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ANALYTICAL INVESTIGATION OF THERMOELECTRIC PERFORMANCE AND STABILITY OF Bi_2Te_3, SnSe, AND DOPED OXIDE ALLOYS UNDER CHHATTISGARH-SPECIFIC CONDITIONS

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Abstract

Thermoelectric materials convert a temperature difference directly into electrical power, but a material with a high laboratory figure of merit is not automatically the best material for a real industrial environment. This paper analytically compares Bi_2Te_3-based alloys, SnSe, and representative doped oxide thermoelectrics for deployment under Chhattisgarh-specific thermal and environmental conditions. The study uses a descriptive-analytical physics design based on peer-reviewed transport data, stability studies, India Meteorological Department climatology, and the industrial profile of Chhattisgarh. Performance is compared through the Seebeck coefficient, electrical conductivity, thermal conductivity, power factor, dimensionless figure of merit zT, temperature matching, and a stability-oriented screening framework. Bi_2Te_3-based alloys remain the strongest candidate for near-ambient and low-grade waste-heat recovery, with nanostructured p-type Bi-Sb-Te reporting a peak zT of about 1.4 near 373 K. SnSe provides the highest intrinsic high-temperature performance among the materials examined, including a reported zT of 2.6 near 923 K in single crystals; however, anisotropy, brittleness, and oxidation-sensitive surfaces make packaging and sealing decisive. Doped oxides, represented by Tb-doped $Ca_3Co_4O_9$ and Nb-doped $SrTiO_3$/YSZ, generally show lower zT but stronger compatibility with hot oxidizing atmospheres. Chhattisgarh's monsoon humidity, heavy rainfall, dust-bearing industrial sites, repeated start-stop thermal cycling, and large steel, cement, and power sectors create a deployment environment in which long-term stability can reverse the ranking suggested by peak zT alone. The central finding is therefore temperature- and environment-dependent: Bi_2Te_3-based modules are preferred for protected low-temperature recovery; SnSe is attractive for sealed high-grade systems; and doped oxides are the most robust choice for exposed high-temperature oxidizing service. Segmented or cascaded modules are recommended where the temperature span is wide.

Keywords: thermoelectric materials; Bi_2Te_3; SnSe; oxide thermoelectrics; $Ca_3Co_4O_9$; $SrTiO_3$; figure of merit; waste heat; Chhattisgarh; stability

1. Introduction

Thermoelectric conversion is a solid-state route for recovering useful electrical energy from heat. When the two ends of a thermoelectric leg are maintained at different temperatures, charge carriers diffuse from the hot side toward the cold side and produce a thermoelectric voltage. The same coupled transport physics also permits Peltier cooling when an electrical current is applied. Because a thermoelectric generator has no moving working fluid and can be placed directly on a heat source, the technology is attractive for industrial waste-heat recovery, distributed sensing, and systems in which reliability and low maintenance are important. The main materials challenge is that the transport coefficients required for high conversion efficiency are strongly coupled. A high Seebeck coefficient S is desirable because it increases the generated voltage, high electrical conductivity σ reduces Joule loss, and low thermal conductivity κ helps preserve the temperature gradient. These requirements are summarized by $zT = S^2\sigma T/\kappa$. Increasing carrier concentration commonly improves σ but lowers S and increases the electronic contribution to κ. Consequently, thermoelectric development is a problem of optimization rather than maximization of a single parameter.

This paper compares three materially different strategies. The first is the Bi_2Te_3 family, especially Bi-Sb-Te and Bi-Te-Se alloys derived from the layered Bi_2Te_3 parent phase, which dominate near-room-temperature thermoelectric applications. The second is SnSe, a layered chalcogenide whose strong lattice anharmonicity and anisotropic bonding produce exceptionally low thermal conductivity and very high high-temperature zT. The third is the broad class of doped oxide thermoelectrics. Because the title does not specify one oxide composition, the oxide class is represented

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here by p-type Tb-doped $Ca_3Co_4O_9$ and n-type Nb-doped $SrTiO_3$ with YSZ nano-inclusions. These examples illustrate the central oxide trade-off: lower peak zT than the best chalcogenides, but greater chemical and thermal tolerance in air. Chhattisgarh is a useful case for such a comparison because material selection is linked to both climate and industry. The state contains major steel, cement, and thermal-power activity, creating multiple waste-heat grades. At the same time, monsoon operation introduces high relative humidity, wet-dry cycling, and condensation risk during shutdown. An analytical paper focused only on peak zT would therefore be incomplete. The physically relevant question is which material retains useful performance after temperature matching, oxidation risk, thermal cycling, packaging, and interface stability are considered together.

1.1 Research Problem

The research problem is the mismatch between laboratory thermoelectric performance and field durability. Bi_2Te_3-based materials can be highly efficient at low and moderate temperatures but are not intended for unprotected very-high-temperature service. SnSe can deliver exceptional high-temperature zT, yet its practical response depends on crystal direction, surface chemistry, microstructure, and sealing. Oxides can survive harsher oxidizing environments but often sacrifice conversion efficiency. Chhattisgarh adds an environmental constraint: high monsoon humidity and rainfall coexist with high-temperature industrial heat sources. A material selection rule must therefore combine transport performance with thermal-window matching and stability rather than use a single peak zT value.

1.2 Objectives of the Study

- To explain the transport physics governing thermoelectric power factor, thermal conductivity, zT, and conversion efficiency.
- To compare the temperature-dependent thermoelectric performance of Bi_2Te_3-based alloys, SnSe, and representative doped oxide materials.
- To analyse oxidation, moisture exposure, thermal cycling, mechanical brittleness, contact diffusion, and interface degradation as stability constraints.
- To construct a Chhattisgarh-specific operating envelope using official monsoon climatology and the state's steel, cement, and power-sector context.
- To develop a transparent analytical screening framework for low-grade, sealed high-grade, and exposed high-grade waste-heat scenarios.

2. Review of Literature

The modern thermoelectric literature shows that high zT can arise from different physical mechanisms. In Bi_2Te_3-based compounds, band engineering and alloy/nanostructure scattering are used to preserve favorable electronic transport while reducing lattice thermal conductivity. Poudel et al. (2008) demonstrated a peak zT of 1.4 at 100 °C (373 K) in nanocrystalline p-type Bi-Sb-Te bulk alloy. The result is especially relevant to low-grade heat because the performance maximum lies close to the temperature range obtainable from warm process surfaces, condensate lines, low-pressure steam systems, electronics, and other sub-500 K sources. More recent work also shows that mechanical limitations of classic brittle Bi_2Te_3-based semiconductors can be altered through defect design; Deng et al. (2024) reported defect-enabled room-temperature plasticity while maintaining zT up to about 1.05 at 300 K. These results reinforce the maturity of the Bi_2Te_3 family while also highlighting the importance of microstructure for mechanical reliability.

SnSe represents a different route. Zhao et al. (2014) reported zT = 2.6 ± 0.3 at 923 K along the b axis of single-crystal SnSe, with lower values along the other crystallographic directions. The high zT was linked to intrinsically ultralow lattice thermal conductivity arising from strongly anharmonic, anisotropic bonding. The anisotropy is technologically important: a material that performs exceptionally in one crystallographic direction may not deliver the same result in a randomly oriented polycrystal or poorly aligned device. Later polycrystalline work showed that surface tin oxides can mask intrinsic performance. Zhou et al. (2021) reported roughly zT = 3.1 at 783 K after minimizing deleterious SnO_x phases, demonstrating that surface chemistry can control both charge and heat transport at grain boundaries.

The same sensitivity creates a stability issue. Shimizu et al. (2021) studied nanocrystalline SnSe thin films under atmospheric annealing and observed strong modification of electrical and thermoelectric properties from oxidation; the authors explicitly emphasized realistic sealing technologies for energy-harvesting devices. Their thin-film system

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is not identical to a dense bulk module, so its kinetics cannot be directly transferred to an industrial leg. Nevertheless, it provides strong evidence that oxygen exposure at elevated temperature is a first-order engineering variable for high-surface-area or imperfectly sealed SnSe structures.

Oxide thermoelectrics are attractive because chemical stability in air is built into the material family rather than achieved solely by hermetic protection. Saini et al. (2017) reported zT = 0.74 at 800 K for Tb-doped polycrystalline $Ca_3Co_4O_9$, attributing the improvement to a combination of larger Seebeck coefficient and reduced thermal conductivity. For n-type oxide operation, Wang et al. (2013) enhanced Nb-doped $SrTiO_3$ through YSZ nano-inclusions and obtained zT up to 0.21 at 900 K. These zT values are lower than the best SnSe benchmarks, but the operating temperatures are directly relevant to hot exhaust, kiln surfaces, and furnace-associated systems where oxidation-resistant ceramics may be preferred.

Table 1. Thematic synthesis of literature used in the study.

Theme	Representative evidence	Physical contribution	Relevance to this paper
Bi_2Te_3-based performance	Poudel et al. (2008); Deng et al. (2024)	Nanostructuring/defects can reduce κ and improve mechanical response	Low-temperature benchmark and mechanical reliability
SnSe high-zT transport	Zhao et al. (2014); Zhou et al. (2021)	Anharmonic lattice, anisotropy, oxide-sensitive grain boundaries	High-temperature benchmark and processing sensitivity
SnSe environmental stability	Shimizu et al. (2021)	Air annealing changes surface chemistry and thermopower	Justifies sealing/encapsulation analysis
p-type oxide thermoelectric	Saini et al. (2017)	Tb doping raises S and suppresses κ in $Ca_3Co_4O_9$	High-temperature oxidizing-service option
n-type oxide thermoelectric	Wang et al. (2013)	YSZ inclusions scatter phonons and improve σ in Nb:$SrTiO_3$	Complementary oxide leg and stability reference
Chhattisgarh environment	IMD Raipur climatology; CSIDC sector profiles	High monsoon RH plus steel/cement/power heat sources	Defines the deployment stress envelope

3. Research Methodology

The study adopts a descriptive-analytical research design. It is descriptive because it summarizes published thermoelectric transport and stability behavior. It is analytical because the published results are reorganized around a common physics framework and then evaluated against a deployment envelope specific to Chhattisgarh. No new laboratory sample, field survey, or proprietary plant dataset is claimed. Reported zT values remain literature values for their original compositions, crystallographic directions, microstructures, and measurement conditions.

The unit of comparison is a thermoelectric material system operating between a hot-side temperature T_h and cold-side temperature T_c. Five property groups are considered: (i) electronic transport represented by S and σ; (ii) thermal transport represented by $\kappa = \kappa_e + \kappa_l$; (iii) combined thermoelectric response represented by power factor $PF = S^2\sigma$ and zT; (iv) stability represented by oxidation, moisture sensitivity, phase/interface integrity and mechanical response; and (v) deployment fit represented by temperature range, atmosphere, expected cycling, and packaging burden. The Chhattisgarh environmental envelope is constructed conservatively. For the monsoon case, official IMD climatology is used for Raipur, Pendra Road, Jagdalpur, and Ambikapur. Industrial relevance is established from the Chhattisgarh State Industrial Development Corporation, which identifies steel, cement, and power as core sectors. The analysis does not assume that ambient climate determines hot-side temperature; process temperatures are set by the industrial heat source. Climate instead affects cold-side conditions, condensation, corrosion of contacts and enclosures, insulation resistance, and the severity of packaging required during operation and shutdown.

Table 2. Methodological framework of the analytical paper.

Element	Description	Purpose

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Research design	Descriptive-analytical, secondary literature	Compare performance and field stability without inventing experimental data
Materials	Bi_2Te_3-based alloys; SnSe; Tb:$Ca_3Co_4O_9$ and Nb:$SrTiO_3$/YSZ	Represent low-temperature chalcogenide, high-zT chalcogenide and robust oxide classes
Physics metrics	S, σ, PF, κ, zT, temperature match	Provide a common transport framework
Stability metrics	Oxidation, interfaces, moisture exposure, cycling, mechanical damage	Move beyond peak zT toward lifetime suitability
Regional inputs	IMD monsoon climatology; CSIDC steel/cement/power context	Define Chhattisgarh-specific deployment conditions
Output	Scenario ranking and module recommendations	Support material selection by heat grade and atmosphere

4. Thermoelectric Transport Physics and Analytical Parameters

The Seebeck effect arises from carrier diffusion under a temperature gradient. For a one-dimensional leg, the open-circuit thermovoltage is approximately $V = -S\Delta T$ when S can be treated as constant over the temperature interval. In a practical generator, current flow introduces internal electrical resistance and heat transport by both carriers and phonons. The output is therefore governed by the coupled transport equations rather than by Seebeck coefficient alone. A material with very high S but extremely poor σ may produce voltage but little useful power; a highly conducting material with large κ may short-circuit the temperature gradient thermally.

$$\mathbf{PF = S^2\sigma}$$

Power factor measures the electrical part of thermoelectric performance.

$$\mathbf{zT = S^2\sigma T / \kappa = PF \cdot T / (\kappa_e + \kappa_l)}$$

Dimensionless figure of merit combines electronic and thermal transport.

The lattice contribution κ_l is especially important because it can often be reduced by alloy disorder, grain boundaries, nanoscale inclusions, anharmonic bonding, or complex crystal structures without proportionally damaging charge transport. This is why nanostructured Bi-Sb-Te, intrinsically anharmonic SnSe, and interface-rich oxide composites can all improve zT through different microscopic mechanisms. However, a low κ generated by a fragile microstructure is useful only if the structure survives thermal gradients, cycling, joining, and the intended atmosphere.

$$\mathbf{\eta max = (T_h - T_c)/T_h \times [\sqrt{(1 + z\bar{T})} - 1] / [\sqrt{(1 + z\bar{T})} + T_c/T_h]}$$

Idealized maximum generator efficiency using an average $z\bar{T}$ over the operating interval.

This equation shows why temperature matching is central. A high peak zT at one temperature does not guarantee high device efficiency over a wide gradient. The relevant quantity is an average transport response across the leg, together with electrical and thermal contact losses. The best material may therefore change along the temperature gradient. This motivates segmented generators in which a low-temperature Bi_2Te_3-based stage is coupled to a higher-temperature SnSe or oxide stage.

Table 3. Key physical quantities used in the comparison.

Quantity	Expression / unit	Interpretation	Deployment meaning
Seebeck coefficient, S	$V K^{-1}$ (often $\mu V K^{-1}$)	Thermovoltage per unit temperature difference	Controls voltage polarity and magnitude
Electrical conductivity, σ	$S m^{-1}$	Ease of charge transport	Low resistance reduces Joule loss
Thermal conductivity, κ	$W m^{-1} K^{-1}$	Heat leakage through material	Lower κ helps maintain ΔT
Power factor, PF	$S^2\sigma$ ($W m^{-1} K^{-2}$)	Electronic performance index	Useful for power-density screening

Figure of merit, zT	$S^2\sigma T/\kappa$	Combined dimensionless material metric	Primary efficiency-related comparison
Stability retention	Property after exposure / initial property	Change under thermal/environmental stress	Links laboratory performance to service life

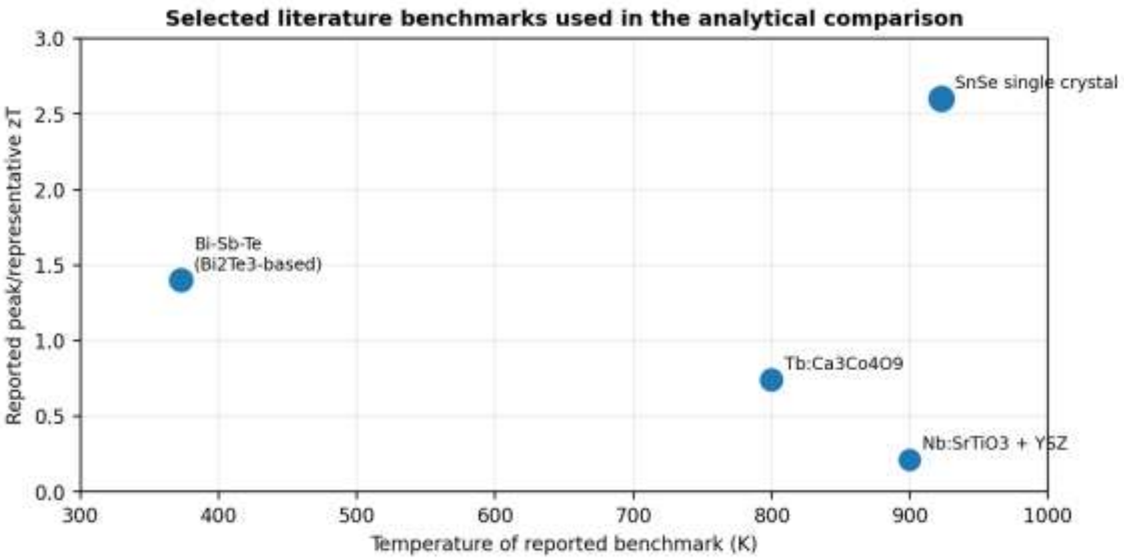
5. SnSe: Exceptional High-Temperature zT with Anisotropy and Oxidation Constraints

SnSe gained exceptional interest because its crystal lattice is an unusually poor heat conductor while remaining a useful semiconductor. Zhao et al. measured zT = 2.6 ± 0.3 at 923 K along the b axis, zT = 2.3 ± 0.3 along c, and a much lower value along a. The result is a direct demonstration that orientation is not a minor detail. In a device using single-crystal legs, crystallographic alignment must be controlled. In polycrystalline material, texture, grain orientation, grain-boundary phases and porosity influence the effective transport coefficients.

The very low lattice thermal conductivity of SnSe is linked to anharmonic bonding and strong phonon scattering. In principle, this gives SnSe an efficiency advantage over oxide thermoelectrics in the 700–950 K region. The 2021 polycrystalline result is especially significant because removal of surface SnO_x helped reveal zT of roughly 3.1 at 783 K. That result simultaneously demonstrates promise and risk: oxygen-derived secondary phases can increase heat conduction and degrade charge transport at grain boundaries, so chemical control is central to realizing the intrinsic physics.

Atmospheric stability must therefore be treated explicitly. Shimizu et al. observed strong changes in nanocrystalline SnSe thin-film thermopower during air annealing and showed that oxygen exposure at elevated temperature was responsible for the change. Their experiment used a high-surface-area film and should not be interpreted as a direct lifetime prediction for a dense industrial leg. The correct analytical inference is narrower: high-temperature SnSe performance is sensitive to surface oxidation, so hermetic sealing, inert or reducing encapsulation, stable diffusion barriers, and controlled processing are prerequisites when high zT is to be retained.

Figure 1. Selected literature zT benchmarks for the material systems compared here.



6. Chhattisgarh-Specific Thermal and Environmental Operating Envelope

A Chhattisgarh-specific analysis should separate process temperature from ambient climate. Steel reheating, cement kilns and thermal-power systems can expose heat exchangers to temperatures far above the outdoor air temperature. Material temperature matching must therefore be based on the heat source. Ambient climate becomes important through the cold-side temperature, heat-rejection capacity, condensation, corrosion, dust adhesion, insulation performance, and shutdown conditions. The two temperature scales act together but should not be confused. The monsoon environment is well constrained by IMD station climatology. For Raipur in August, average rainfall is 334.2 mm, the average number of rainy days is 14.4, relative humidity is typically about 87–79%, mean maximum

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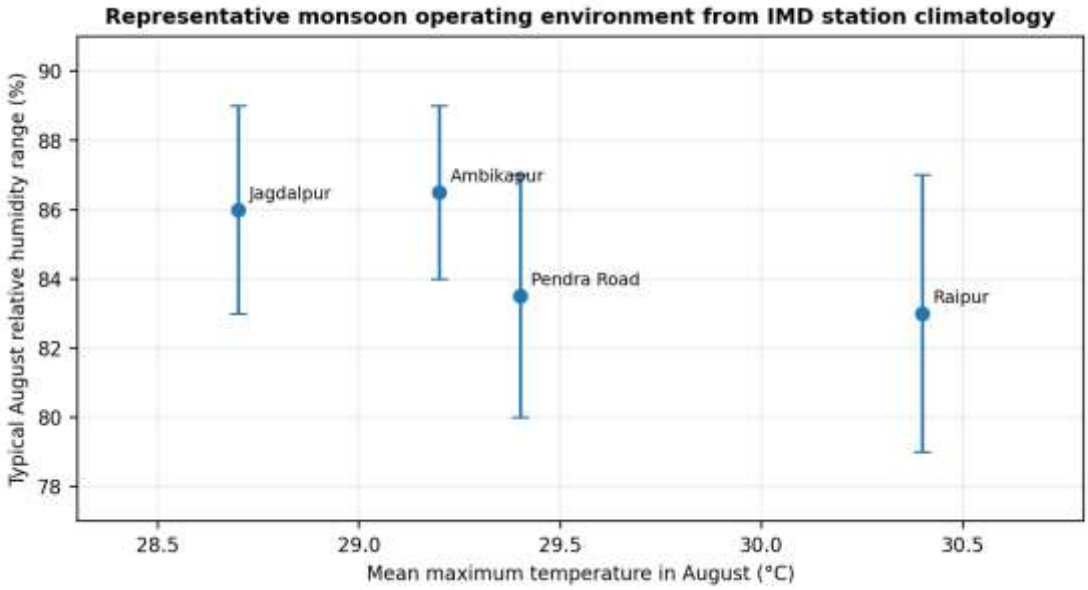
temperature is 30.4 °C, and mean minimum temperature is about 24.5 °C. Pendra Road is reported around 87–80% RH, Jagdalpur around 89–83%, and Ambikapur around 89–84%. These are not extreme laboratory humidity exposures; they are ordinary seasonal conditions. Therefore, any field module intended for year-round operation should assume that high humidity is recurrent rather than exceptional.

This environment has four consequences for thermoelectric systems. First, cooling by ambient air becomes less effective when air temperature and humidity are high, so heat-sink design must avoid assuming a very low T_c. Second, when a hot system is shut down, enclosure and connector temperatures cross through the dew-point region, creating condensation risk on exposed metallic or ceramic surfaces. Third, airborne dust can retain moisture and form conductive or corrosive films on terminals. Fourth, repeated wet-dry and hot-cool cycles stress seals and diffusion barriers even if the bulk thermoelectric remains dry.

Figure 2. Representative August humidity and temperature conditions at selected Chhattisgarh IMD stations.



7. Analytical Screening Model for Performance and Stability

The analytical comparison begins with a temperature-match filter. A material cannot receive a high score simply because its peak zT is large if that peak lies outside the source temperature. Bi_2Te_3-based alloys therefore receive a strong low-grade score; SnSe and the selected oxides receive stronger high-grade scores. A second filter is atmosphere. Open oxidizing air favors oxide ceramics; sealed or inert systems permit SnSe to exploit its high intrinsic zT. A third filter is lifecycle stress, including thermal cycling and the probability that seals, contacts and metallization remain intact.

$$\mathrm{MSS} = 0.35\mathrm{Tmatch} + 0.25\mathrm{Airstab} + 0.15\mathrm{Moist} + 0.15\mathrm{Cycle} + 0.10\mathrm{Practical}$$

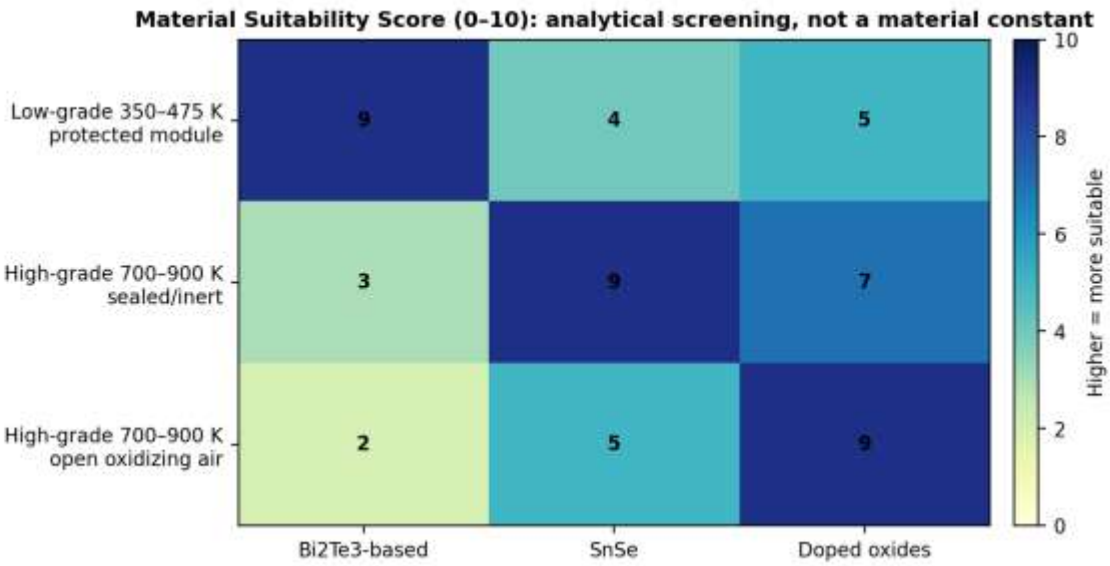
Each sub-score is an ordinal 0–10 rating. MSS is a screening index proposed in this paper, not a measured property.

Three representative deployment scenarios are defined. Scenario A is protected low-grade recovery with hot-side temperature roughly 350–475 K. Scenario B is high-grade recovery at 700–900 K in a sealed or inert cartridge. Scenario C is high-grade recovery at 700–900 K in open oxidizing industrial air, where sealing is difficult and maintenance access may be limited. The score matrix uses conservative whole-number ratings to avoid false numerical precision. Its role is to make the reasoning auditable: if a plant places greater value on efficiency than lifetime, the weights can be changed and the ranking recalculated.

Table 4. Scenario logic used for the Chhattisgarh screening analysis.

Scenario	Thermal envelope	Atmosphere / environmental burden	Physics priority	Expected leader
A. Protected low-grade	350–475 K hot side	Sealed module; humid external monsoon air	Low-T zT, mature contacts, low thermal stress	Bi_2Te_3-based
B. Sealed high-grade	700–900 K hot side	Hermetic/inert or well-controlled secondary heat loop	Maximum high-T zT with engineered interfaces	SnSe
C. Exposed high-grade	700–900 K hot side	Oxidizing air, dust, cycling, possible seal degradation	Chemical stability and retained performance	Doped oxides

Figure 3. Material Suitability Score for the three analytical deployment scenarios.



The ranking illustrates a central analytical result. Peak zT and field suitability are not equivalent. SnSe wins the high-temperature performance comparison under controlled atmosphere, while oxide thermoelectrics win the severe-environment comparison. Bi_2Te_3-based materials dominate only when the source temperature overlaps their low-temperature performance window. A rational material choice is therefore a constrained optimization problem in which temperature and stability determine whether the intrinsic zT can actually be used.

8. Data Interpretation and Major Findings

The analytical evidence produces six major findings. First, temperature matching is the primary filter. Bi_2Te_3-based alloys are optimized for low and moderate temperatures, SnSe for higher temperatures, and the representative oxides for high-temperature operation. Comparing peak zT without considering the heat-source temperature can therefore produce a physically meaningless ranking. Second, SnSe has the strongest intrinsic high-temperature performance in the selected literature, but its advantage is conditional. The anisotropy reported for single crystals and the oxide sensitivity observed in both polycrystalline processing and atmospheric thin-film studies show that device architecture determines whether the bulk transport potential is realized. A high zT value should therefore be interpreted as a material opportunity, not a guaranteed field efficiency.

Third, oxide thermoelectrics demonstrate a stability-performance trade-off. Tb-doped $Ca_3Co_4O_9$ and Nb-doped $SrTiO_3$/YSZ do not match the highest SnSe zT values, but their oxide chemistry is compatible with hot air. In an exposed industrial location, a lower but retained zT can be more valuable than a higher initial zT that requires fragile environmental control.

Fourth, Chhattisgarh's monsoon climate mainly changes module reliability rather than the intrinsic high-temperature transport of a hot thermoelectric leg. IMD climatology shows repeated RH near 80–90% during August across representative stations. That level of humidity makes condensation, seal integrity and cold-side corrosion routine design considerations. The correct response is not to reject chalcogenides solely because the outdoor air is humid; it is to engineer the enclosure so the active material is not exposed.

Fifth, the industrial structure of Chhattisgarh supports a segmented material strategy. Steel, cement and power systems provide both high-grade and low-grade waste heat. A Bi_2Te_3-only generator wastes high-temperature potential, while an oxide-only generator sacrifices low-temperature efficiency. A cascaded arrangement can place an oxide or sealed SnSe stage near the hot source and a Bi_2Te_3-based stage downstream, allowing each material to operate closer to its favorable zT region.

Sixth, stability must be measured as retention, not merely absence of catastrophic failure. Long-term tests should monitor Seebeck coefficient, electrical resistance, thermal conductance, contact resistance, mass/phase change, and power output after cycling. A module that remains mechanically intact but loses 30% of power is not stable in the engineering sense. Future Chhattisgarh trials should therefore report property retention versus time and cycle count.

9. Recommendations for Chhattisgarh Deployment and Future Physics Work

- Use Bi_2Te_3-based p/n modules for protected low-grade sources with hot-side temperatures broadly below about 475 K, especially where compactness and mature joining technology are priorities.
- Use SnSe only when its high-temperature advantage can be protected by a hermetic or controlled-atmosphere module. Texture, grain-boundary oxygen, contact metallurgy and seal leakage should be treated as primary design variables.
- Use doped oxide thermoelectrics for high-temperature oxidizing locations where long-term air exposure, dust and maintenance constraints are more important than achieving the maximum possible zT.
- For steel and cement applications with wide temperature spans, evaluate a segmented generator: oxide at the hottest exposed interface, optional sealed SnSe in a protected intermediate stage, and Bi_2Te_3-based material on the lower-temperature stage.
- Design the cold side for monsoon operation. Heat sinks, electrical feedthroughs and enclosures should be rated for sustained high RH and condensation during shutdown; dew-point crossings should be included in qualification cycling.
- Characterize complete modules, not only pellets. Track contact resistance, thermal contact resistance, open-circuit voltage, matched-load power and insulation resistance together with material zT.
- Run accelerated aging in three atmospheres: dry air, humid air during cool-down, and the actual plant gas or a chemically representative surrogate. Include dust deposition where relevant.
- Report retention after fixed dwell times and cycle counts. A useful target metric is $P(t)/P(0)$ under controlled ΔT, supplemented by post-test XRD/SEM/EDS or surface analysis to identify the mechanism of loss.
- Develop locally relevant heat-source maps before pilot deployment. Plant-specific T_h, T_c, heat flux, surface geometry and duty cycle are required to convert this material-level ranking into an energy-yield calculation.

For physics research, the most valuable next experiment is not another isolated room-temperature Seebeck measurement. It is a controlled comparison of complete legs or small couples under a common thermal gradient and Chhattisgarh-relevant exposure protocol. Bi_2Te_3-based, SnSe and oxide specimens should be operated at their appropriate temperature windows rather than forced to one identical temperature. The outcome variable should be retained electrical power after thermal cycling. Such a study would directly test the central hypothesis of this paper: stability-adjusted performance can change the preferred material even when the initial peak zT ranking is known.

10. Conclusion

Bi_2Te_3-based alloys, SnSe and doped oxide thermoelectrics occupy different parts of the performance-stability design space. Bi_2Te_3-based materials provide strong near-room-temperature and low-grade waste-heat performance and benefit from mature module technology. SnSe provides exceptional high-temperature thermoelectric potential because of its ultralow lattice thermal conductivity and favorable electronic transport, but anisotropy and oxidation-

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sensitive surfaces demand controlled processing and sealing. Doped oxides provide lower zT yet offer the most natural compatibility with high-temperature oxidizing industrial atmospheres.

Chhattisgarh-specific conditions make this trade-off practically important. The state's monsoon climatology introduces repeated high humidity and condensation risk at the module level, while its steel, cement and power sectors provide heat sources spanning low to very high temperatures. No single material is therefore universally optimal. The most defensible selection is conditional: Bi_2Te_3-based modules for protected low-temperature recovery, SnSe for sealed high-temperature recovery where efficiency justifies the packaging burden, and doped oxides for exposed hot-air service where robustness dominates.

The main analytical conclusion is that peak zT should be replaced by stability-adjusted, temperature-matched thinking in field thermoelectric design. The material, interfaces, atmosphere and duty cycle form one coupled physical system. For Chhattisgarh, the strongest future pathway is a segmented or cascaded generator combined with local lifetime testing, so that each thermoelectric family is used in the temperature and environmental regime where its transport physics can be retained rather than merely demonstrated in the laboratory.

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