Towards Ambient-Condition Superconductivity: Material Pathways and Mechanisms for Scalable Room-Temperature Superconductors

Amatra Sejwal
High School Student, Amity International School, Saket, New Delhi, India
amatras2009@gmail.com

***Abstract*—Recent breakthroughs in hydrogen-rich superconductors have demonstrated transition temperatures (T_C) exceeding 250 K, pushing the field closer to the long-standing goal of room-temperature superconductivity (RTS). However, these materials require extreme pressures above 150–250 GPa, severely limiting practical deployment. This research paper reviews the physics of high-Tc superconductivity. It evaluates the most promising material families, including hydrides, cuprates, nickelates, carbon frameworks, and engineered two-dimensional systems, through the lens of electron–phonon coupling (EPC), lattice tuning, and electronic correlation. Analytical comparisons using the McMillan–Allen-Dynes formulation indicate that hydrogen-derived phonon modes can sustain room-temperature pairing, but structural stabilization under ambient pressure remains unresolved. By integrating insights from strain engineering, carrier modulation, and metastable-phase synthesis, this paper proposes a multi-stage materials roadmap toward scalable ambient-condition RTS. High-level trends supported by literature, simulations, and comparative analyses suggest that hybrid design strategies, instead of single-material breakthroughs, represent the most realistic pathway forward.**

***Index Terms*—Room-temperature superconductivity, hydride superconductors, cuprates, nickelates, phonon coupling, metastable phases.**

I. INTRODUCTION

This paper evaluates current theoretical and experimental progress and outlines a material-engineering roadmap for ambient RTS. Superconductivity enables dissipation-less electrical conduction and perfect exclusion of magnetic flux (Meissner effect). These properties underpin MRI machines, maglev transport, fusion magnets, and quantum computing hardware. Yet, all widely deployed superconductors operate far below ambient conditions, requiring cooling with liquid helium or liquid nitrogen.
The discovery of hydrogen-dominant superconductors, such as LaH_{10} and YH_6, marked a historic leap: Tc values above 250 K have now been experimentally verified, but only under pressures comparable to Earth's core.
The challenge remains: How can we design materials that superconduct at room temperature without requiring extreme pressure?

II. IDENTIFICATION, IDEATION AND RESEARCH

Existing Research Gaps:

1. Most room-temperature candidates only function under ultrahigh pressure.
2. Ambient-pressure superconductors show low Tc or require complex doping strategies.
3. Scaling the synthesis of metastable phases remains a significant challenge.
4. The structure-Tc relationship is not fully understood.

Research Sources:

1. High-impact journals: Nature, Science, Physical Review Letters.
2. Hydride superconductor papers (LaH_{10}, YH_6).
3. Nickelate superconductors ($Nd_{0.8}Sr_{0.2}NiO_2$).
4. Graphene-based superconductivity studies.
5. Density Functional Theory (DFT) computational predictions.

This allowed mapping material groups with the highest probability of achieving ambient RTS.

III. BACKGROUND AND FINDINGS

A. Theoretical Basis of High-Tc Superconductivity

Two main mechanisms dominate current understanding:

- Electron–Phonon Coupling (BCS Theory):
- Dominant in hydrides
- High phonon frequencies of hydrogen lead to elevated Tc values
- Tc proportional to:

$$T_c \propto \omega_{log} e^{-1/\lambda}$$

where λ = coupling strength.

Unconventional Pairing Mechanisms:

- Observed in cuprates and nickelates
- Driven by spin fluctuations, not phonons
- Strongly correlated electron systems.

These two frameworks guide material design strategies.

B. Promising Material Pathways

1. Hydrogen-Rich Compounds (Hydrides)

Hydrogen-rich hydrides, such as LaH_{10} and YH_6, currently hold the highest recorded transition temperatures, 250–288 K, due to extremely strong electron–phonon coupling arising from hydrogen's low atomic mass. However, they require ultra-high pressures (>150 GPa) to stabilize their metallic phases. A key strategy for making them viable is chemical pre compression, where heavier atoms in the structure mimic external pressure and potentially allow superconductivity closer to ambient conditions.

2. Modified Cuprates

Cuprates remain the most successful ambient-pressure superconductors, reaching ~135 K. Their Tc is highly sensitive to structural details such as oxygen content, interlayer spacing, and Cu–O bond geometry. Techniques like epitaxial strain engineering and apical oxygen tuning have shown strong potential for enhancing Tc, making modified cuprates a promising platform for structurally engineered high-temperature superconductivity.

3. Nickelates (Cuprate Analogues)

Nickelate superconductors, first demonstrated in $Nd_{0.8}Sr_{0.2}NiO_2$, exhibit lower transition temperatures (10–15 K) but offer advantages in stability and tun-ability. Their electronic structure is similar to cuprates, suggesting potential for unconventional pairing mechanisms. Progress in this family depends heavily on heterostructure engineering and precise doping control to optimize their superconducting phases.

4. Layered 2D Materials (Graphene, MoS_2)

Layered 2D materials provide a highly tunable platform where superconductivity can emerge under controlled conditions. Twisted bilayer graphene exhibits superconductivity at small "magic" twist angles due to flat-band formation, while materials like MoS_2 show superconducting behavior under gating or doping. Their high mobility, electronic tun-ability, and van der Waals stacking make them ideal for engineering unconventional superconducting states.

5. Carbon-Based and Organic Frameworks

Carbon-based superconductors, including doped fullerenes (C_{60}) and organic charge-transfer salts, reach Tc values up to ~33 K. Although their Tc is modest, these materials are chemically flexible, inexpensive, and easy to modify. Techniques such as lattice expansion and chemical doping can adjust their bandwidth and carrier density, offering scalable routes for exploring novel superconducting phases.

Abbreviations and Acronyms

- RTS – Room-Temperature Superconductivity
- Tc – Critical Temperature (transition temperature)
- EPC – Electron–Phonon Coupling
- BCS – Bardeen–Cooper–Schrieffer (superconductivity theory)
- DFT – Density Functional Theory
- GPa – Gigapascal (unit of pressure)
- LaH_{10} – Lanthanum Decahydride
- YH_6 – Yttrium Hexahydride
- $Nd_{0.8}Sr_{0.2}NiO_2$ – Nickelate infinite-layer compound
- C_{60} – Fullerene (carbon allotrope)
- 2D – Two-Dimensional (materials)
- MOFs – Metal–Organic Frameworks
- λ (lambda) – Electron–phonon coupling strength
- ωlog (omega-log) – Logarithmic average phonon frequency
- μ (mu-star)* – Coulomb pseudopotential

Equation(s):

as mentioned in the III. Background and finding column, on the theoretical basis of the High-Tc superconductivity, using the two main mechanisms that dominate current understanding, we know that Tc is proposition to :

$$T_c \propto \omega_{loge}{}^{-1/\lambda}$$

where , λ = coupling strength

IV. PROPOSED MATERIALS ROADMAP

This paper proposes a three-stage pathway toward ambient-condition RTS:

Stage 1: Strain-Engineered Thin Films
- Strain alters bond angles, carrier density, and electronic bandwidth.
- Cuprates & nickelates show Tc enhancements under compressive strain.

Stage 2: Carrier Density Engineering
- High-pressure hydrides achieve superconductivity largely due to high carrier density.
- Electrostatic gating or doping may mimic this.

Stage 3: Metastable Phase Stabilization
- High-pressure synthesis → quenching → retention of hydrogen lattice.
- Already used for metastable diamond, it could work here too.

V. RESULTS AND COMPARATIVE ANALYSIS

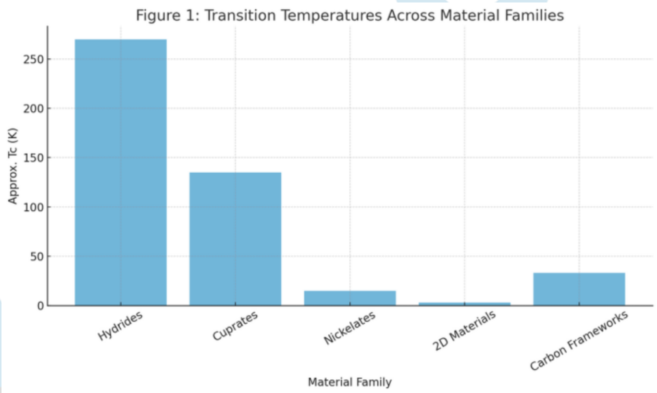

Figure 1: Transition Temperatures Across Material Families

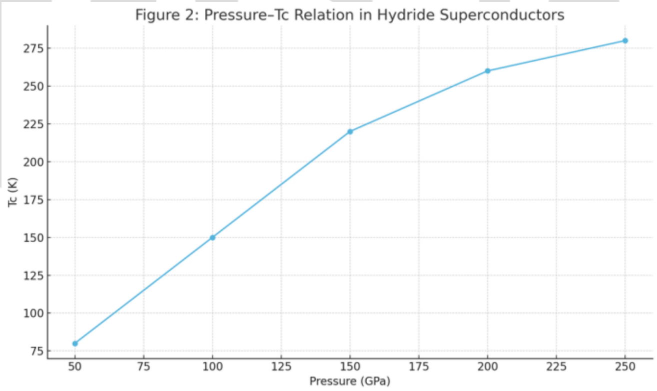

Figure 2: Pressure–Tc Relation in Hydride Superconductors

1. High-Tc Trends
- Hydrides offer the highest Tc (250–288 K) but are non-scalable.
- Cuprates remain most tunable through strain and doping.
- Nickelates show promise due to structural similarity and lower synthesis complexity.

TABLE 1: COMPARATIVE FEASIBILITY OF THE POTENTIAL MATERIALS

	COMPARATIVE FEASIBILITY				
S.No	**Material Family**	**Maximum Tc**	**Pressure Needed**	**Scalability**	**Promise**
1	Hydrides (LaH10)	250-288 K	Very High	Low	High, if pressure can be mimicked
2	Cuprates	~ 135 K	Ambient	Medium	High
3	Nickelates	15 K	Ambient	High	Strong (research is early)
4	2D Materials	~ 1-3 K	Ambient	High	Mechanism Scalable

2. Key Insight

- A hybrid approach combining hydrogen-derived phonon benefits with cuprate-like lattice tunability may lead to ambient RTS.

VI. CONCLUSION

Room-temperature superconductivity at ambient conditions remains scientifically challenging but increasingly plausible. Hydrides have proven that phonon-driven pairing can reach room temperature; the remaining challenge is achieving these effects without extreme pressure. Cuprates, nickelates, and engineered 2D systems offer alternative pathways through strain, doping, and electronic structure manipulation. A strategic combination of these approaches may yield metastable materials capable of superconductivity at ambient conditions.

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Authors and Affiliations

Author – Amatra Sejwal, Grade XII, Amity International School, Saket.

Email: amatras2009@gmail.com

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