Possible metal extraction techniques for lunar use to date (updated from Shaw et al. 2021 [1])

Process	*Research Target Resource*	*Useful By-products*	*Refs*	*Condition Requirements*	*Reagents/Required wear parts*
Carbothermal Reduction	Oxygen Oxygen Fe_xSi, SiC Oxygen Al, Si, Oxygen	Fe Fe, TiC, Fe_xSi, P	[2-4] [5-8] [9] [10-16] [16, 17]	<1150 °C >1200 °C 1300-1500 °C >1600 °C 1800-2100 °C	Carbon (Solid, Methane, CO)
Hydrogen Reduction of Ilmenite (HRI)	Oxygen	Fe	[16, 18-31]	700-1100 °C	Hydrogen
Hydrogen Plasma Reduction	Oxygen		[32]	?	Hydrogen plasma
HRI and Carbonylation	Oxygen, Low-c Steel		[33]	720-1020 °C	Hydrogen, $CO/NH_3/H_2S$[#]
Molten Oxide Electrolysis (MOE)	Oxygen Oxygen, Al-Si Alloy	Al, Si, Fe, Ti Alloy	[12, 34-39] [40]	850-1250 °C 960-980 °C	Electrolyte ($CaCl_2$ - CaO, or SiO_2 - B_2O_3 – Na_2O, LiF, CaF_2, MgF_2, Na2O, $NaBO_4$, Na_3PO_4, $Na_5P_3O_{10}$, NaF – AlF_3) Anodes
Molten Regolith Electrolysis (MRE)	Oxygen Oxygen, Fe_xSi	Fe, Si	[15, 33, 35, 41-52] [16, 53]	1300-2000 °C ~1450 °C	Anodes Anodes/Cathodes
Solid Electrolysis or Molten Salt Electrolysis (MSE)	Oxygen Oxygen Oxygen + FeSiTi	Mixed Metal Alloy Mixed Metal Alloy	[33, 54-56] [57] [58]	900-950 °C 660-850 °C ?	Electrolyte ($CaCl_2$ – CaO, $CaCl_2$ – KCl/LiCl/NaCl, AlF_3) Anodes
Chemically Assisted Solid Electrolysis *	Oxygen + Mixed Metal Alloy (FeSiTiAlCr)		[59]	850 °C	Electrolyte ($CaCl_2$) Anodes (Carbon)
Thermal Decomposition †	Oxygen Entire Composition Fe, Na, K Oxygen Oxygen Oxygen, Si	Fe, Oxygen Metals	[16, 60-69] [70] [71] [72] [73] [29, 74]	1200-2000 °C 900-1800 °C 900-1200 °C 1427-1827 °C 2230 °C 2700 °C	 Hydrogen
(& Selective Ionisation)	Oxygen		[49, 68, 75, 76]	>7000 °C	
Ionic Liquid & Aqueous Electrolysis	Oxygen, Metals Oxygen	 Metals	[77-80] [81]	0-300 °C 100°C	Ionic Liquids[‡], Water, Electrodes, Sulfuric acid or Phosphoric acid in some cases. HF, Liquid Ga, Bifluoride IL, Electrodes
Aluminothermic Reduction	Oxygen, Fe, Ti, Si, and Al, Mg Oxygen, Si, Al, Ca		[29, 82] [83, 84]	900-1000 °C ?	Conducted in electrolyte (NaF, AlF) Anode ($Fe_{0.58}$-$Ni_{0.42}$) Initial reactant (Al)
Silicothermic Reduction	Fe, Ti, REEs (Ce, Nd, Sm, Th, U, P)		[85]	1600 °C	High purity Si
Lithium Reduction	Oxygen	Mixed Metal Alloy	[86, 87]	900 °C	Electrodes ($FeSi_2Li_x$, Pt, $La_{0.89}Sr_{0.1}MnO_3$), Reactant (LiF, LiCl or Li_2O), Electrolyte (ZrO_2), Catholyte ($La_{0.89}Sr_{0.1}MnO_3$)
Acid Reduction	Oxygen Oxygen	Fe	[12, 13, 15, 39, 88] [16]	20-110 °C 950 -1000 °C	HF, H_2SO_4[¶] HF, H_2SO_4
Fluorine Reduction	Oxygen	Mixed Metal Alloy (Si, Fe, Ti, Al, etc..), CaO, MgO	[16, 89-93] [49] [94]	500-750 °C 900 °C ?	KF, LiF, NaF, HF, or H_2TiF_6
Bio-Reduction	Fe(II)	N/A	[95-97]	20-40 °C	Bacteria, Water, Defined Minimal Medium [§]
Carbochlorination	Oxygen, Al, Fe,	TiO_2, CaO, SiO_2	[14, 49, 83]	675-770 °C	Cl (g), Carbon (s), Hydrogen and /or water
Chlorine plasma Reduction	Oxygen	Fe, Ti	[98]	800-1100 °C	Cl (cold plasma)
Calcium Reduction	Oxygen	Metal Alloy	[99]	900-1000 °C	Molten Salt ($CaO/CaCl_2$) Electrodes Initial reactant (Ca)

† Volatile extraction methods (such as water ice evaporation [100, 101]) have been excluded from the current review as they don't cover temperature ranges relevant for metal extraction.

‡ 1-ethyl-3-methylimidazolium hydrogen sulfate, 1-methylimidazolium hydrogen sulfate, 1-methylpyrrolidinium hydrogen sulfate, 3-[butyl-4-sulfonic acid]-1-methylimidazolium hydrogen sulfate, 3-[butyl-4-sulfonic acid]-1-methylimidazolium triflate [79].

§ NaCl, sodium 4(2-hydroxyethyl)-1-piperazineethanesulphonic acid, NaOH, NH_4Cl, KCl, $NaH_2PO_4{\cdot}2H_2O$, and trace mineral supplement [95].

¶ H_2SO_4 processing only targeted Ilmenite as an Fe/O_2 source [88]

* Requires second stage of CO_2 recovery, used Li_2CO_3-Na_2CO_3-K_2CO_3 electrolyte with a $Ni_{11}Fe_{10}Cu$ or Pt/Ti anode at 650 °C [59]

[#]Fe removal step is described in more detail by Visnapuu [102] (paper not related to ISRU). Process requires v.high pressure to form the Fe