Claims

1. A composite catalyst comprising:

a first catalytic material incorporated with a second catalytic material, wherein the first catalytic material comprises carbon doped with (i) nitrogen and (ii) at least one non-precious transition metal, and wherein the second catalytic material comprises a carbon-based supporting material incorporated with platinum nanoparticles.

2. The composite catalyst of claim 1, wherein the first catalytic material is porous.

3. The composite catalyst of claim 1 or 2, wherein the at least one non-precious transition metal is present in the first catalytic material in an amount ranging from 0.1 wt% to 20 wt% of the first catalytic material.

4. The composite catalyst of any one of claims 1 to 3, wherein the at least one non-precious transition metal comprises cobalt, copper, iron, molybdenum, and/or nickel.

5. The composite catalyst of any one of claims 1 to 4, wherein in the second catalytic material, the platinum nanoparticles are formed on the carbon-based supporting material, wherein the carbon-based supporting material comprises carbon particles, carbon nanotubes, graphenes, or a mixture thereof.

6. The composite catalyst of any one of claims 1 to 5, wherein:

the platinum nanoparticles comprise an average diameter ranging from 1.6 nm to 10 nm; and/or

the platinum nanoparticles are present in an amount ranging from 5 % to 80 % by mass of the second catalytic material.

7. The composite catalyst of any one of claims 1 to 6, wherein the first catalytic material and the second catalytic material are present in a mass ratio of 5:95 to 95:5.

8. The composite catalyst of any one of claims 1 to 7, further comprising an ionomer, wherein the ionomer comprises nafion, perfluorinated sulfonic acid, sulfonated tetrafluoroethylene, or a mixture thereof.

9. A method of producing a composite catalyst comprising a first catalytic material incorporated with a second catalytic material, wherein the first catalytic material comprises carbon doped with (i) nitrogen and (ii) at least one non-precious transition metal, and wherein the second catalytic material comprises a carbon-based supporting material incorporated with platinum nanoparticles, the method comprising:

providing a mixture comprising the first catalytic material and the second catalytic material; and

subjecting the mixture to a size reduction step.

10. The method of claim 9, wherein providing the mixture comprises:

dispersing the first catalytic material in an alcohol to form a first dispersion;

dispersing the second catalytic material in an alcohol to form a second dispersion; and

mixing the first dispersion and the second dispersion to form the mixture.

11. The method of claim 10, wherein dispersing the first catalytic material in the alcohol comprises dispersing an ionomer in the alcohol to form the first dispersion, and/or dispersing the second catalytic material in the alcohol comprises dispersing an ionomer in the alcohol to form the second dispersion, wherein the ionomer comprises nafion, perfluorinated sulfonic acid, sulfonated tetrafluoroethylene, or a mixture thereof.

12. The method of claim 10 or 11, wherein the alcohol to form the first dispersion and the second dispersion comprises ethanol, iso-propanol, n-propanol, ethylene glycol, or a mixture thereof.

13. The method of any one of claims 9 to 12, wherein providing the mixture comprises forming the first catalytic material.

14. The method of claim 13, wherein forming the first catalytic material comprises:

dispersing a structure-directing agent in an aqueous medium, wherein the aqueous medium comprises (i) at least one metal salt and/or at least one metal oxide and (ii) at least an organic compound comprising an amine;

mixing the aqueous medium and at least one non-precious transition metal precursor to form a liquid ink;

drying the liquid ink to form a viscous solid; and

pyrolyzing the viscous solid in an inert atmosphere to form the first catalytic material.

15. The method of claim 14, wherein the at least one metal salt and/or the at least one metal oxide comprise a metal selected from the group consisting of an alkali metal and a transition metal.

16. The method of claim 14 or 15, wherein the organic compound comprising the amine comprises ethylenediamine, pentaethylenehexamine, or a polyamine.

17. The method of any one of claims 14 to 16, wherein the structure-directing agent comprises a xerogel, wherein the xerogel comprises a silica xerogel, MCM-41, MCM-48, ZnO, an analogue thereof, or a mixture thereof.

18. The method of any one of claims 14 to 17, wherein the aqueous medium comprises water.

19. The method of any one of claims 14 to 18, wherein mixing the aqueous medium and the at least one non-precious transition metal precursor comprises mixing the aqueous medium and an alcoholic solution comprising the at least one non-precious transition metal precursor, wherein the alcoholic solution comprises ethanol, iso-propanol, n-propanol, ethylene glycol, or a mixture thereof.

20. The method of any one of claims 14 to 19, wherein the at least one non-precious transition metal precursor comprises a cobalt salt, a copper salt, an iron salt, a molybdenum salt, and/or a nickel salt.

21. The method of any one of claims 14 to 20, wherein pyrolyzing the viscous solid comprises heating the viscous solid at a temperature ranging from 300°C to 1200°C.

22. The method of any one of claims 14 to 21, further comprising:

washing the first catalytic material with an alkali;

washing the first catalytic material with an acid; and

washing the first catalytic material with water, wherein washing the first catalytic material with acid is (i) after washing with the alkali and (ii) prior to washing with water.

23. The method of claim 13, wherein forming the first catalytic material comprises:

mixing a solid mixture comprising (i) at least one non-precious transition metal precursor and (ii) an organic compound comprising an imidazole; and

pyrolyzing the solid mixture in an alkaline atmosphere to form the first catalytic material.

24. The method of claim 23, wherein mixing the solid mixture comprises (i) ball milling the solid mixture or (ii) mixing the solid mixture in a liquid medium.

25. The method of claim 23 or 24, wherein the at least one non-precious transition metal precursor comprises a cobalt salt, a copper salt, an iron salt, a molybdenum salt, and/or a nickel salt.

26. The method of any one of claims 23 to 25, wherein the organic compound comprising an imidazole comprises 2-methylimidazole, benzimidazole, or a mixture thereof.

27. The method of any one of claims 23 to 26, wherein pyrolyzing the solid mixture comprises heating the solid mixture in the alkaline atmosphere at a temperature ranging 300°C to 1200°C.

28. The method of any one of claims 9 to 27, wherein providing the mixture comprises forming the second catalytic material, wherein forming the second catalytic material comprises:

mixing a carrier ink and a precursor solution;

adding a base to render a pH greater than 10; and

heating the carrier ink and the precursor solution to form the second catalytic material.

29. The method of claim 28, wherein mixing the carrier ink and the precursor solution comprises:

dispersing the carbon-based supporting material in an alcohol to form the carrier ink; and

mixing a platinum precursor and a (i) citrate or (ii) citric acid in an alcohol to form the precursor solution.

30. The method of claim 29, wherein the alcohol to form the carrier ink and the precursor solution comprises ethanol, iso-propanol, n-propanol, ethylene glycol, or a mixture thereof.

31. The method of claim 29 or 30, wherein the carbon-based supporting material comprises carbon powder, graphene, carbon nanotubes, or a mixture thereof.

32. The method of any one of claims 29 to 31, wherein the platinum precursor comprises chloroplatinic acid, potassium chloroplatinate, platinum nitrate, or a mixture thereof.

33. The method of any one of claims 29 to 32, wherein the citrate comprises sodium citrate or potassium citrate.

34. The method of any one of claims 28 to 33, wherein heating the carrier ink which is mixed with the precursor solution is carried out at a temperature ranging from 100°C to 250°C.

35. The method of any one of claims 28 to 34, further comprising separating the second catalytic material to obtain a solid form of the second catalytic material after precipitating the second catalytic material by subjecting the second catalytic material to a pH in the acidic range, wherein the precipitating is carried out after heating of the carrier ink and the precursor solution.