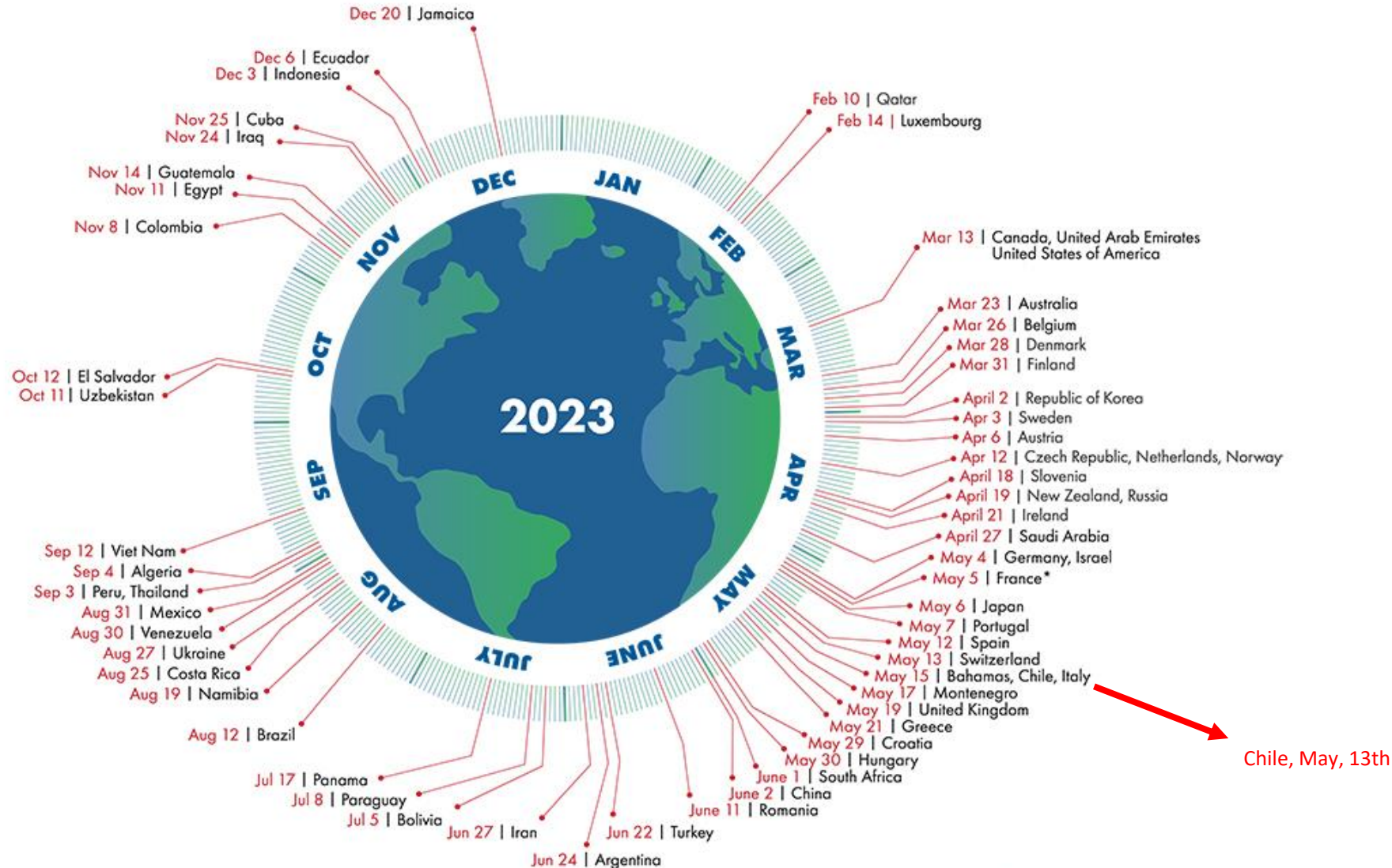


# Country Overshoot Days 2023

When would Earth Overshoot Day land if the world's population lived like...

<https://overshoot.footprintnetwork.org/newsroom/country-overshoot-days/>



For a full list of countries, visit [overshootday.org/country-overshoot-days](https://overshootday.org/country-overshoot-days).  
\*French Overshoot Day based on nowcasted data. See [overshootday.org/france](https://overshootday.org/france).

Source: National Footprint and Biocapacity Accounts, 2022 Edition  
[data.footprintnetwork.org](https://data.footprintnetwork.org)





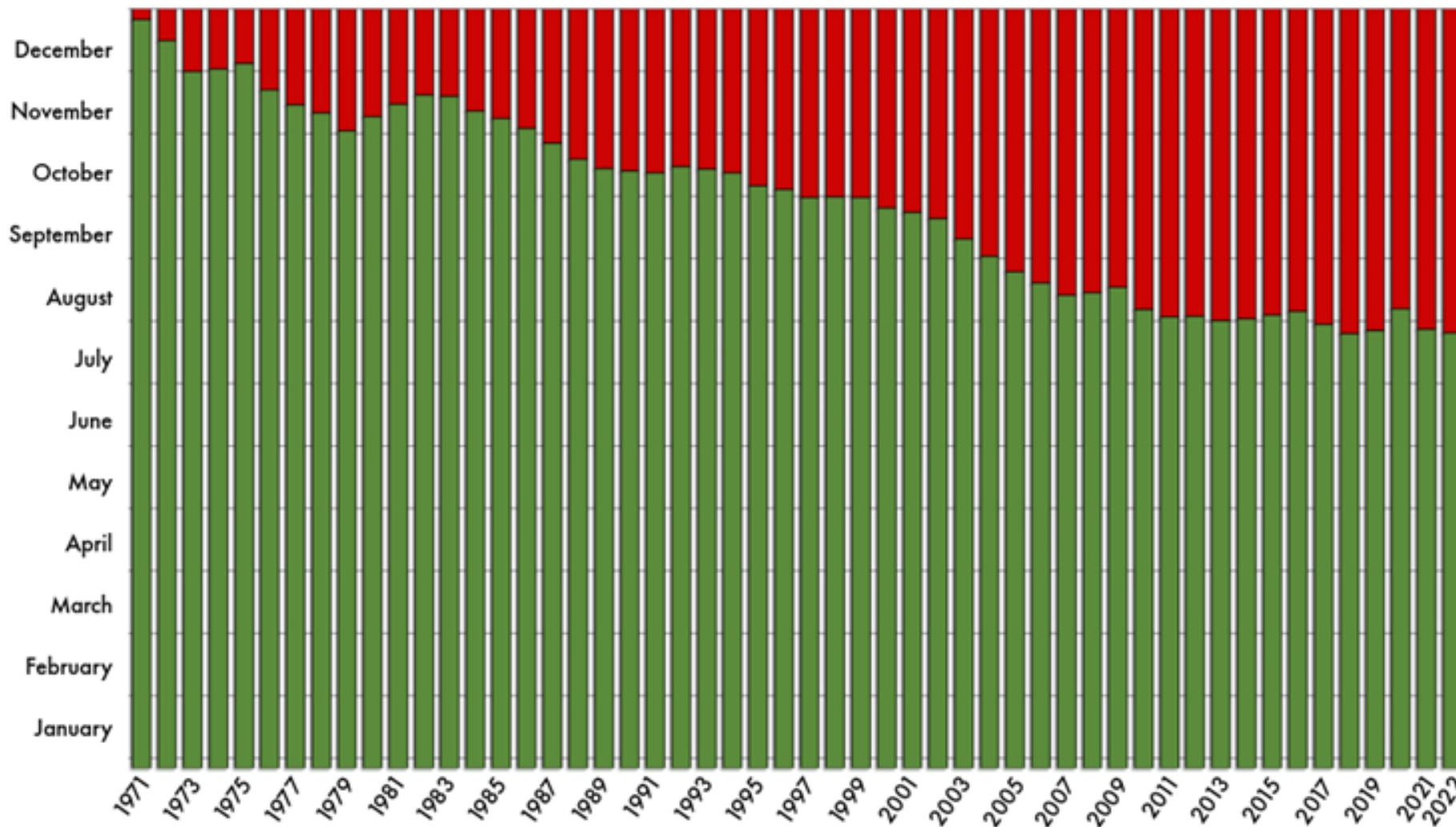
1 Earth

# Earth Overshoot Day

## 1971 - 2022



1.75 Earths



EARTH OVERSHOOT DAY

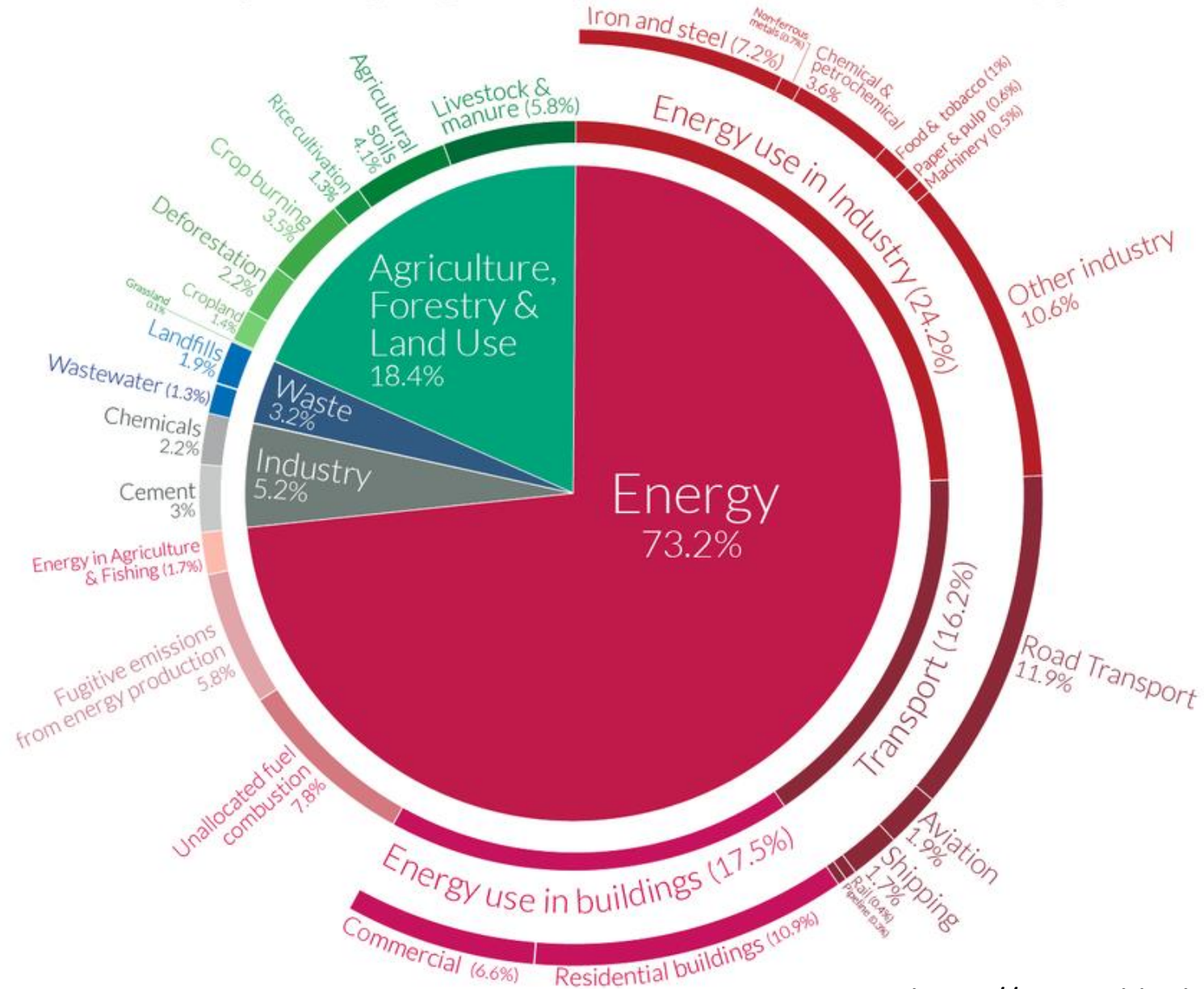


Source: National Footprint and Biocapacity Accounts 2022 Edition  
data.footprintnetwork.org

<https://wwf.es>

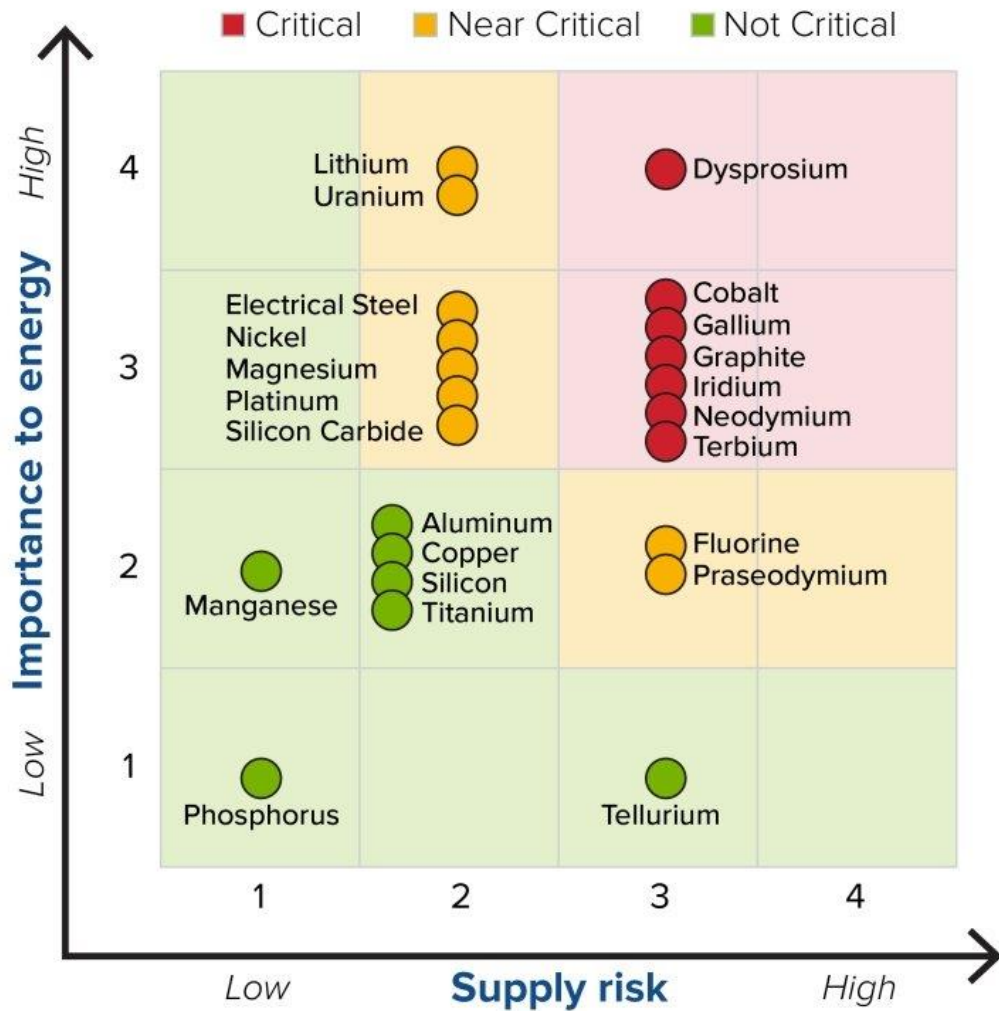
# Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO<sub>2</sub>eq.

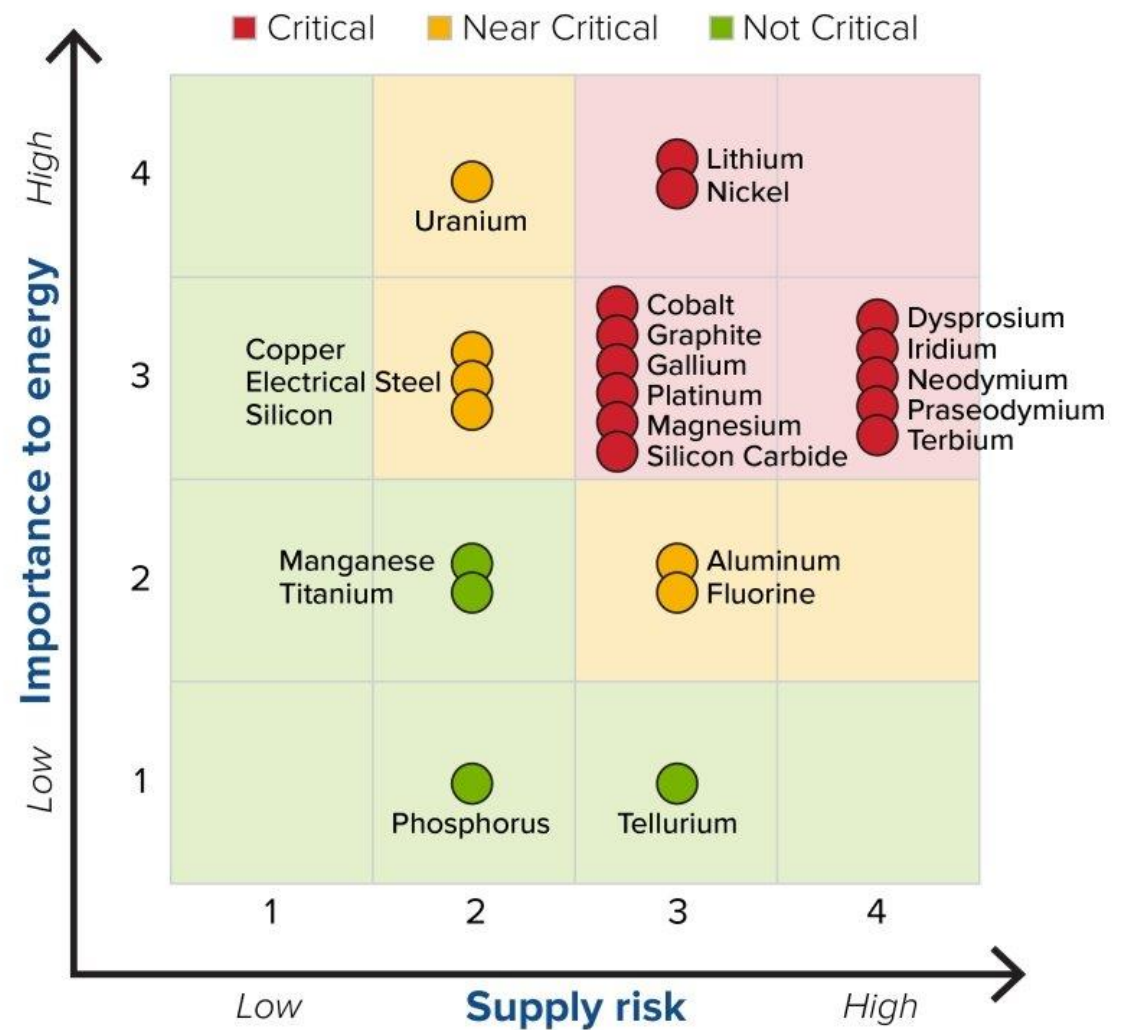


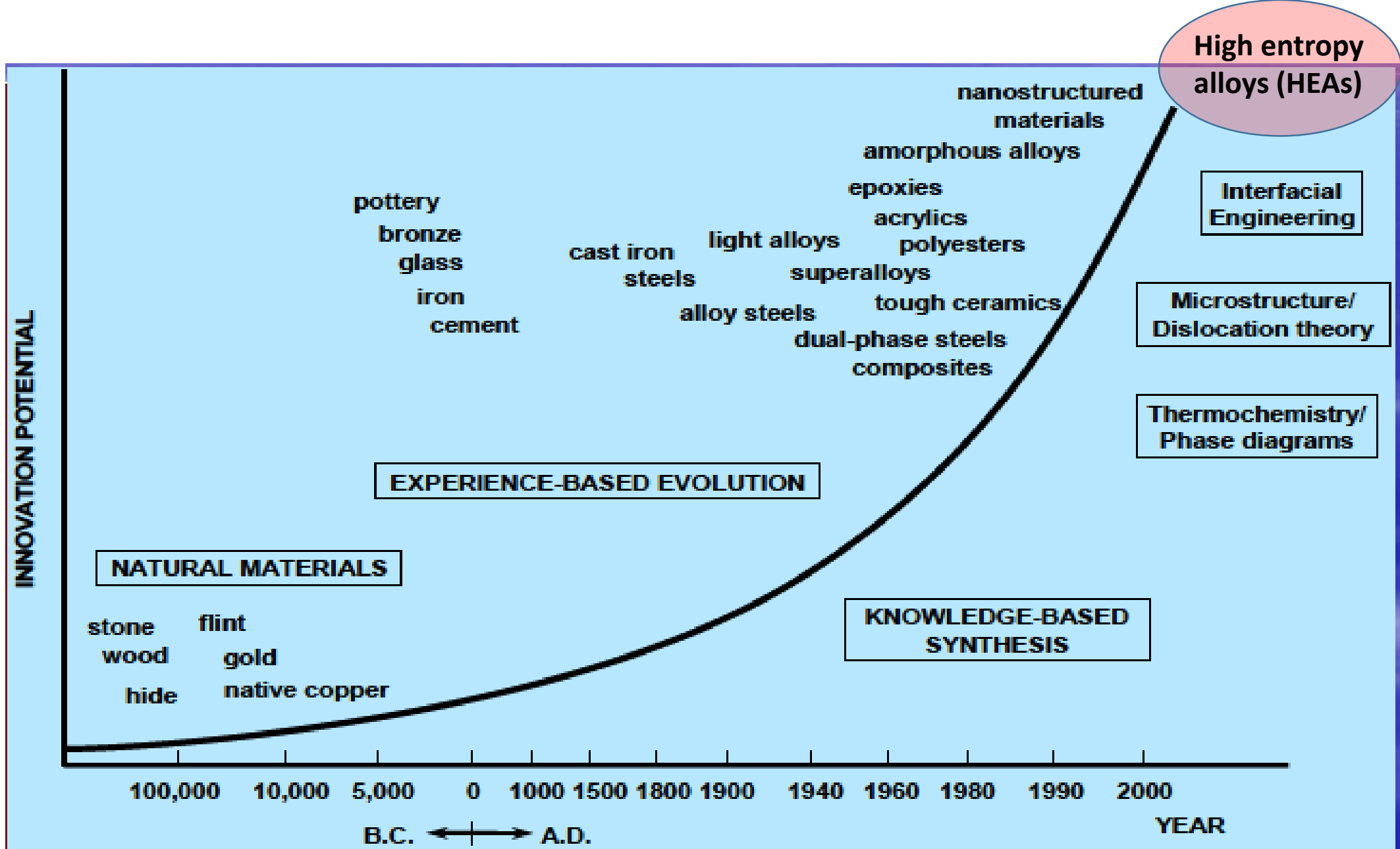
<https://ourworldindata.org/emissions-by-sector>

## SHORT TERM 2020-2025



## MEDIUM TERM 2025-2035







**1<sup>ST</sup> LATAM MEETING ON GREEN  
AMMONIA AND POWER-to-X**

**10 Y 11 DE ENERO DE 2024**

# **Desarrollo de nuevos materiales metálicos para electrodos**

Dr. Claudio Aguilar R.

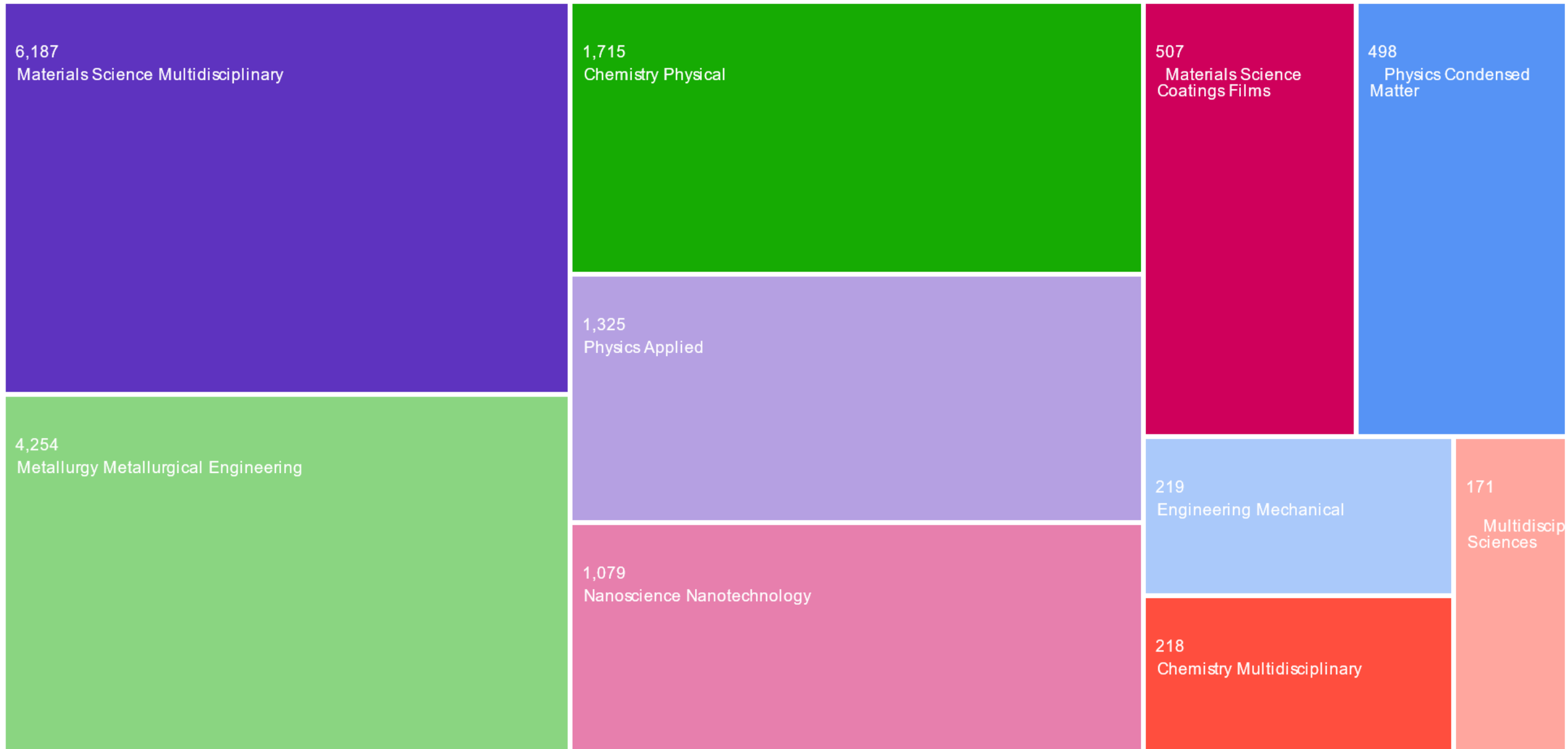
Instituto Milenio para el amoníaco verde como vector energético – MIGA

Departamento de Ingeniería Metalúrgica y Materiales

Universidad Técnica Federico Santa María

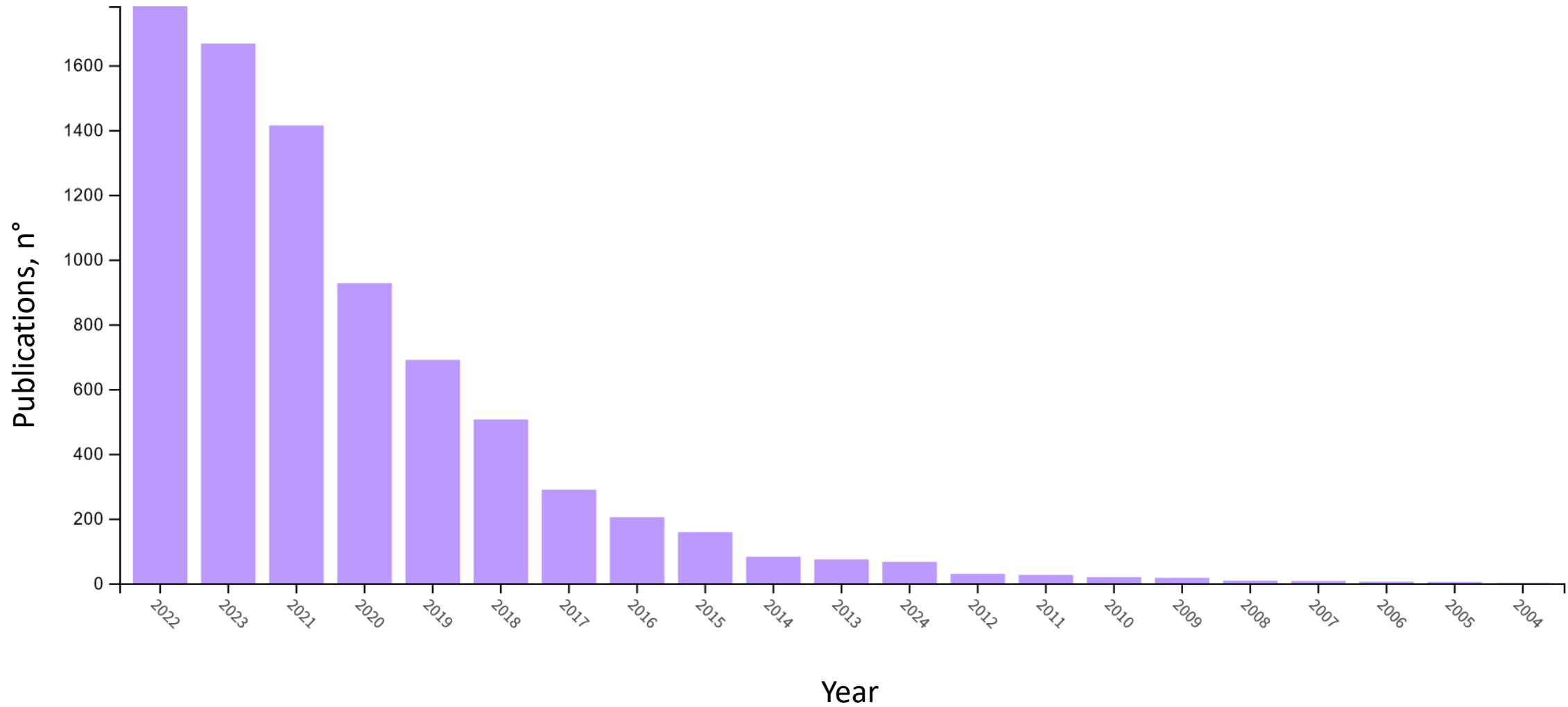
# 1 Introduction | Productivity WoS, area

“High entropy alloys”



# 1 Introduction | Productivity WoS, year

“High entropy alloys”



# 1 Introduction | Productivity WoS, country

“High entropy alloys”



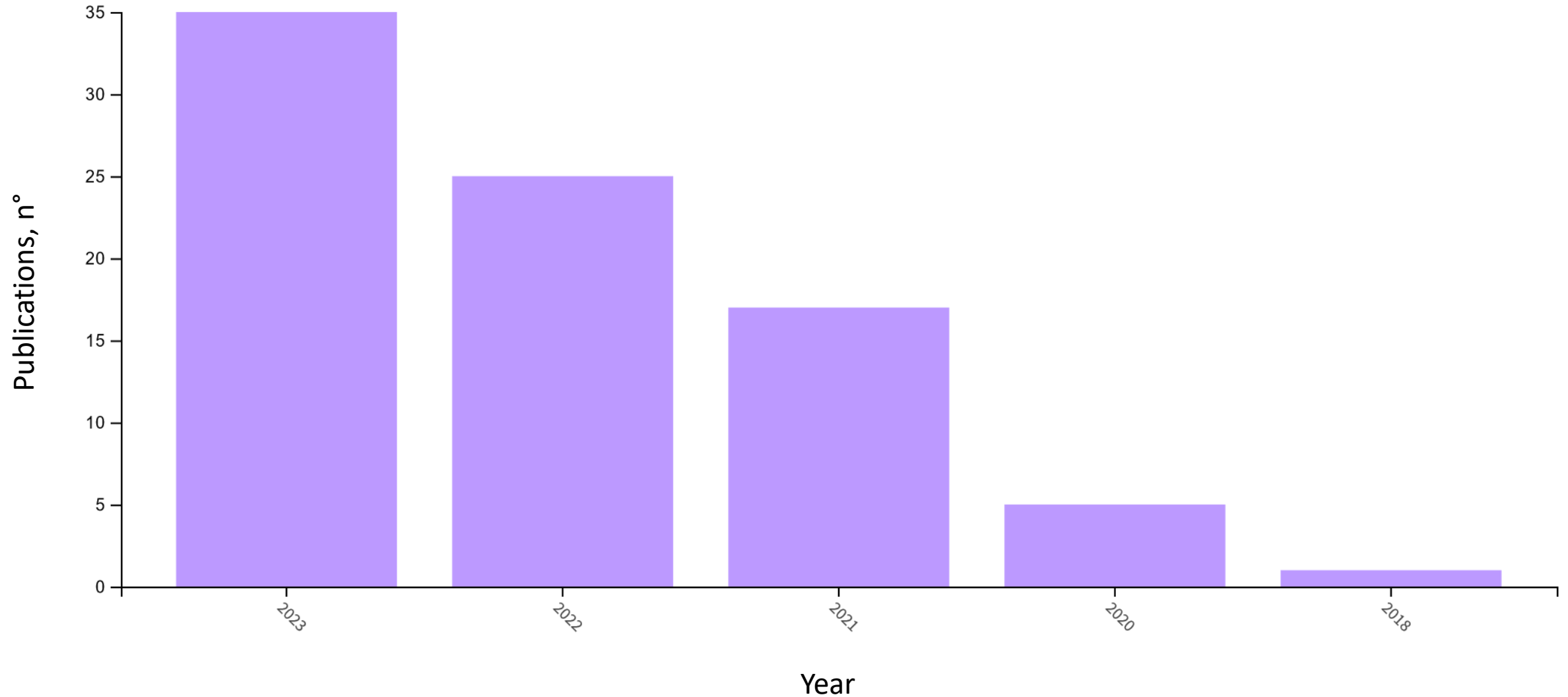
# 1 Introduction | Productivity WoS, area

“HEAs and electrocatalysis”



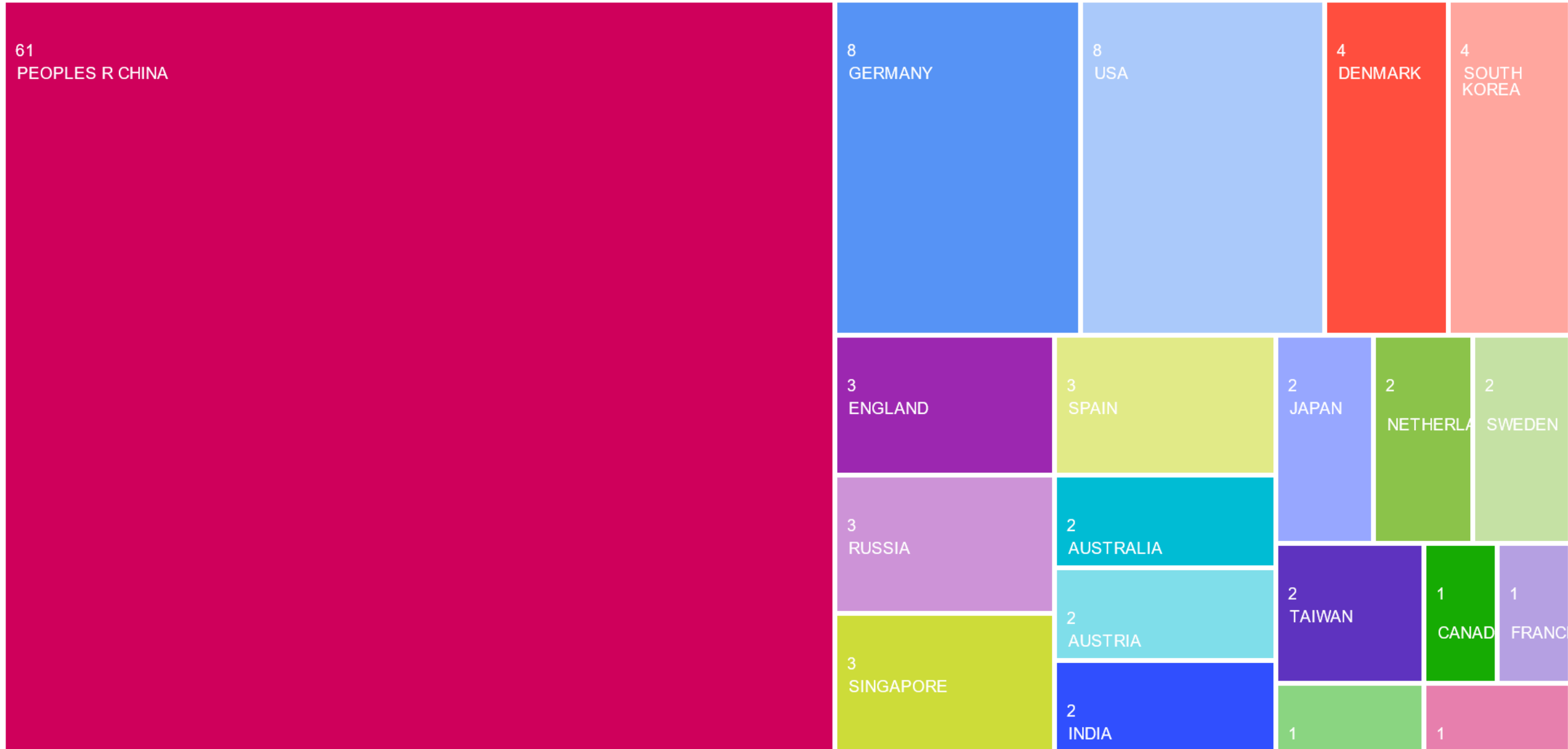
# 1 Introduction | Productivity WoS, year

“HEAs and electrocatalysis”

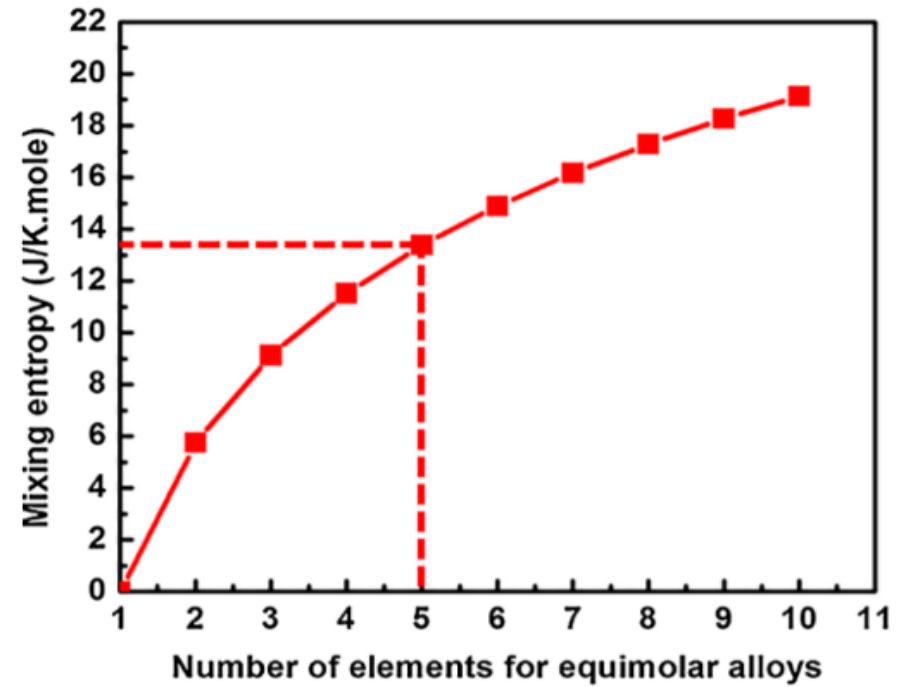
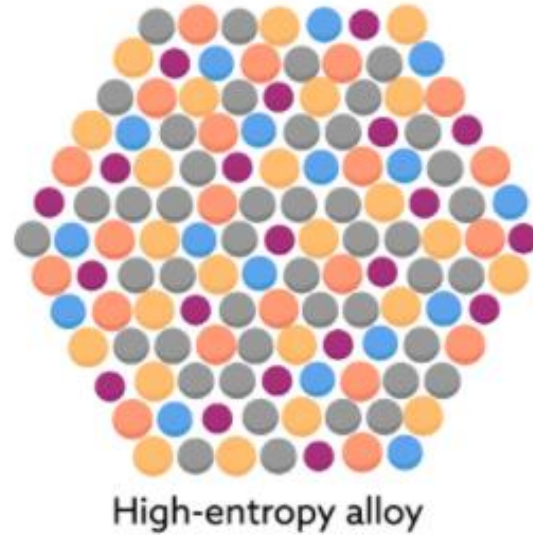
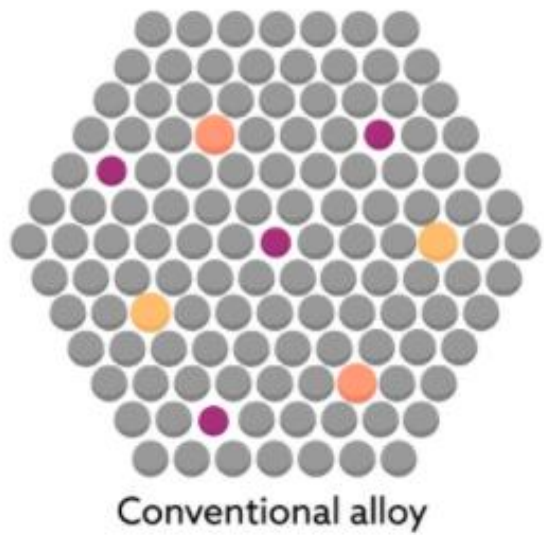


# 1 Introduction | Productivity WoS, country

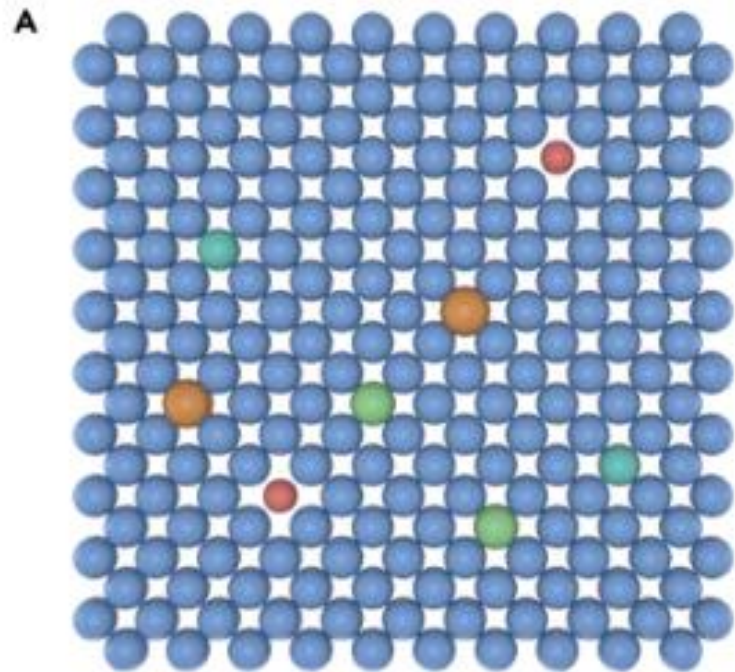
“HEAs and electrocatalysis”



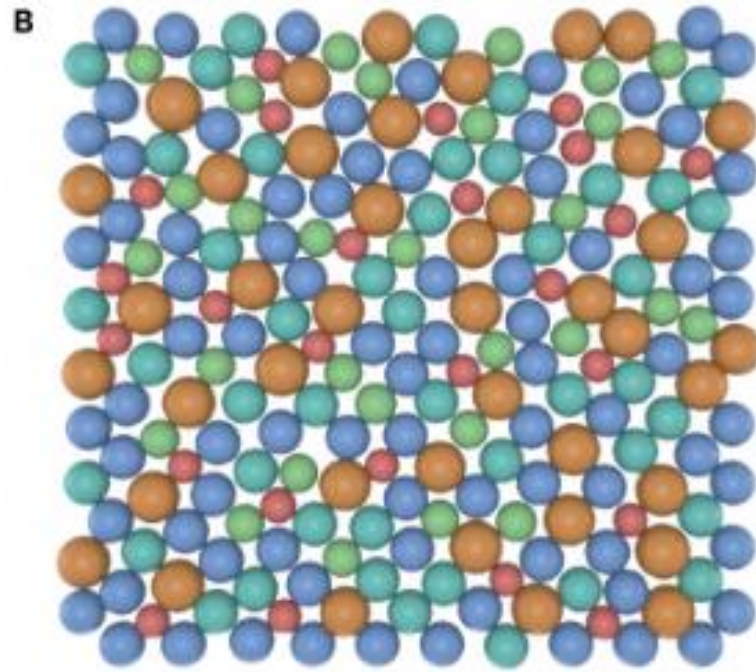
# 1 Introduction | High entropy alloys



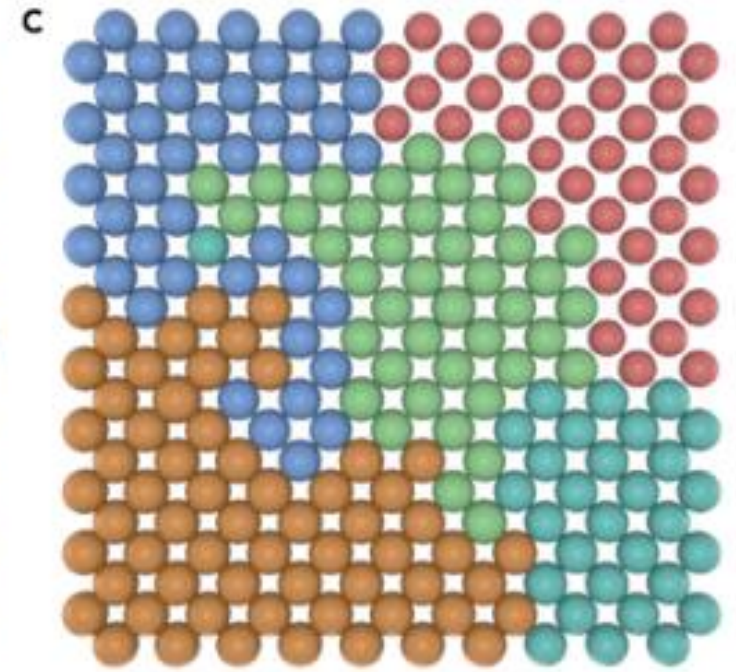
# 1 Introduction | High entropy alloys



**Traditional alloy**

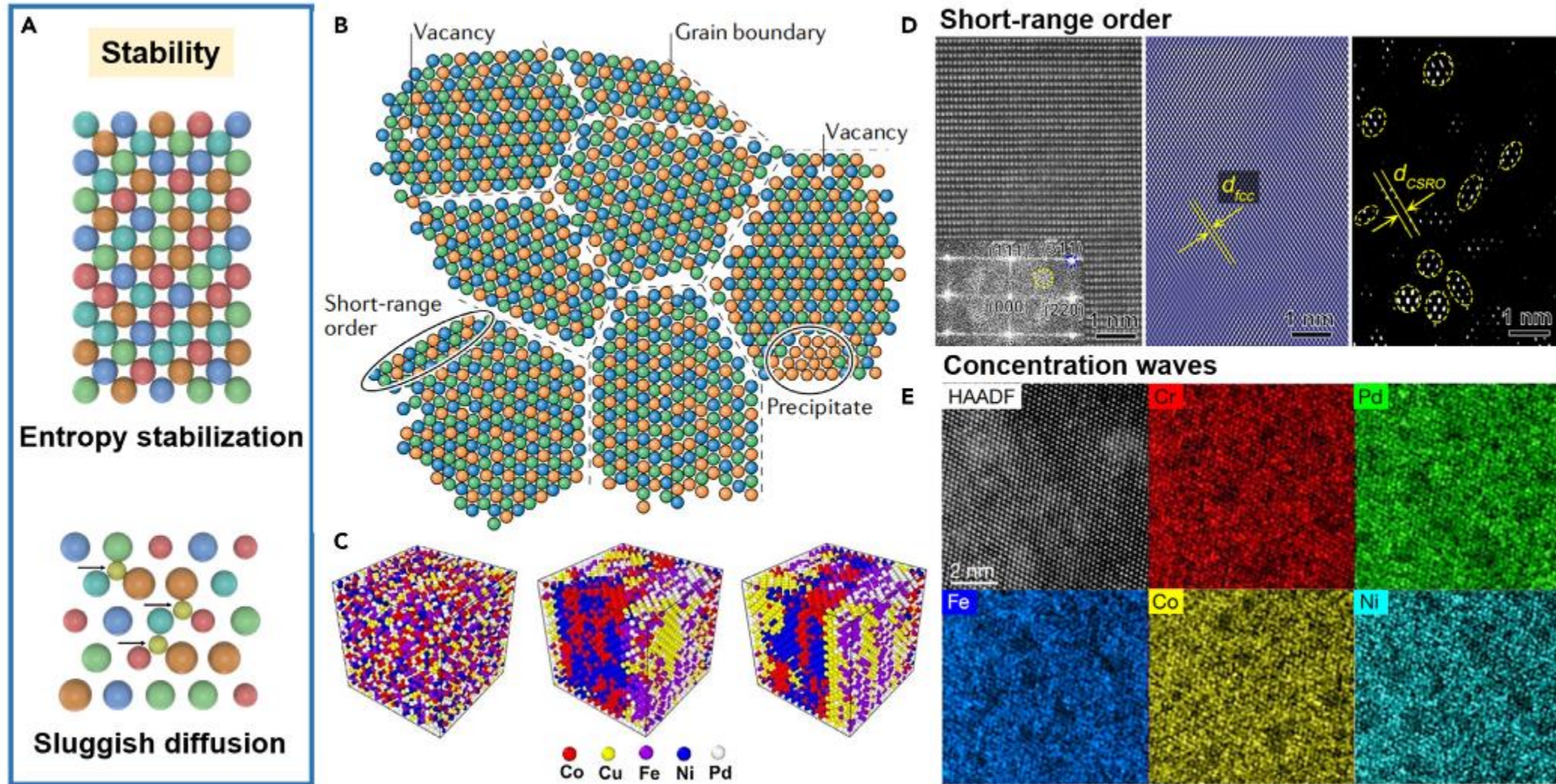


**High entropy alloy**



**Phase-separated heterostructure**

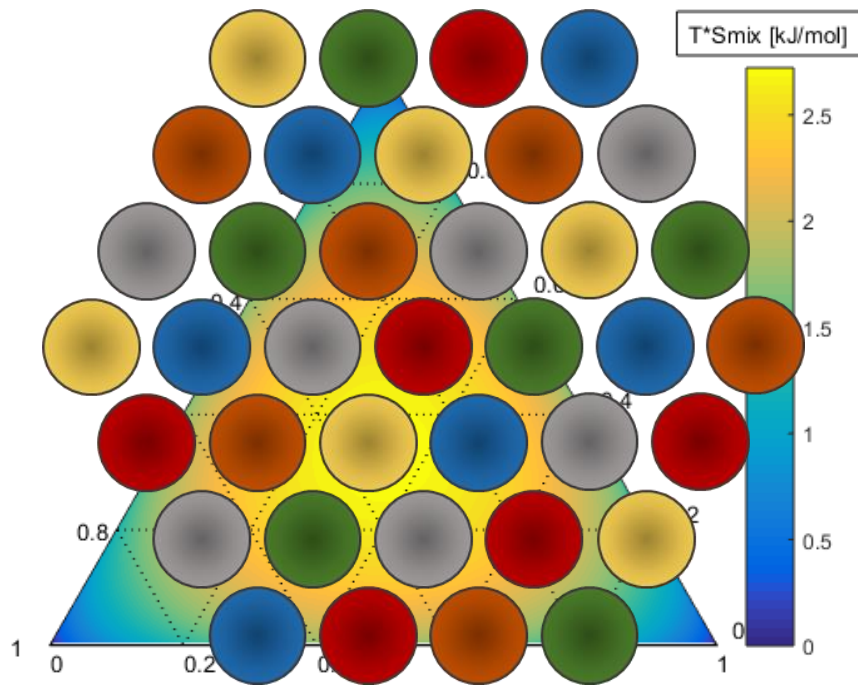
# 1 Introduction | High entropy alloys



# 1 Introduction | High entropy alloys

$$\Delta G = \Delta H - T\Delta S$$

$$\Delta S_{\text{mix}} = -R \sum_{i=1}^N x_i \ln x_i$$



*Solución sólida de seis componentes. Superficie de entropía de mezcla en sistema ternario.*

$$\uparrow \Delta S_{\text{mix}} \rightarrow \downarrow \Delta G_{\text{mix}}$$

Solid  
solution

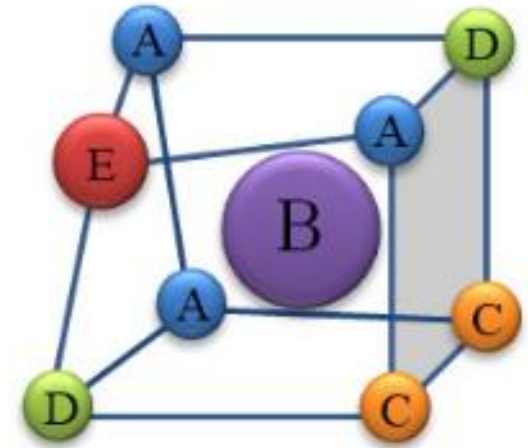
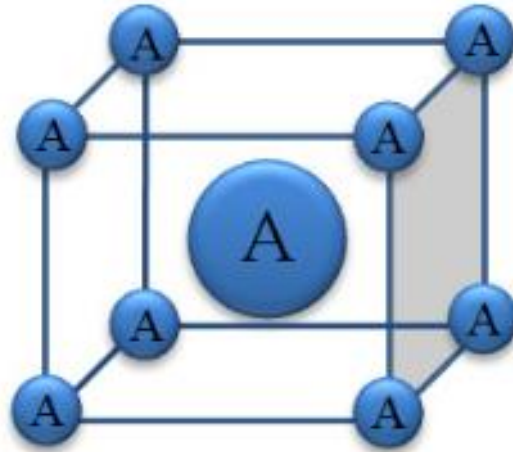
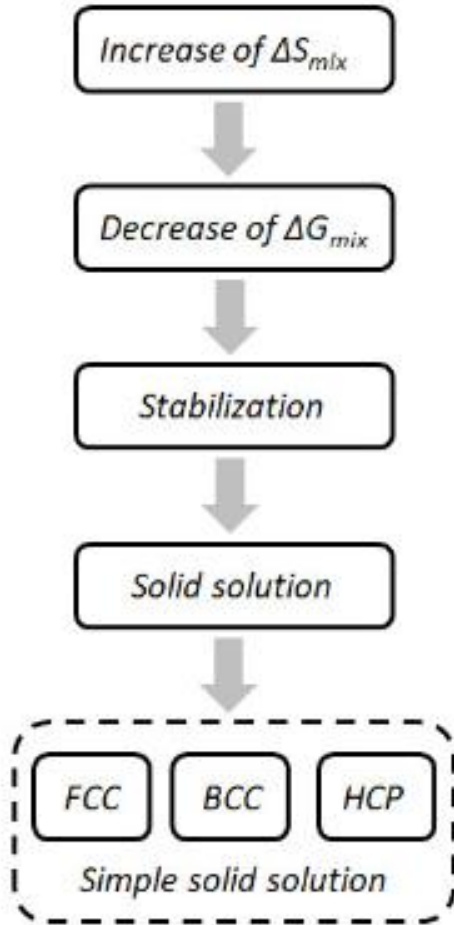
>

Intermetallic  
compounds

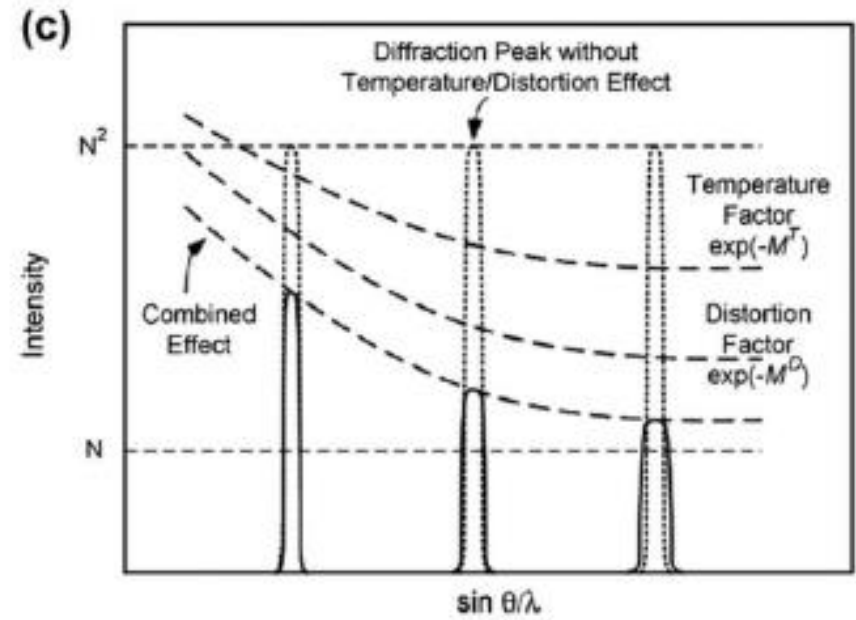
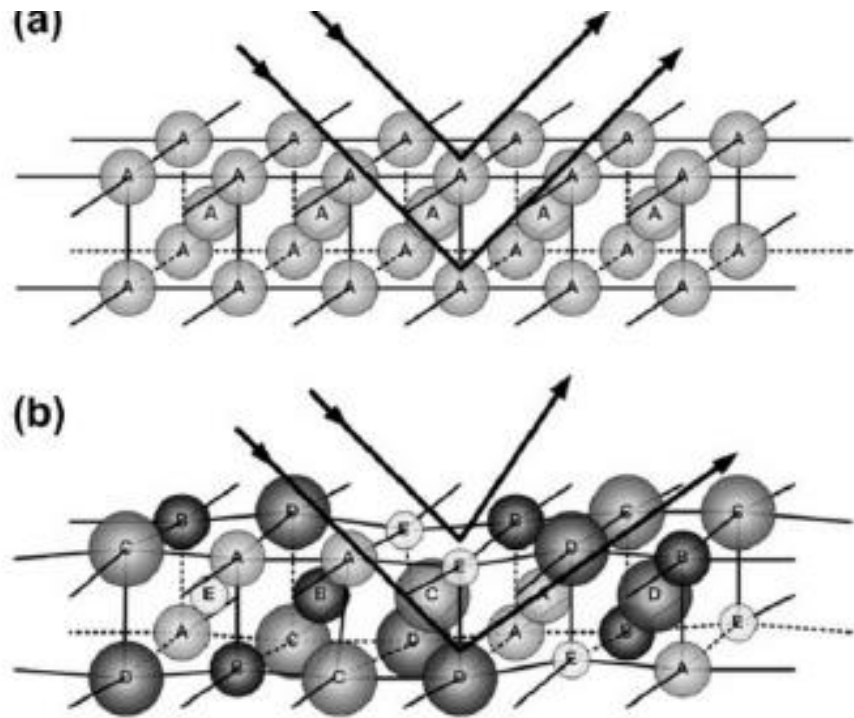
$$(1) \quad n \geq 5 \quad \wedge \quad 5\% \text{ at} \leq x_n \leq 35\% \text{ at}$$

$$(2) \quad \Delta S_{\text{mix}} \geq 1.6R$$

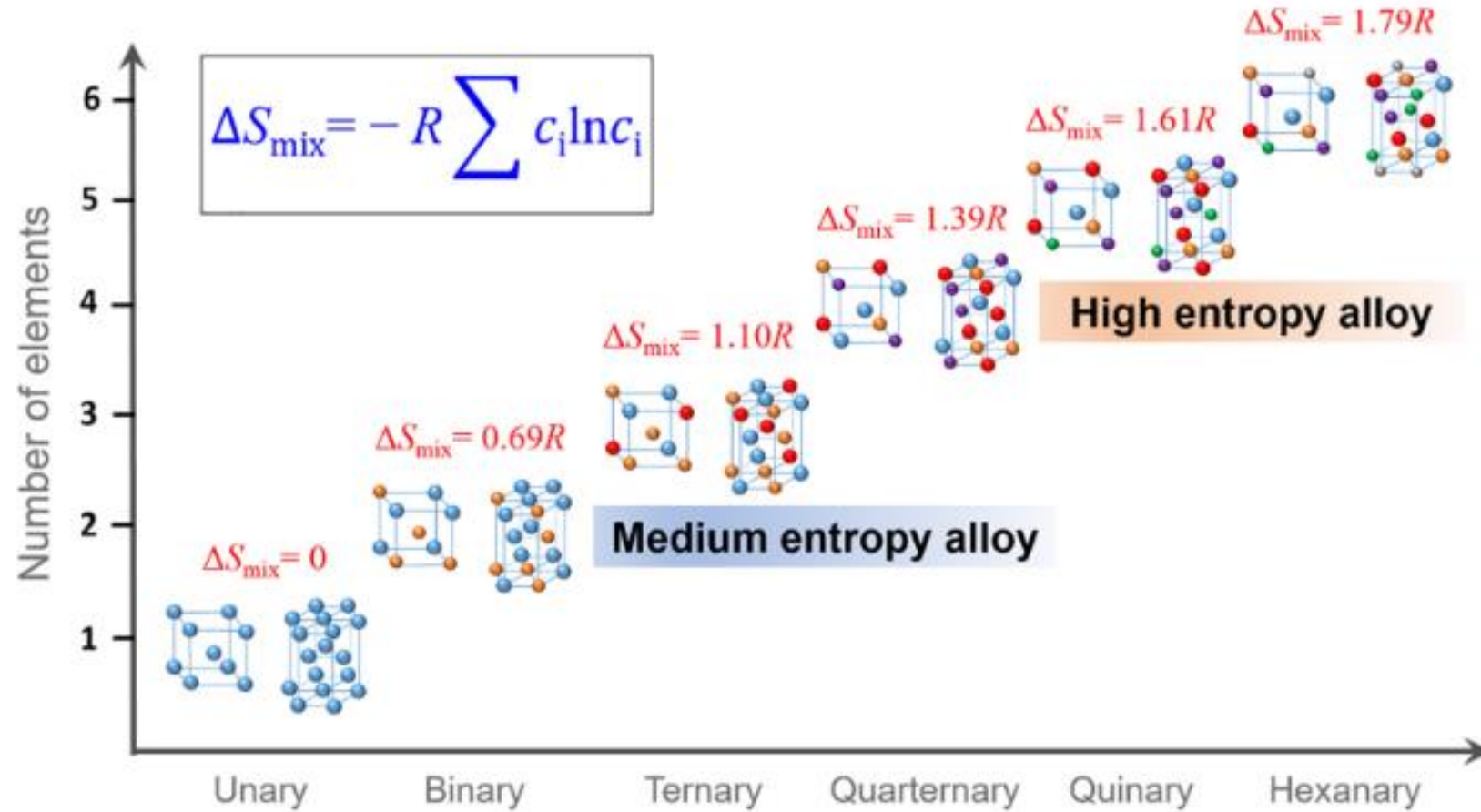
# 1 Introduction | High entropy alloys



# 1 Introduction | High entropy alloys



# 1 Introduction | High entropy alloys



# 1 Introduction | High entropy alloys

$$\Omega = \frac{T_m \Delta S_{mix}}{|\Delta H_{mix}|}$$
$$\delta = \sqrt{\sum \left(1 - \frac{d_i}{\bar{d}}\right)^2}$$

$$VEC = \frac{1}{n} \sum VEC_i$$

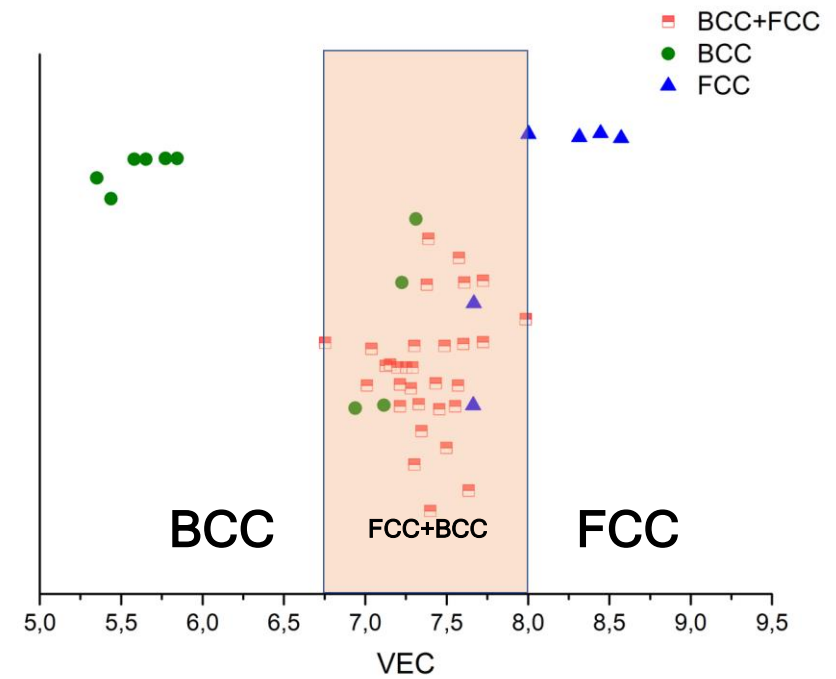
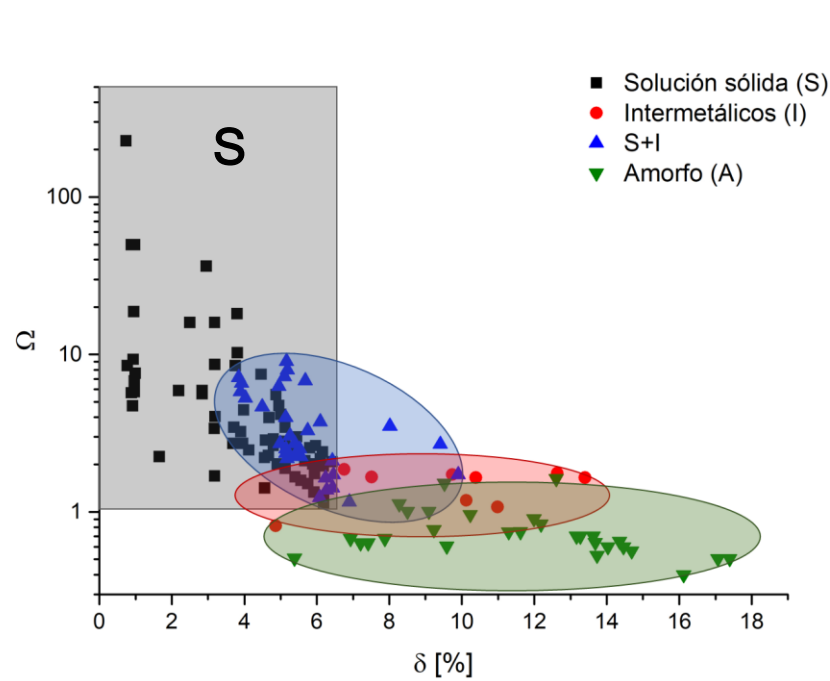
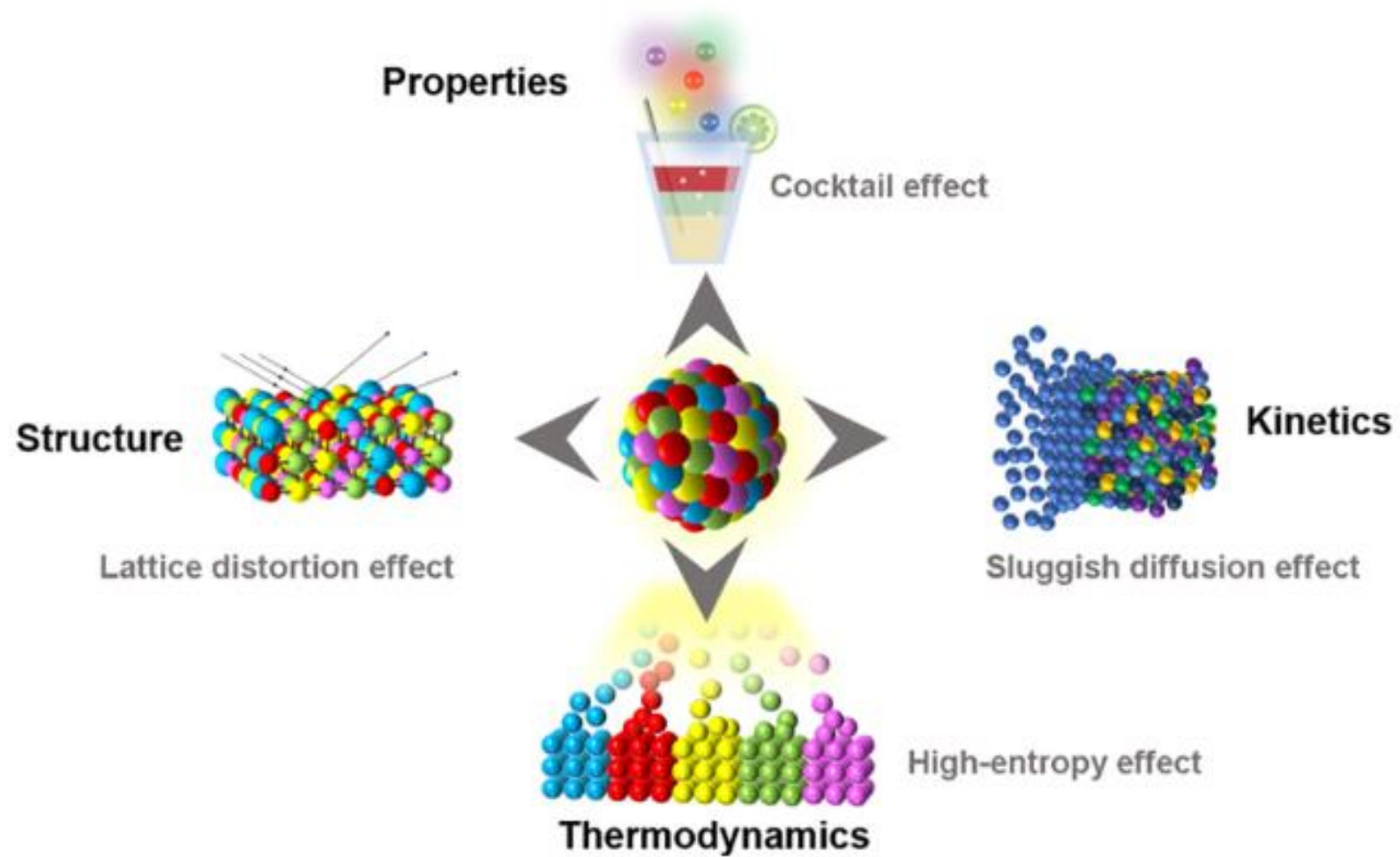
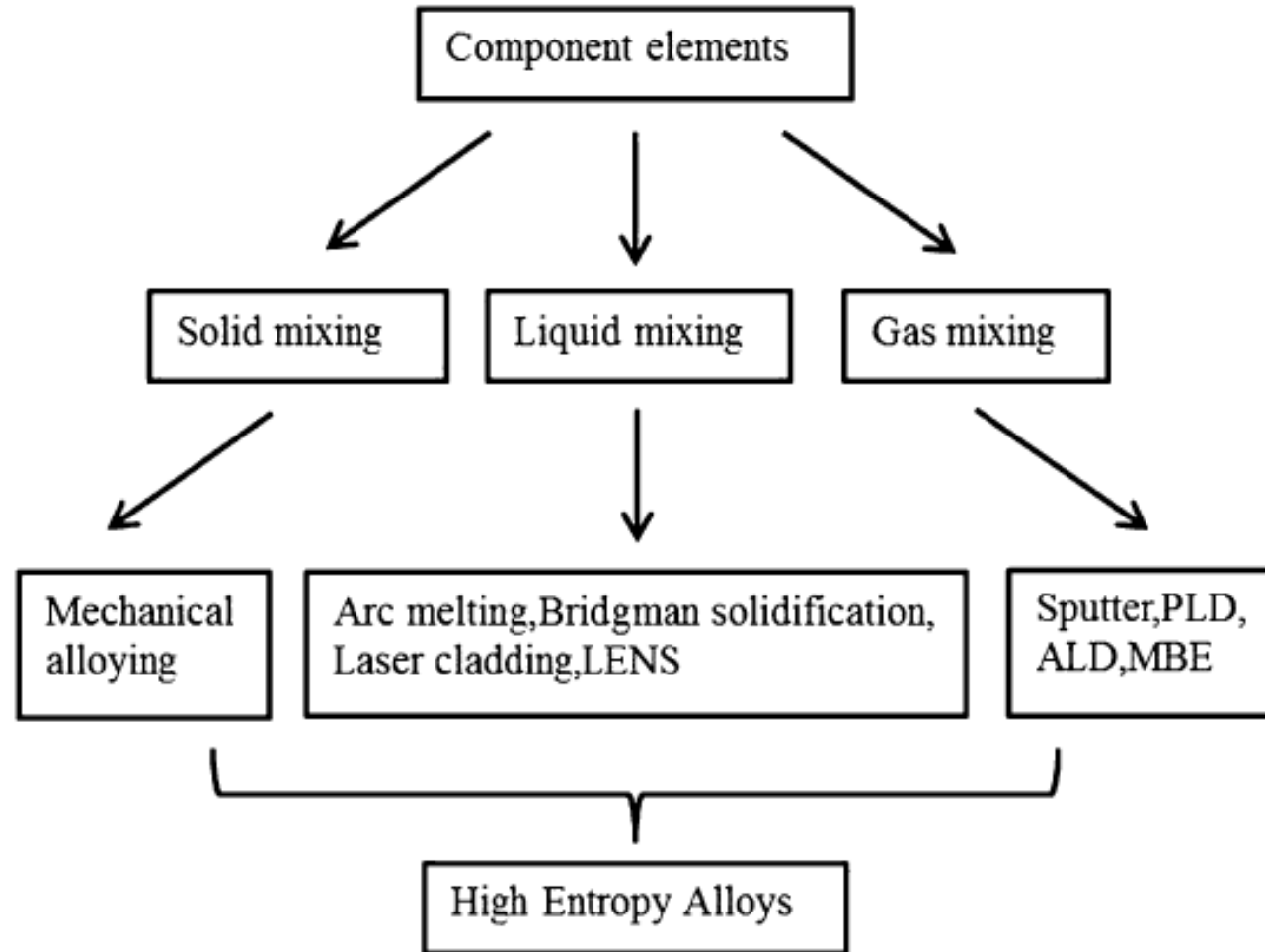


Grafico  $\Omega$  vs  $\delta$  para aleaciones de alta entropía. Fuente: Gao et al. 2016 (Izquierda)  
Gráfica VEC para aleaciones de alta entropía. Fuente: Gao et al. 2016 (Derecha).

# 1 Introduction | High entropy alloys



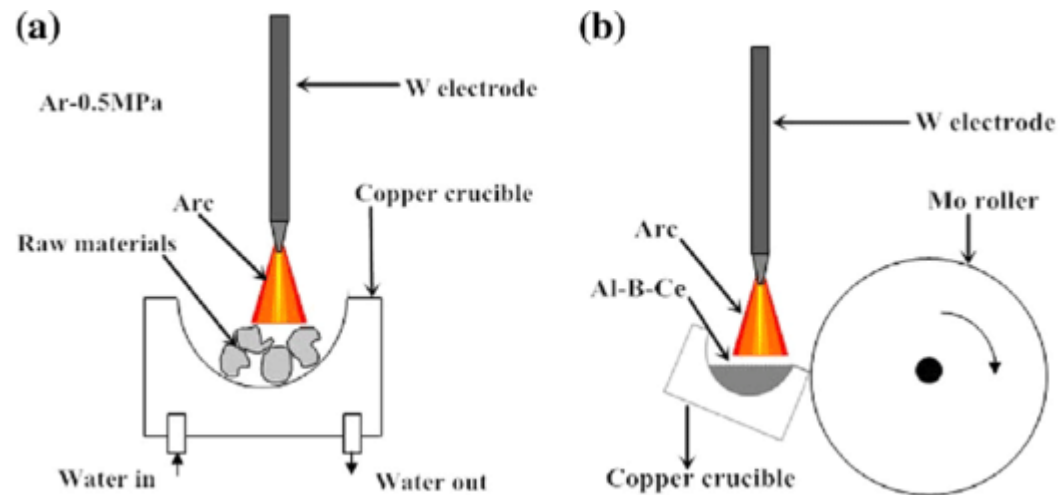
## 2 Synthesis | High entropy alloys | Synthesis



# 2 Synthesis | High entropy alloys | Arc melting

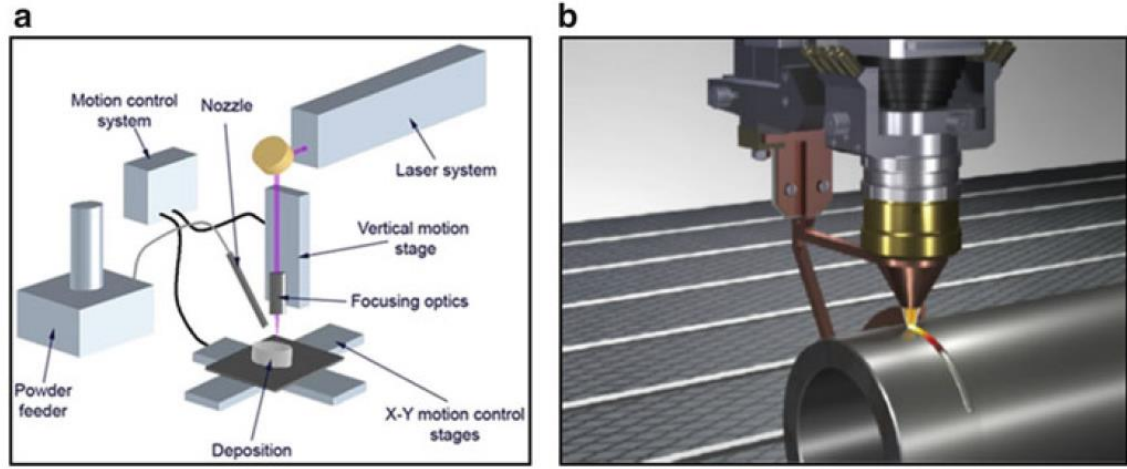


Gao et al. High entropy alloys, Springer, 2016

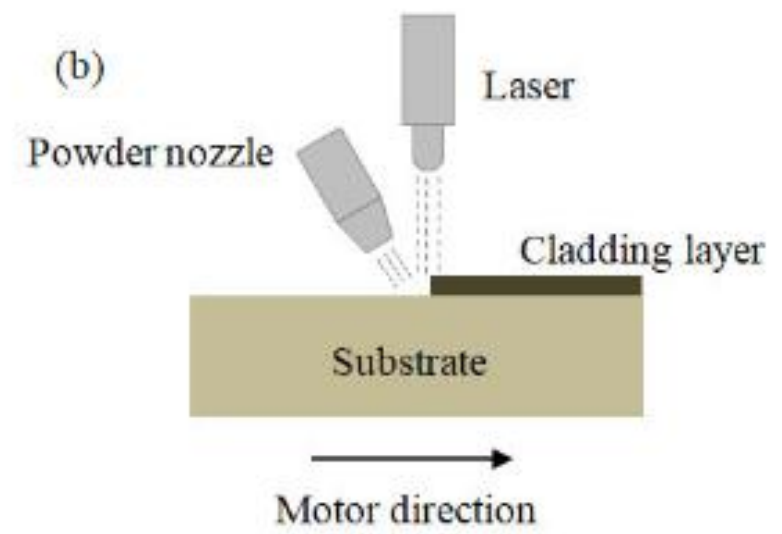
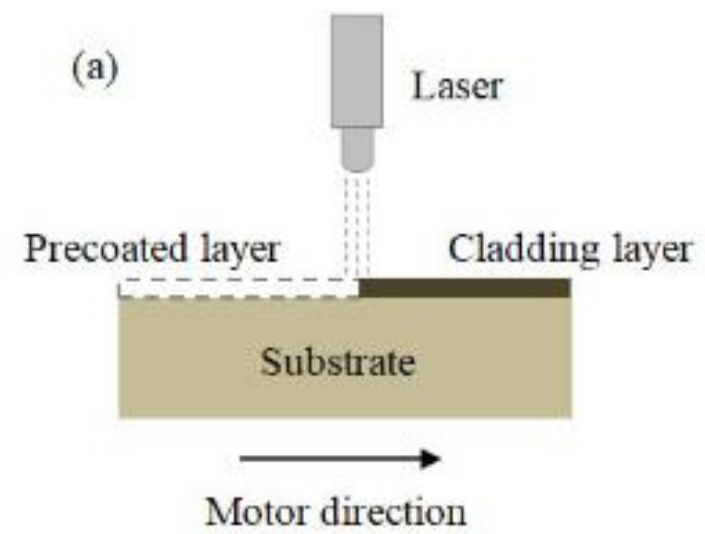


Liu et al. Materials & Design (1980-2015) 65:432-437

# 2 Synthesis | High entropy alloys | Laser Cladding

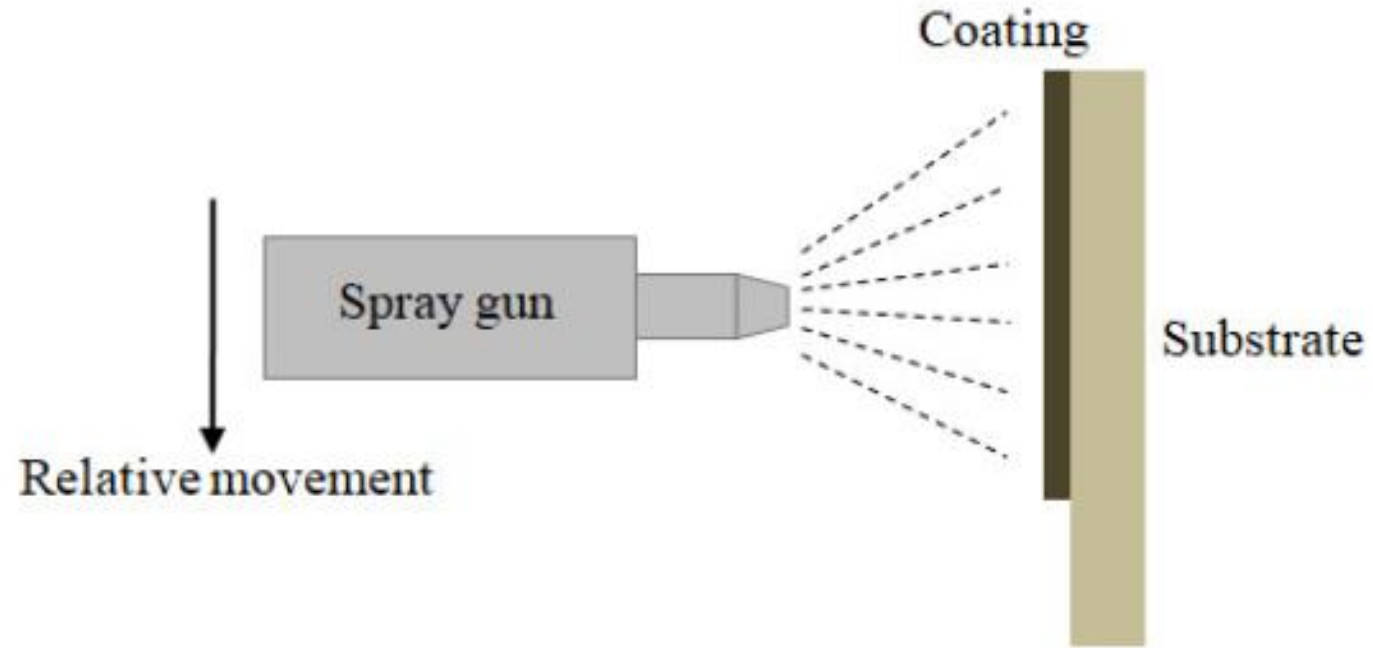


Gao et al. High entropy alloys, Springer, 2016

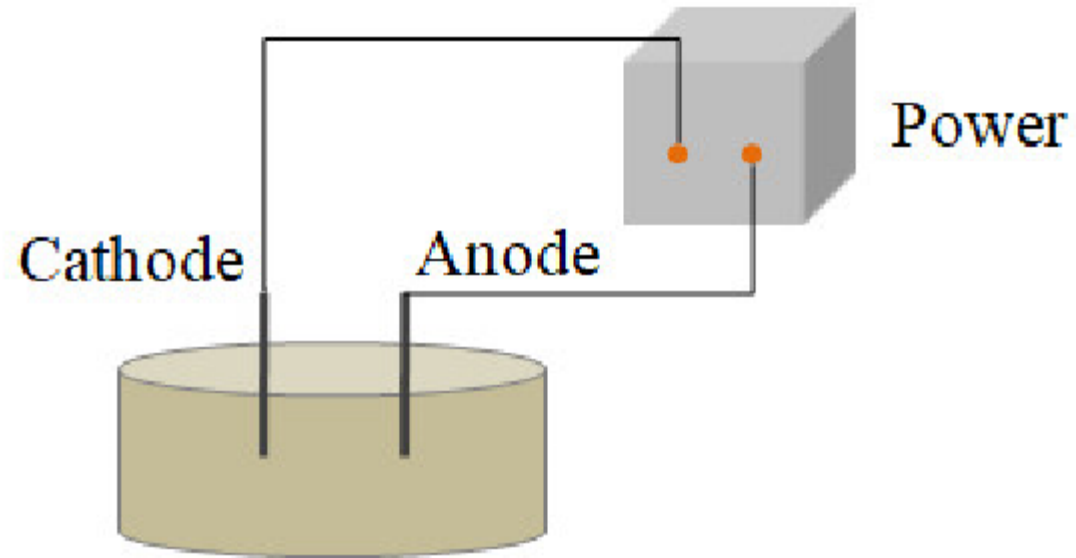


Wang et al. Coating, 2023, 13, 191

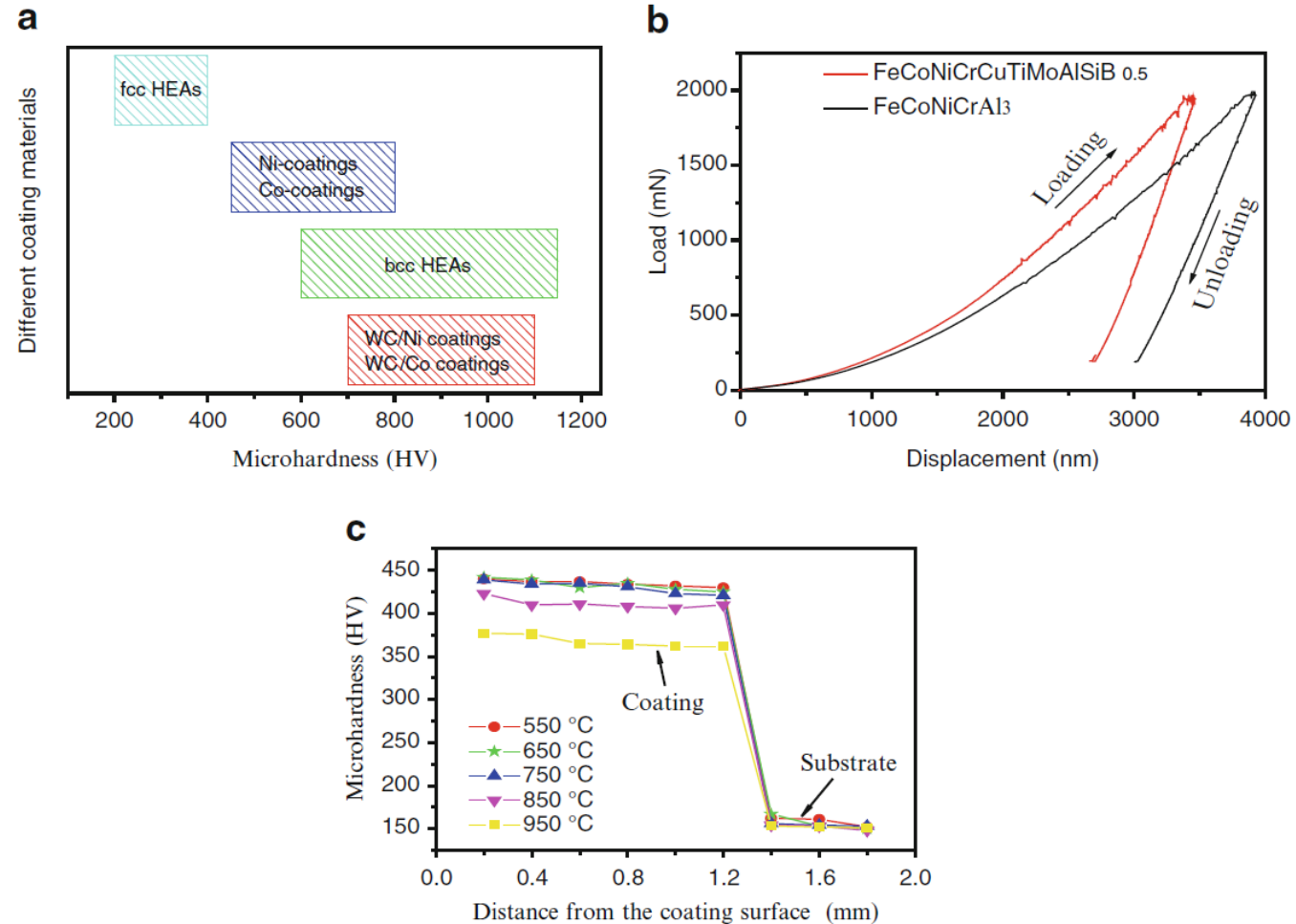
## 2 Synthesis | High entropy alloys | Thermal spraying



## 2 Synthesis | High entropy alloys | Electrochemical deposition

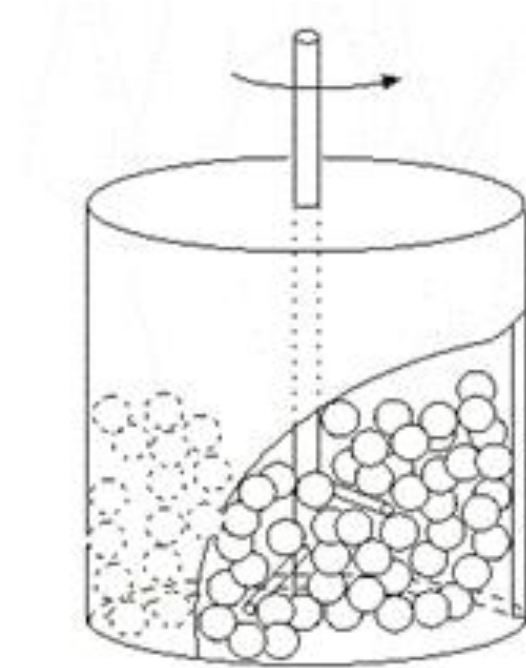
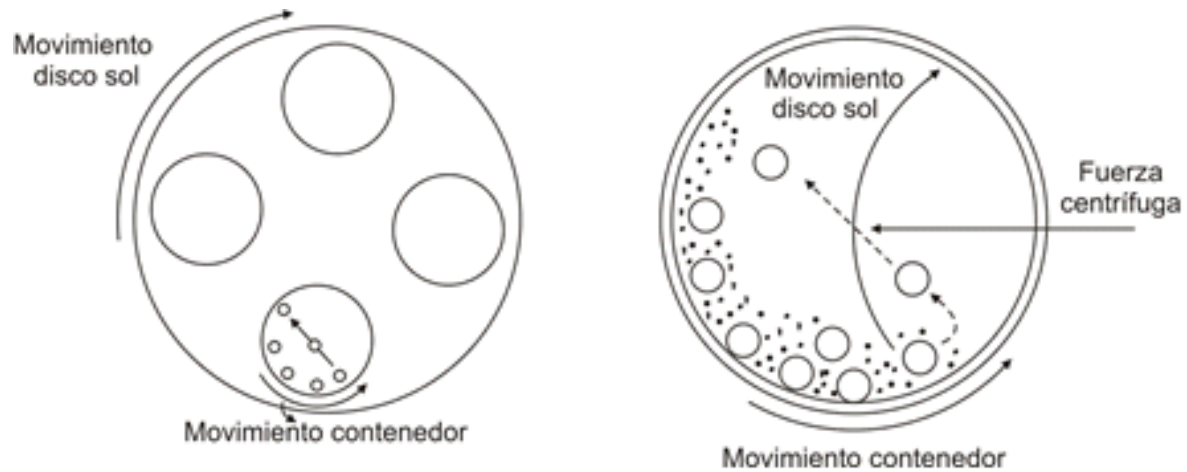
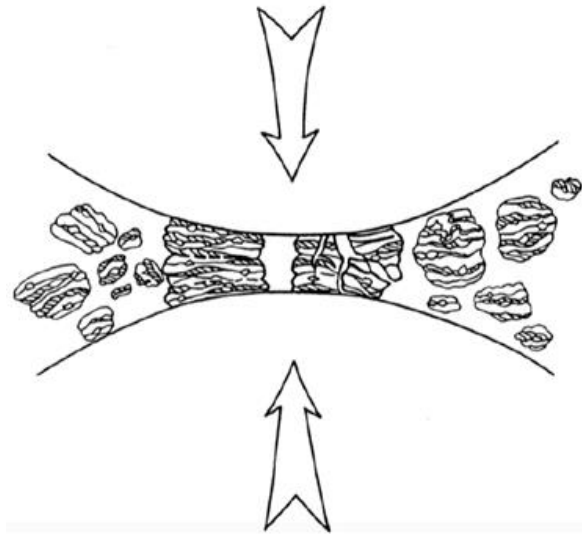


# 2 Synthesis | High entropy alloys | Laser Cladding



**Fig. 5.13** Hardness of the HEA coatings. **(a)** Comparison of the hardness in different coating materials [18, 24]. **(b)** The nanoindentation curves [40]. **(c)** Effect of annealing treatment on the hardness in the CoCrCuFeNi coating [24]

# 2 Synthesis | High entropy alloys | Powder metallurgy



## 2 Synthesis | High entropy alloys | PVD

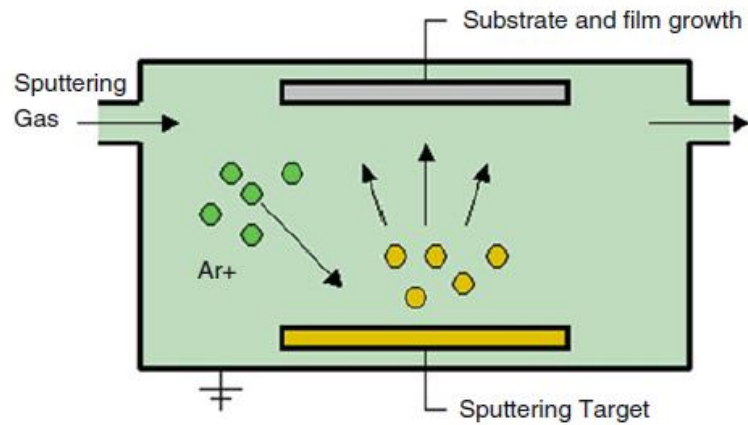


Fig. 5.17 A schematic showing the processing of sputtering deposition [46]

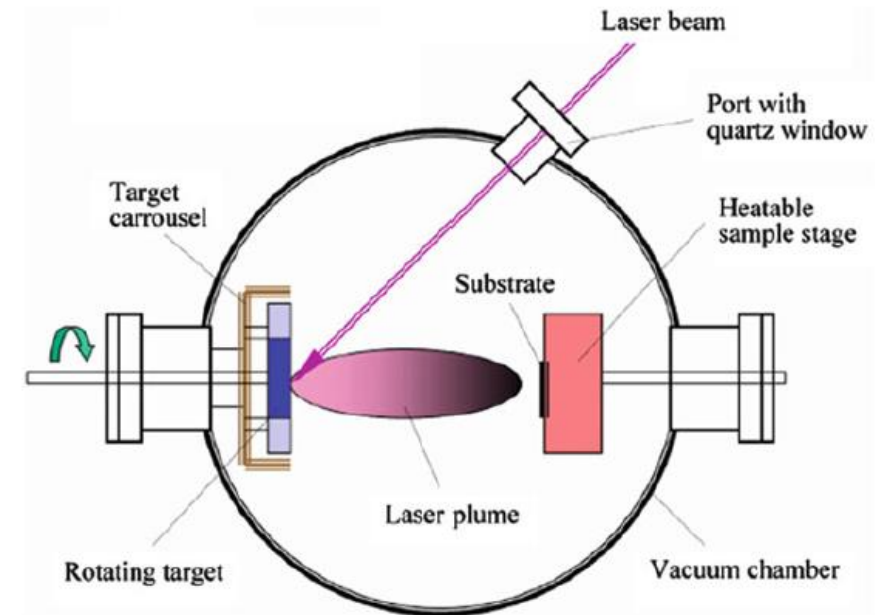
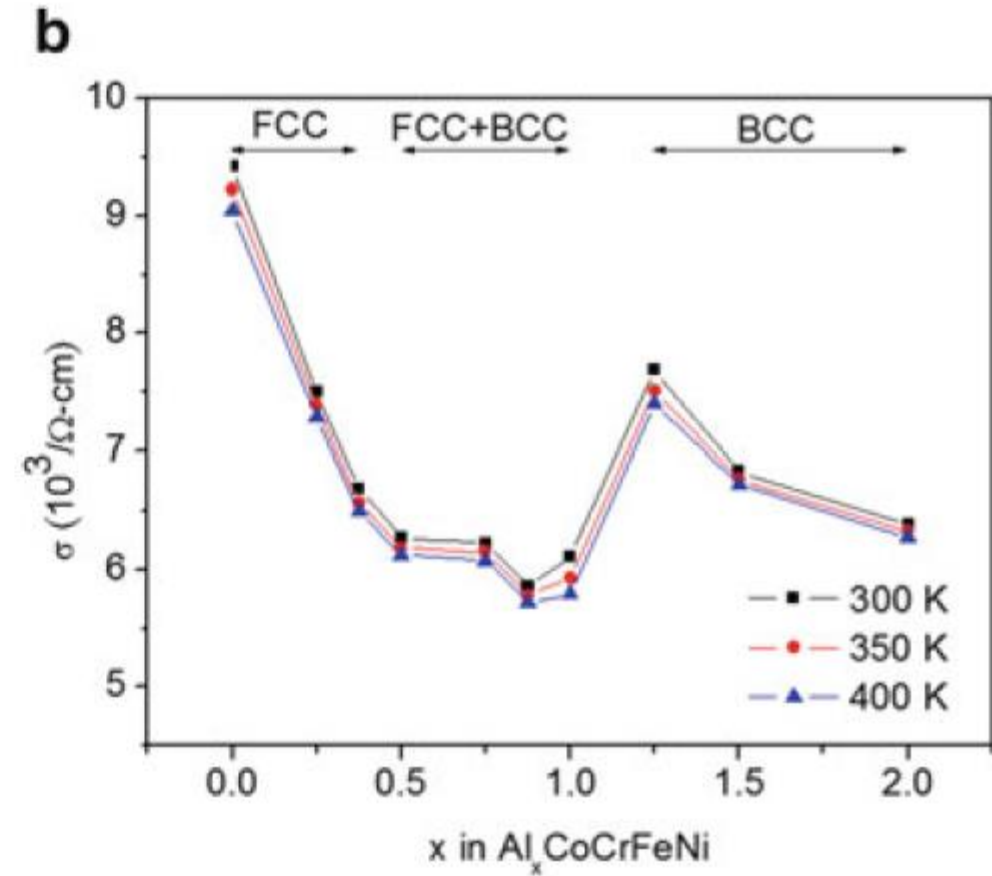
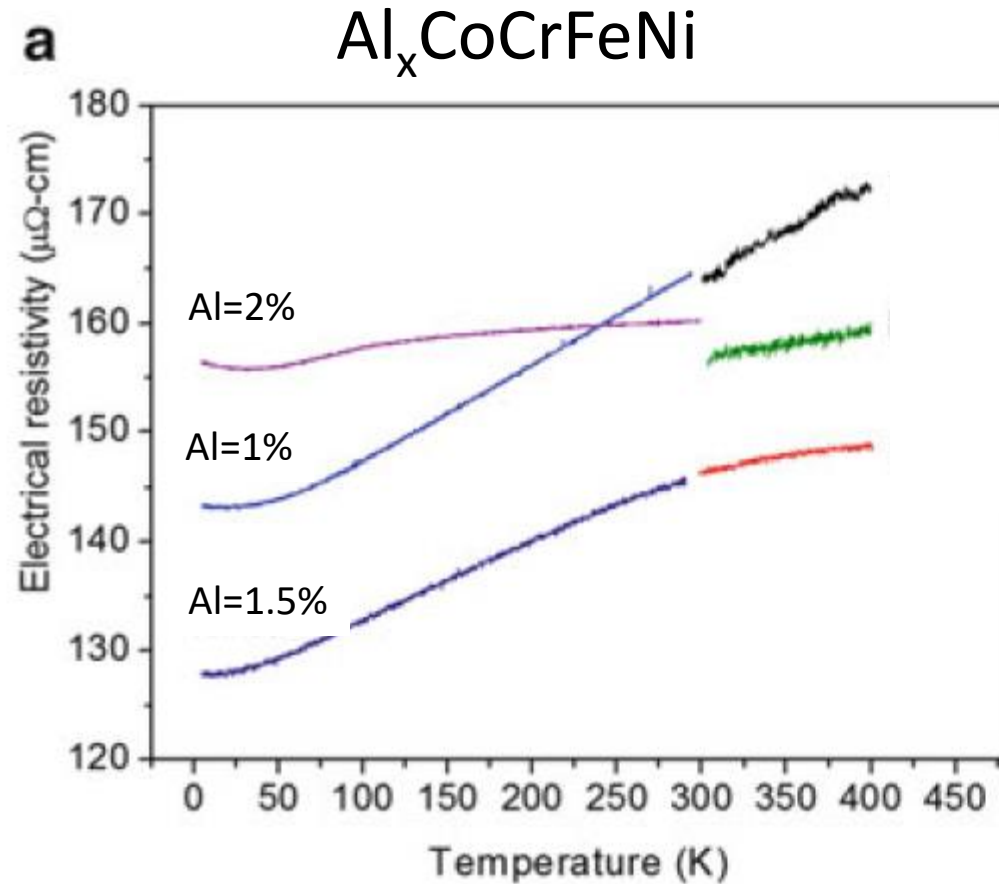


Fig. 5.18 A schematic showing the processing of pulse laser deposition [52]

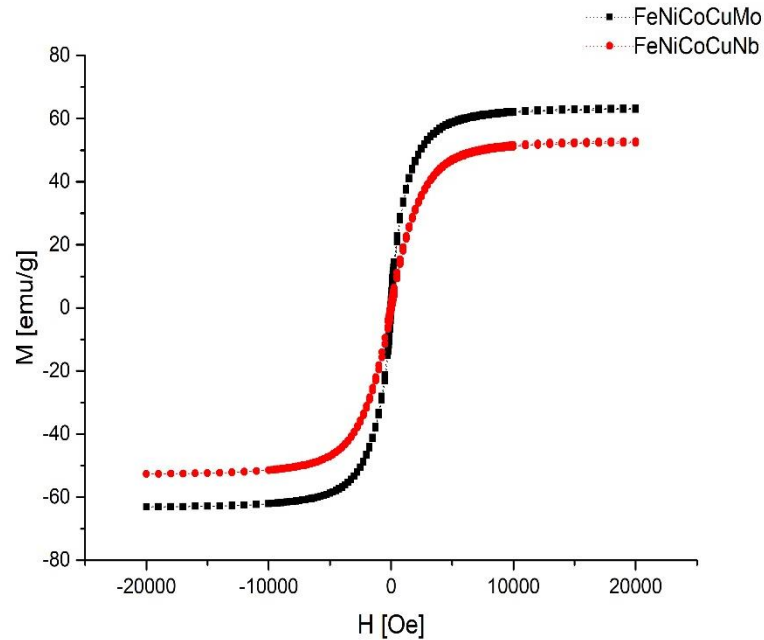
## 2 Synthesis | High entropy alloys | Electrochemical deposition

Preparation Methods	Characteristics
Melting-casting method	The melting temperature is high, and it can be melted many times. The melt is mixed evenly, and the low melting point impurities are volatile.
Mechanical alloying method	The particle size can be controlled and the mechanical properties can be effectively controlled.
Laser cladding	It can rapidly solidify, inhibit the precipitation of intermetallic compounds and promote the nucleation of solid solution.
Magnetron sputtering	The sputtering power can affect the grain size, change the film composition and control the film thickness.
Thermal spray technology	The coating is dense and smooth, the mechanical occlusion between the coating and the substrate is good and the interface bonding is good.
Electrochemical deposition method	The structure of the deposited layer can be accurately controlled, the equipment is simple, the energy consumption is low and the operation is easy.

# 3 Properties | High entropy alloys | Electrical resistivity

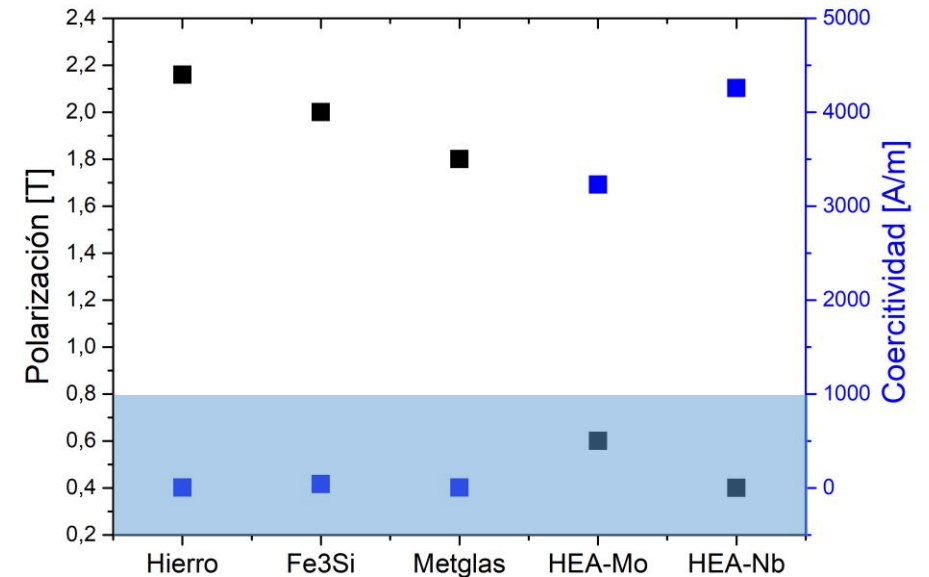


# 3 Properties | High entropy alloys | Magnetic properties



FeNiCoCuMo (HEA-Mo)  
 FeNiCoCuNb (HEA-Nb)

Hysteresis curve of sintered test samples of HEA-Mo and HEA-Nb

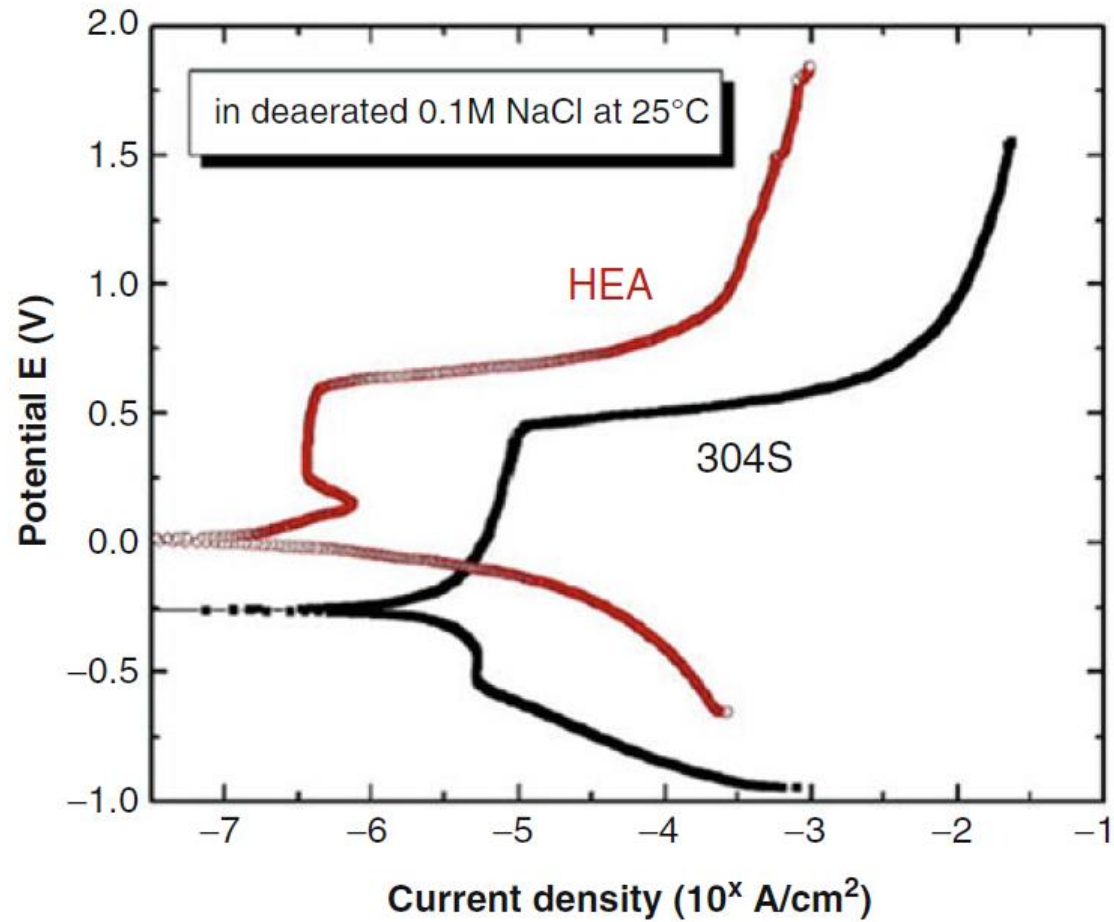


Polarization and coercivity of main soft magnetic materials and HEA

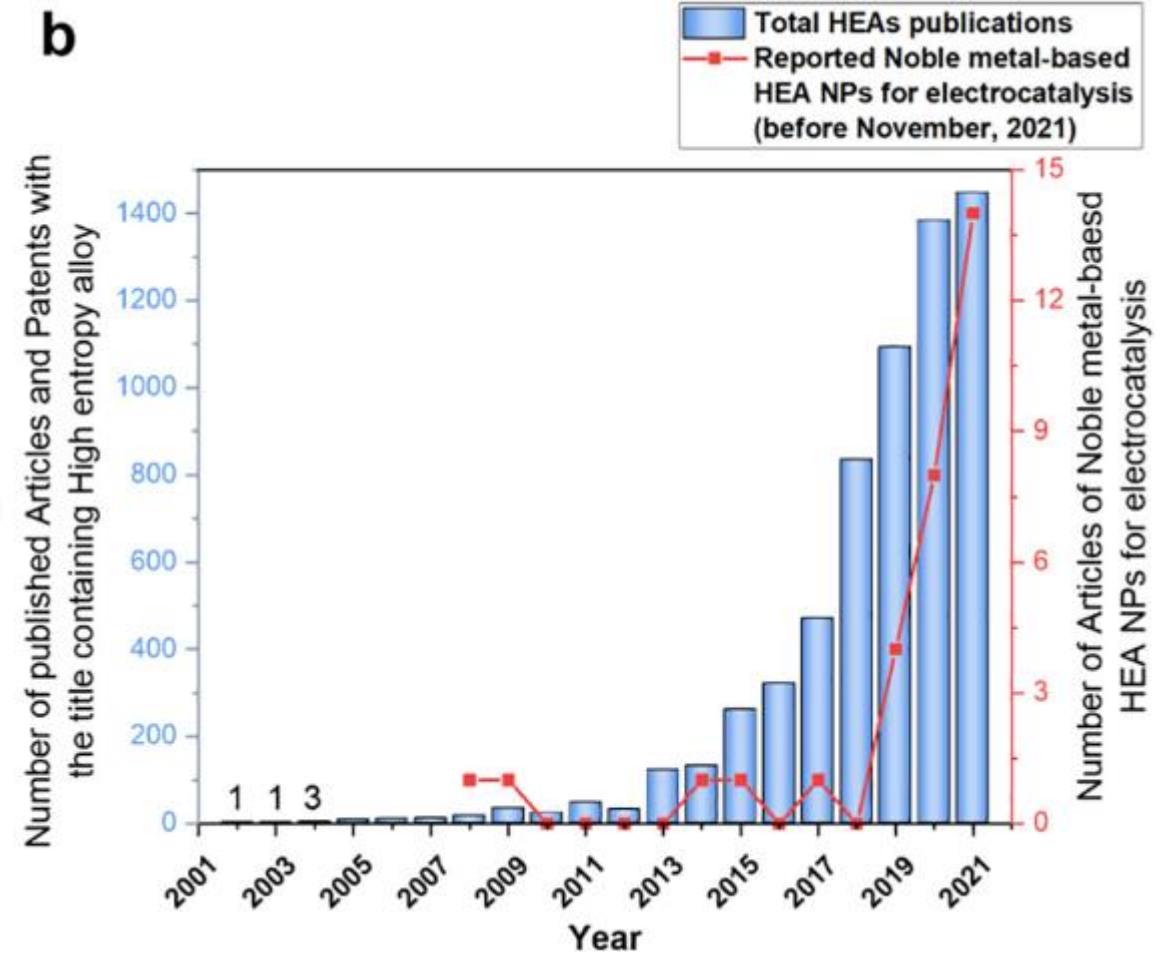
*Propiedades magnéticas de HEA-Mo y HEA-Nb*

Property	HEA-Mo	HEA-Nb
Ms [emu/g]	62.63	53.27
Mr [emu/g]	2.51	1.17
Mr/Ms [%]	4	2.2
Hc [Oe]	40.69	53.49
Hc [A/m]	3230	4256

### 3 Properties | High entropy alloys | Electrochemical properties



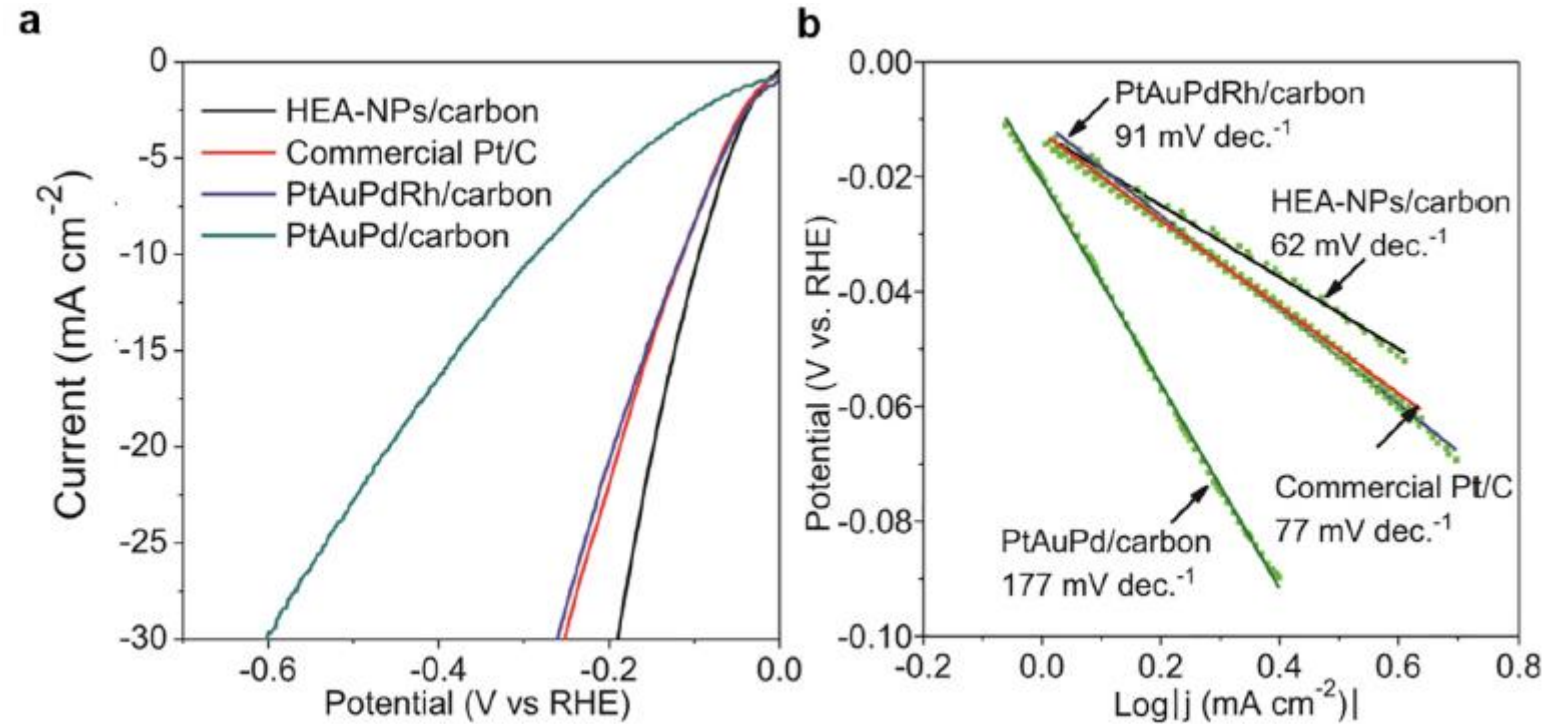
# 3 Properties | High entropy alloys | Electrocatalysis properties



# 3 Properties | High entropy alloys | Electrocatalysis properties-WS

Hydrogen evolution reaction (HER)

- PtAuPdRh
- PtAuPdRhRu
- PtAuPd-NPs
- IrPdPtRhRu HEA-NPs
- PtAuPdRhRu HEA-NPs
- FeCoPdIrPt HEA-NPs
- NiCoFePtRh HEA-NPs
- PdFeCoNiCu HEA-NPs
- FeCoNiCrMo HEA-MPs



(a) Polarization curves and (b) Tafel plots of PtAuPdRhRu HEA-NPs/carbon-700 C, PtAuPdRh/carbon-700 C, PtAuPd/carbon-700 C, and commercial Pt/C catalysts in 1.0 m KOH.

# 3 Properties | High entropy alloys | Electrocatalysis properties-WS

IrO<sub>2</sub> and RuO<sub>2</sub>



Oxygen evolution reaction (OER)

CoFeLaNiPt HEA-NPs

np-AlNiCoIrMo

np-AlNiCoIrCu

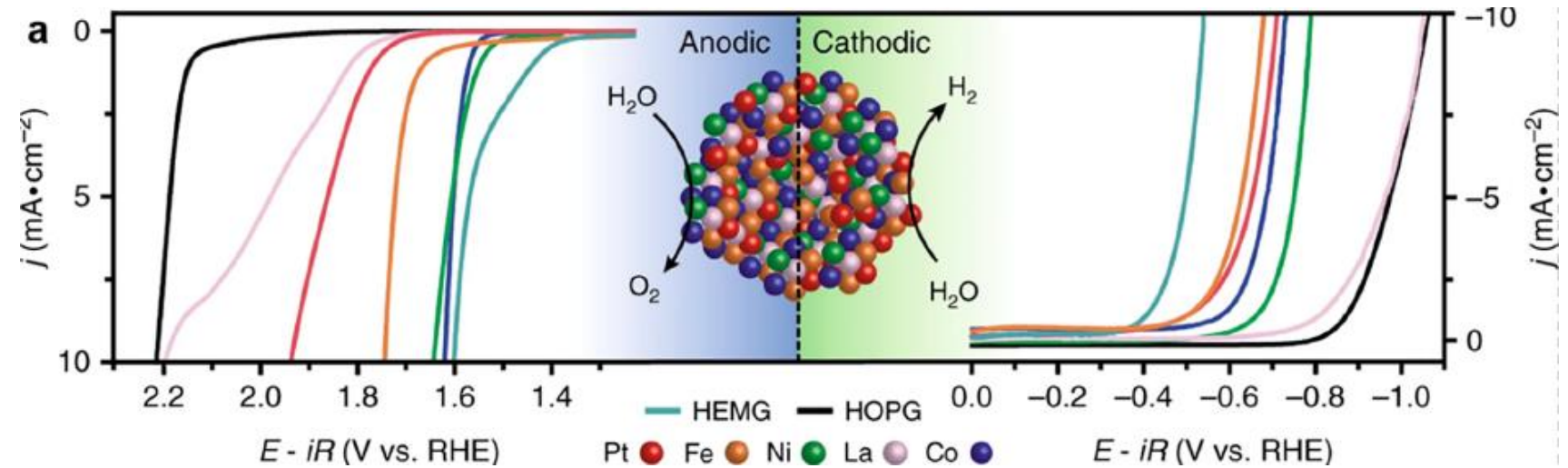
np-AlNiCoIrNb

Np-FeCoNiCrNb

FeCoNiXRu (X = Cu, Cr, and Mn)

MnFeCoNiCu HEA NPs

Np-MnFeCoNiCu



(a) Anodic polarization of the CoFeLaNiPt electrocatalyst and its individual components starting from the equilibrium potential of OER, 1.23 V vs. RHE. Reproduced

# 3 Properties | High entropy alloys | Electrocatalysis properties-WS

**Table 2. Electrocatalytic activity of representative HEAs electrocatalysts**

HER					
Electrocatalyst	Electrolyte	Current density ( $\text{mA cm}^{-2}$ )	Overpotential (mV)	Tafel slope ( $\text{mV dec}^{-1}$ )	Reference
NiCoFePtRh HEA nanoparticles	0.5 M $\text{H}_2\text{SO}_4$	10	27	30.1	Feng et al. <sup>60</sup>
PtNiFeCoCu HEAs nanoparticle	1.0 M KOH	10	11	30	Li et al. <sup>136</sup>
PdPtCuNiP HEMG	1.0 M KOH	10	32	37.4	Jia et al. <sup>95</sup>
	0.5 M $\text{H}_2\text{SO}_4$	10	62	44.6	
Nanoporous NiCoFeMoMn HEAs	1.0 M KOH	1000	150	29	Liu et al. <sup>138</sup>
OER					
Electrocatalyst	Electrolyte	Current density ( $\text{mA cm}^{-2}$ )	Overpotential (mV)	Tafel slope ( $\text{mV dec}^{-1}$ )	Reference
FeCoNiMnRu/CNFs	1.0 M KOH	100	308	67.4	Hao et al. <sup>137</sup>
FeCoNiRu/CNFs	0.5 M $\text{H}_2\text{SO}_4$	10	241	153	Zhu et al. <sup>139</sup>
FeCoNiMo/C	1.0 M KOH	10	250	48.02	Mei et al. <sup>140</sup>
Nanoporous AlNiCoFeX (X = Mo, Nb, Cr) HEAs	1.0 M KOH	10	240	46	Qiu et al. <sup>141</sup>
ORR					
Electrocatalyst	Electrolyte	Half-wave potential (V)	Mass activity ( $\text{A mg}_{\text{ noble metal}}^{-1}$ )	Tafel slope ( $\text{mV dec}^{-1}$ )	Reference
CoFeNiCuPd structure-ordered HEAs	0.1 M KOH	0.90	2.037 @ 0.9 V	55	Zhu et al. <sup>91</sup>
PtPdFeCoNi HEAs	0.1 M $\text{HClO}_4$	0.92	1.230 @ 0.9 V	–	Yu et al. <sup>17</sup>
Nanohollow PdCuMoNiCo HEAs	0.1 M $\text{HClO}_4$	0.86	0.882 @ 0.8 V	–	Zuo et al. <sup>142</sup>
HOR					
Electrocatalyst	Electrolyte	Mass activity ( $\text{A mg}_{\text{ noble metal}}^{-1}$ )	Reference		
PtRuNiCoFeMo HEA subnanometer nanowires	0.1 M KOH	6.75 @ 50 mV	Zhan et al. <sup>85</sup>		
CO <sub>2</sub> RR					
Electrocatalyst	Electrolyte	$\text{FE}_{\text{HCOOH max}}$	$\text{FE}_{\text{C1 max}}$	Potential	Reference
PdCuAuAgBiIn HEA aerogels	0.1 M $\text{KHCO}_3$	98.1%	100%	–1.1 V <sub>RHE</sub>	Zhan et al. <sup>85</sup>

# 3 Properties | High entropy alloys | Electrocatalysis properties-FC

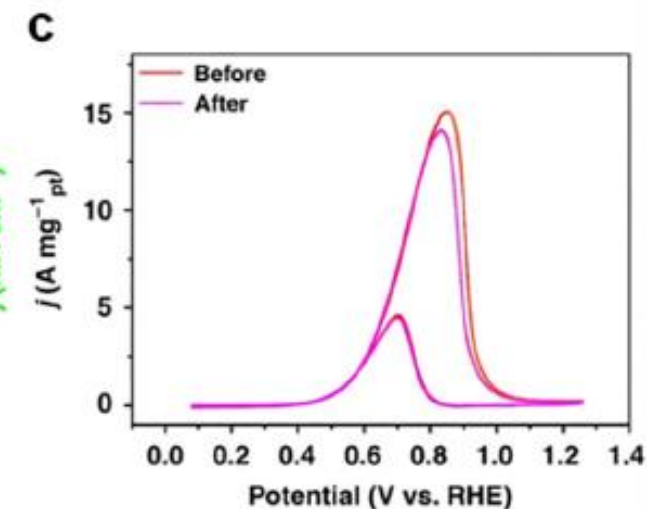
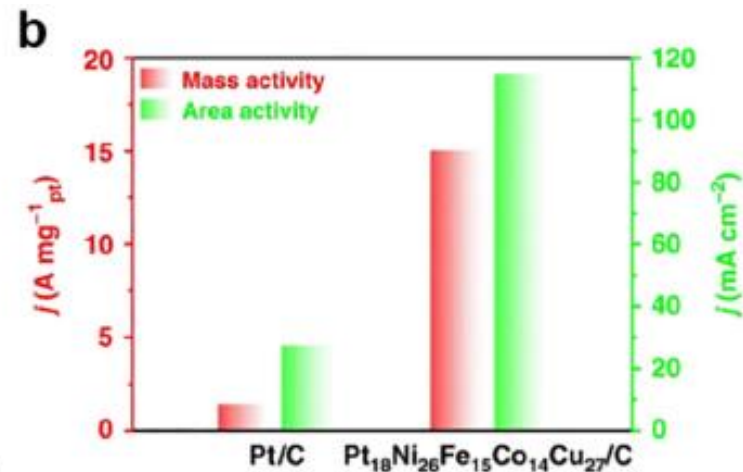
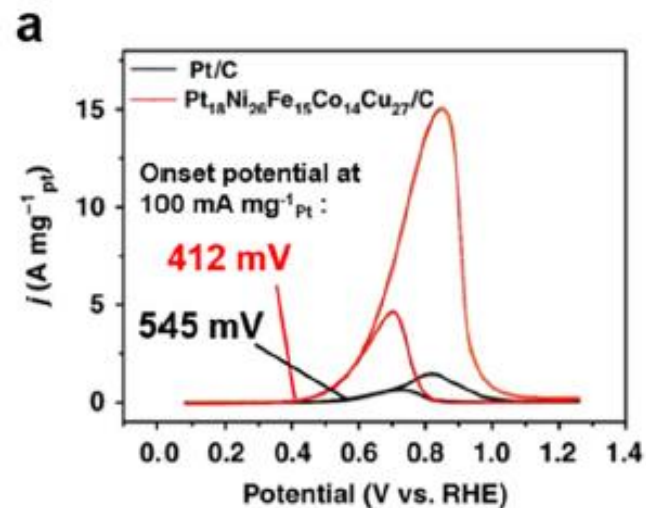
Methanol oxidation reaction

Pt<sub>50</sub>Fe<sub>11</sub>-Co<sub>10</sub>Ni<sub>11</sub>Cu<sub>10</sub>Ag<sub>8</sub> HEA-NPs

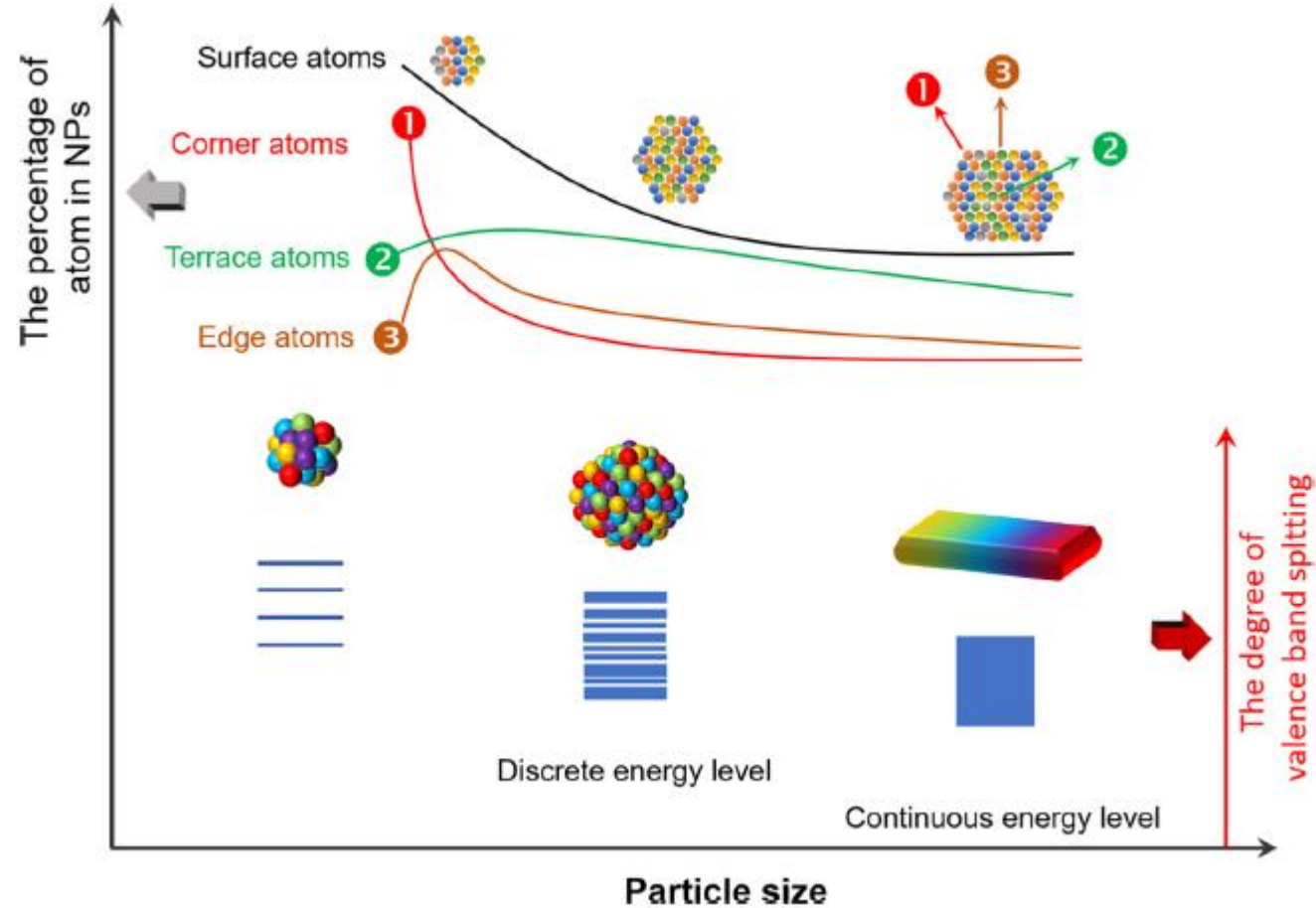
CuAgAuPtPd HEA-NPs

CuAgAuPtPd HEA-NPs

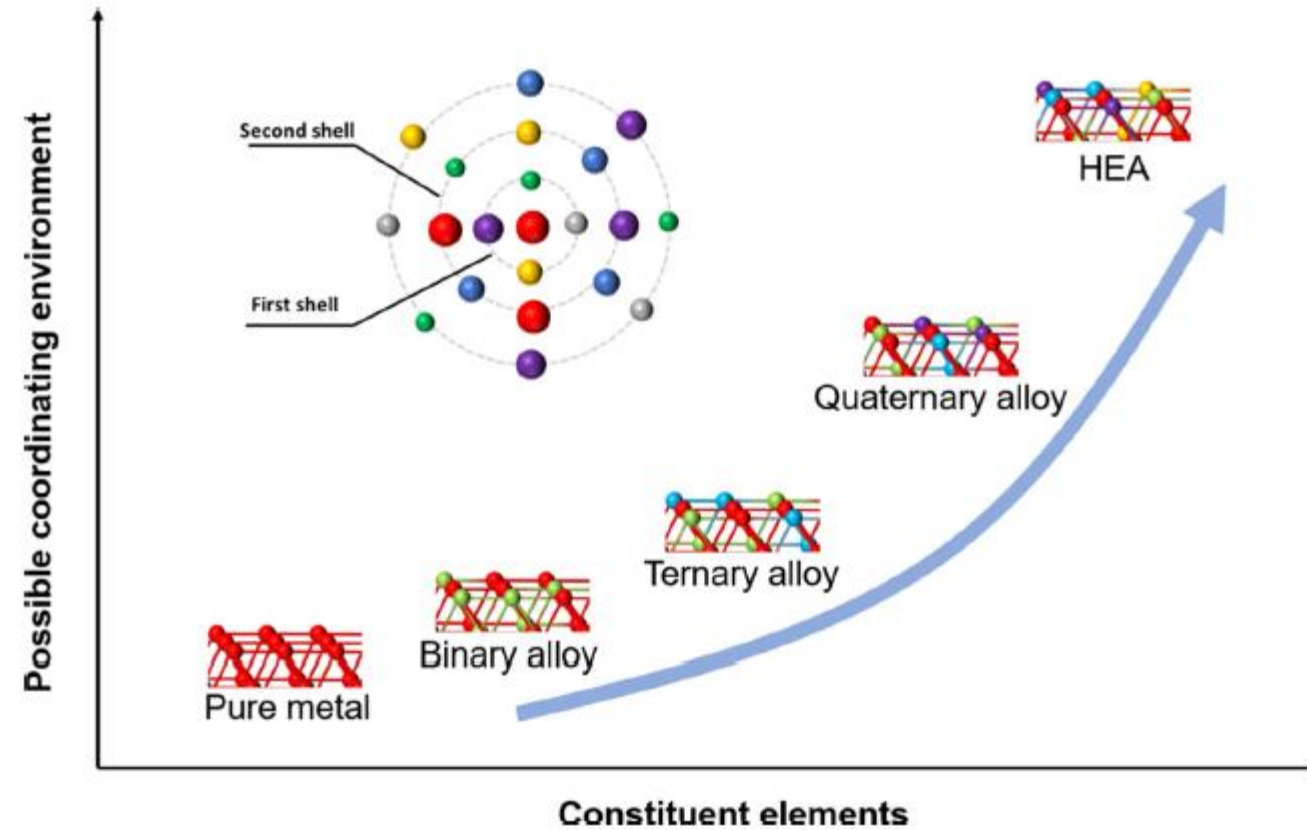
Pt<sub>18</sub>Ni<sub>26</sub>Fe<sub>15</sub>Co<sub>14</sub>Cu<sub>27</sub> HEA-NPs



# 3 Properties | High entropy alloys | Electrocatalysis properties

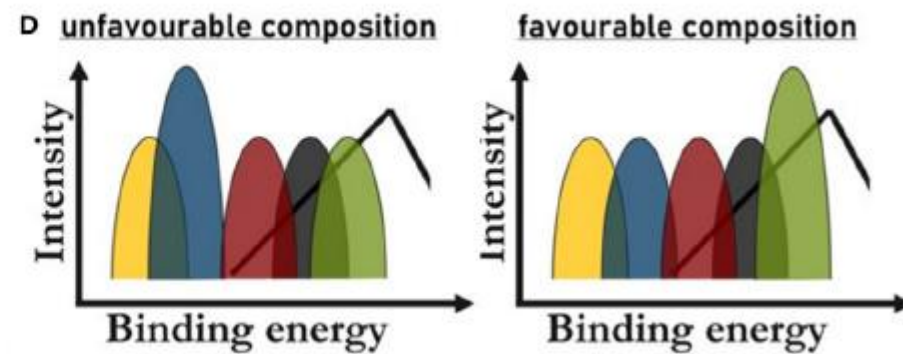
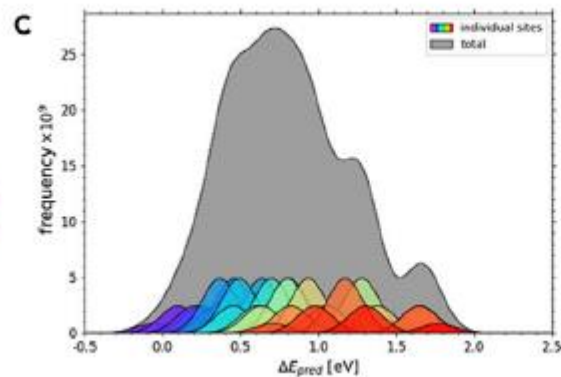
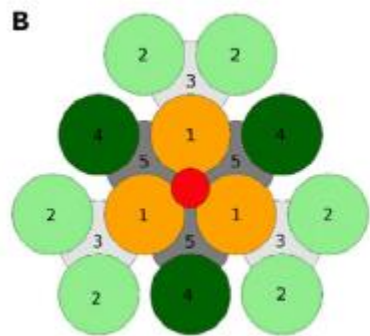
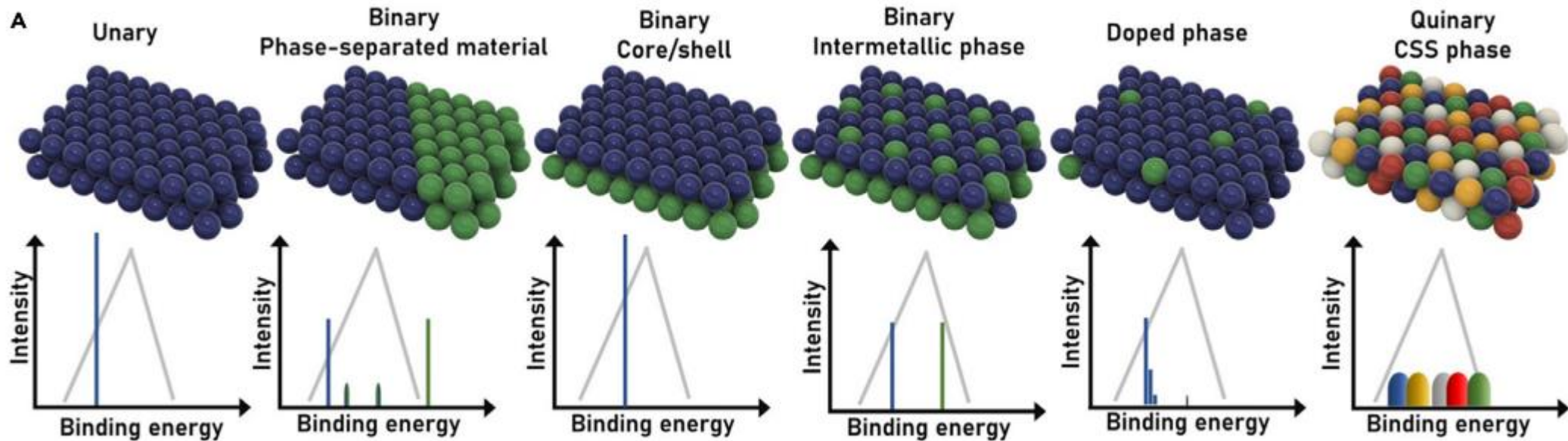


# 3 Properties | High entropy alloys | Electrocatalysis properties-FC

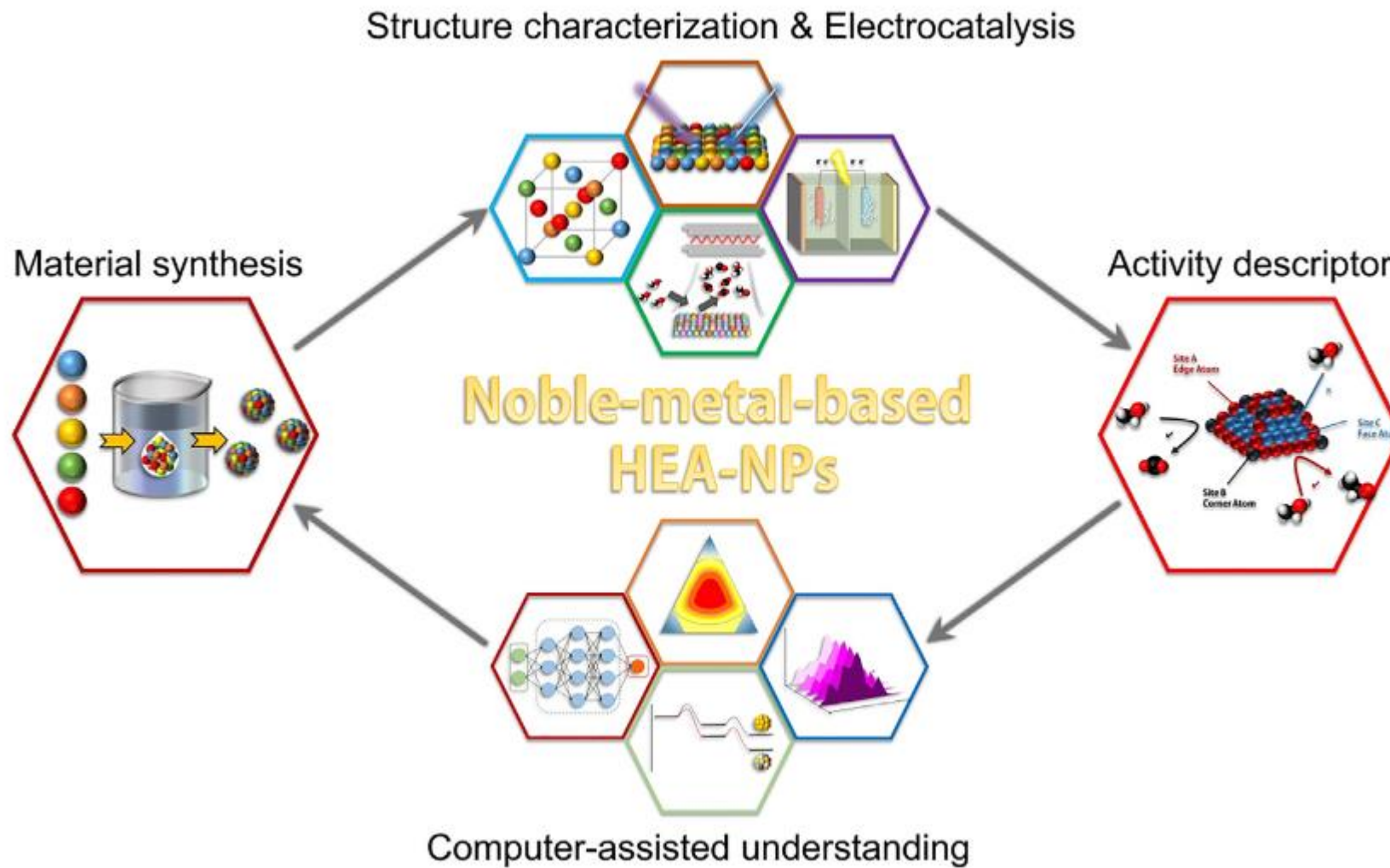


The HEA-NPs exhibit much more atomic arrangements and numerous possible configurations as shown in Fig

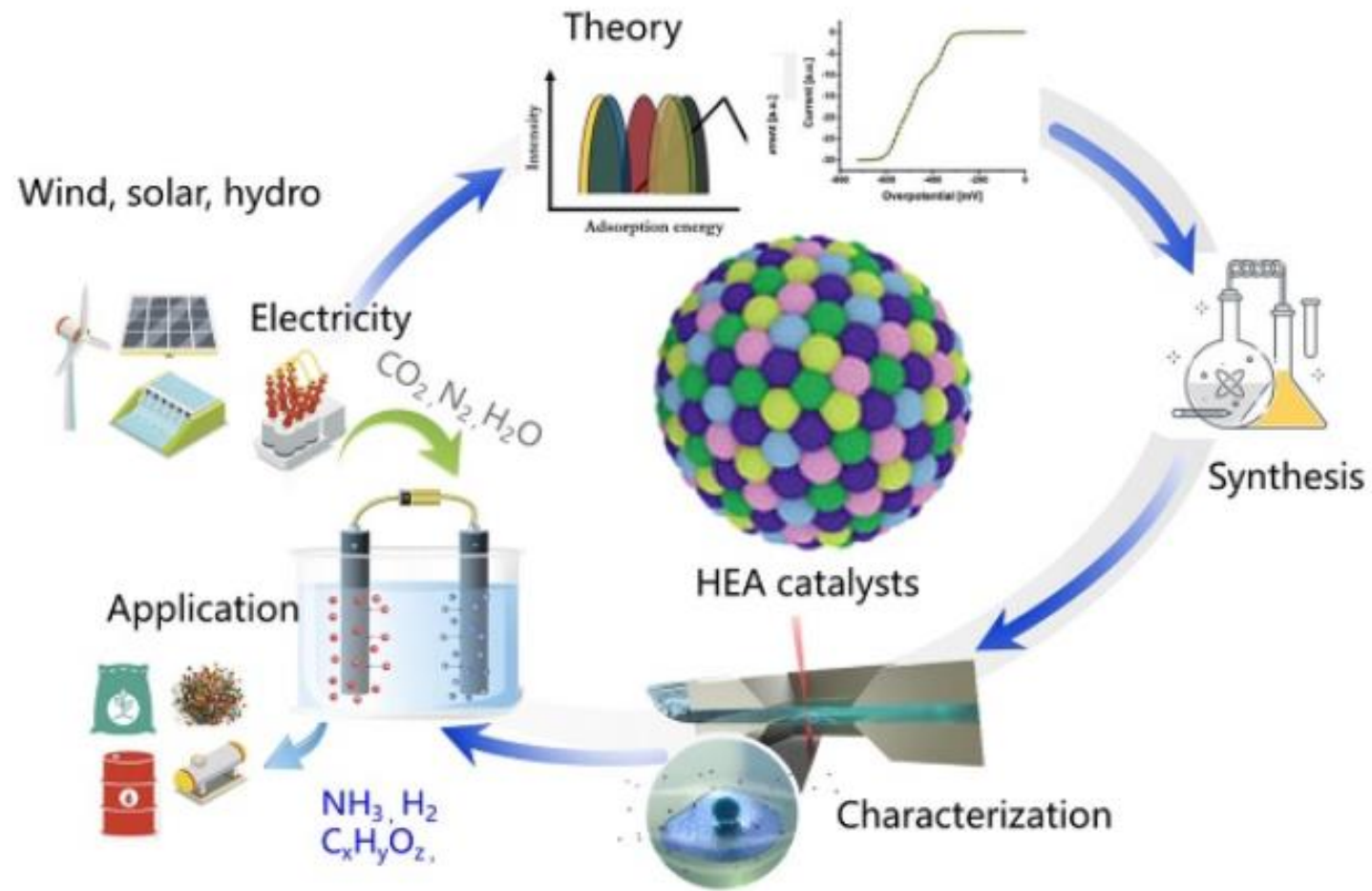
# 3 Properties | High entropy alloys | Electrocatalysis properties



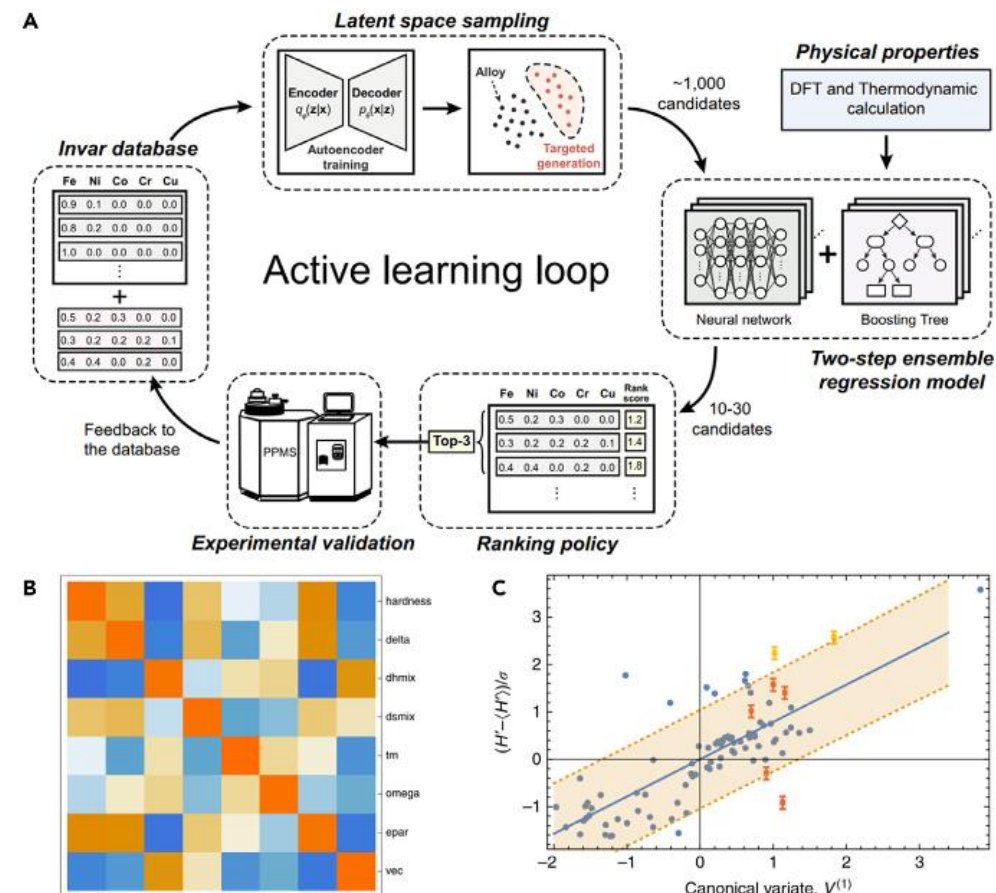
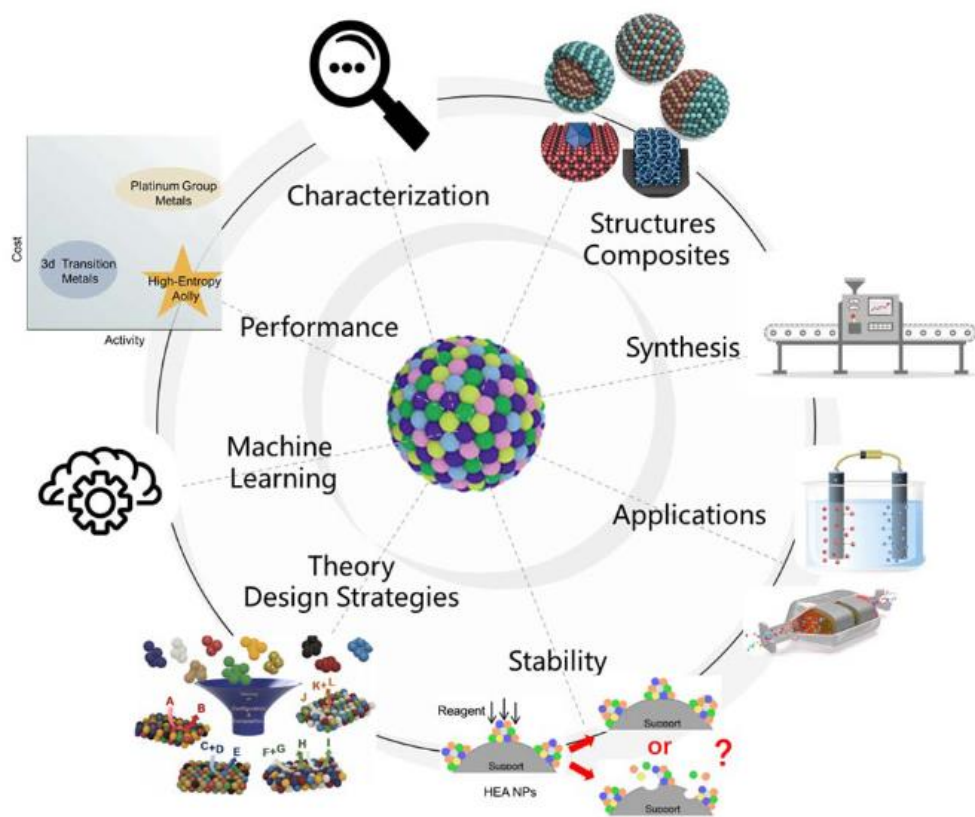
# 4 Remarks | High entropy alloys



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# 4 Remarks | High entropy alloys



X. Huang, Journal of Energy Chemistry 68 (2022) 721–751

Rao, Z et al.. Science 378 (2022) 78–85

Muchas Gracias!



**1<sup>ST</sup> LATAM MEETING ON GREEN  
AMMONIA AND POWER-to-X**

**10 Y 11 DE ENERO DE 2024**

AUDITORIO FADEU CAMPUS LO CONTADOR –UNIVERSIDAD CATÓLICA DE CHILE