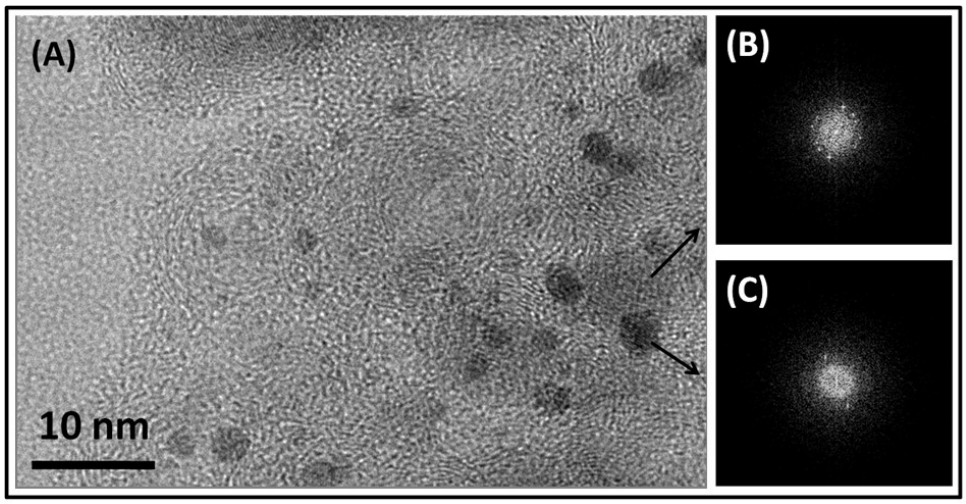

Fig. S6: Structural stability analysis with high resolution TEM micrograph image of Pt_4/Ce-Mn-O catalyst layer after fuel cells testing, with FFT images corresponding to the **(B)** Ce-Mn-O binary oxide and **(C)** Pt particles from selected area represented with arrows.

Table S2: ORR performance (Tafel slope) comparison of Pt_4/Ce-Mn-O catalyst with Pt and noble-metal based catalysts reported in literature in alkaline media

Sr. No.	Catalyst	Tafel Slope (mV dec^{-1})	Reference
1	Pt_4/Ce-Mn-O	55	This work
2	Pt/N-C	70	53
3	Pt/NrEGO_2-CB3	67	54
4	Pt–NbO*x*/TiN	62	55
5	Pt37Cu56Au7	65	56
6	Thin Film Pt/GDL	60	57
7	Pt_2Fe_1/C	63.51	58
8	Pt&Fe_3N&Fe@NC	74.16	59
9	20 wt.–% Pt@XC-72	62	60
10	20 wt.–% Ir@XC-72	85	60
11	$PdMnO_2$.Pd/C	60	61
12	Ru-SAS/SNC	57	62
13	Ag10/MnO_2_MWCNT1	81	63

53. N. Batool, W. Iqbal, X. F. Han, W. T. Wang, H.-T. Teng, X. Hao, R. Yang and J. H. Tian, *ACS Appl. Nano Mater.*, 2021, **4**, 12365–12372.
54. Z. Jia, J. Chen, M. Pérez-Page, Z. Guo, Z. Zhao, R. Cai, M. T. P. Rigby, S. J. Haigh and S. M. Holmes, *J. Energy Chem.*, 2022, **68**, 143.
55. N. F. Daudt, A. Poozhikunnath, H. Yu, L. Bonville and R. Maric, *Mater. Renew. Sustain. Energy*, 2020, **9**, 18.

56. Y. Xie, Y. Yang, D. A. Muller, H. D. Abruna, N. Dimitrov and J. Fang, *ACS Catal.*, 2020, **10**, 9967–9976.

57. E. Marra, H. Grimler, G. Montserrat-Sisó, R. Wreland Lindström, B. Wickman, G. Lindbergh and C. Lagergren, *Electrochim. Acta*, 2022, **435**, 141376.

58. X. Leng, L. Huang, Y. Sun, X. Jin, F. Chen, H. Duan and B. Cao, *Fuel*, 2026, **408**, 137516.

59. X. Feng, H.-J. Zhang, H. Luo, Y. Tao, Z. Ma and Y. Xue, *Int. J. Hydrogen Energy*, 2025, **103**, 701–708.

60. M. F. Fink, J. Eckhardt, P. Khadke, T. Gerdes and C. Roth, *ChemElectroChem*, 2020, **7**, 4822–4836.

61. I. Cruz-Reyes, B. Trujillo-Navarrete, M. I. Salazar-Gastélum, J. R. Flores-Hernández, T. Romero-Castañón and R. M. Félix-Navarro, *Nanomaterials*, 2026, **16**, 71.

62. J. Qin, H. Liu, P. Zou, R. Zhang, C. Wang and H. L. Xin, *J. Am. Chem. Soc.*, 2022, **144**, 2197–2207.

63. J. M. Linge, H. Erikson, P. Ritslaid, A. Kikas, V. Kisand, J. Aruväli, J. Kozlova, A. Tamm, A. Sarapuu and K. Tammeveski, *Catalysts*, 2023, **13**, 976.