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Fuel Selection, Waste-Heat Recovery, and Decarbonization Strategies for Chromite Oxidative Alkali Roasting: A Critical Review

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Abstract

Oxidative alkali roasting of chromite is an oxygen-dependent, high-temperature transformation in which energy-carrier selection must be judged not on thermal efficiency alone, but on chromate formation, solid-state transport, reagent use, and environmental control. This critical review evaluates fossil fuels, hydrogen-containing blends, alternative thermal carriers, waste-heat recovery, process integration, and hybrid electric heating using a structured evidence hierarchy that separates chromite-specific studies from transferable industrial analogs. An integrated assessment framework focuses on useful heat demand, temperature and oxygen distributions, chromium conversion and selectivity, energy and exergy balances, emissions, retrofit feasibility, and life-cycle greenhouse gases. The analysis identifies exhaust-gas and hot-solid heat recovery, control of excess air, and validated thermal integration as pragmatic first-stage actions. Electrification can eliminate on-site fuel combustion, but its net climate benefit depends on marginal electricity emissions, while hydrogen substitution introduces burner, heat-transfer, nitrogen-oxide, and supply-chain uncertainties. High-temperature heat pumps and thermoelectric systems may support auxiliary heat recovery without necessarily meeting the core roasting duty. The review provides fuel-screening criteria, process-specific verification gates, and a staged decarbonization roadmap. Published comparisons cannot yet establish universally superior combinations for chromite roasting because harmonized industrial measurements of conversion, heat duty, oxygen availability, and emissions remain scarce.

Keywords: Chromite roasting; Sodium chromate; Fuel selection; Waste-heat recovery; Industrial electrification; Decarbonization

Highlights

- Fuel substitutions must preserve oxygen availability and chromate conversion.
- Heat recovery should precede replacement of the primary heat source.
- Hydrogen and electrification require process-specific demonstrations.
- Comparable energy and emissions boundaries are essential for route ranking.

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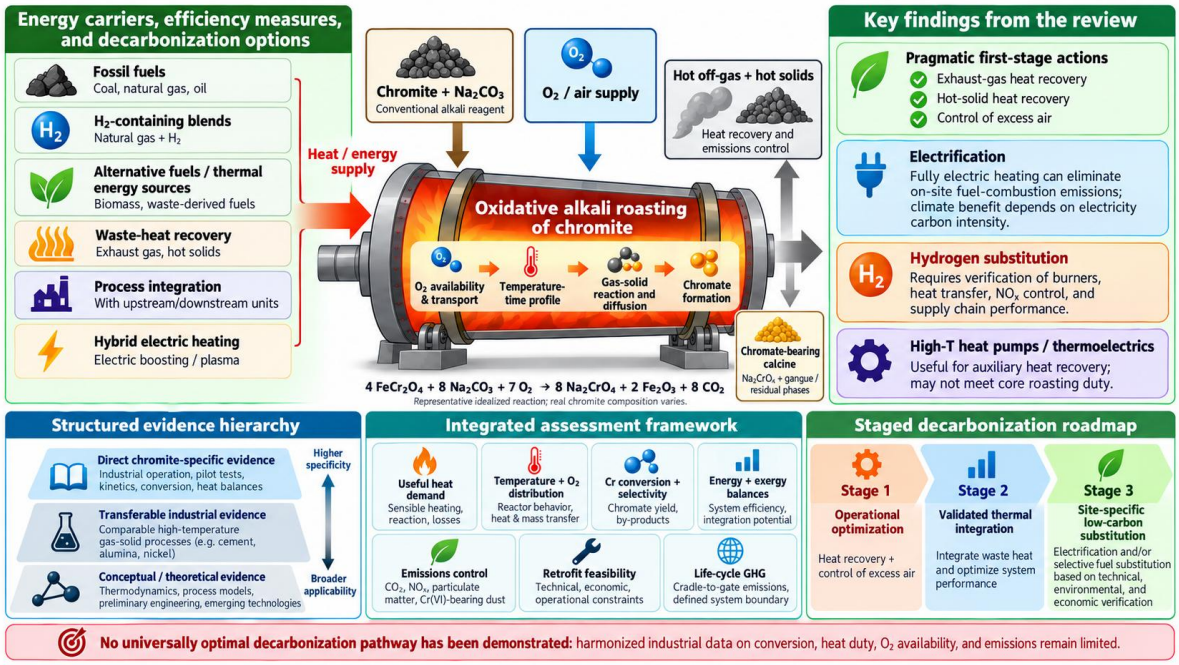
Graphical abstract



1. Introduction

Oxidative alkali roasting converts chromium-bearing spinel minerals into water-soluble chromate compounds, but the apparent simplicity of supplying high-temperature heat masks an interdependence of mineral composition, gas-phase oxygen, alkaline reagents, agglomeration, and conversion kinetics. Chromite-specific studies of soda roasting, thermodynamics, and lime-free processing provide the closest evidence base, whereas many innovations in industrial heating have been assessed in cement, steel, glass, and refinery systems rather than chromite plants (Mvita et al., 2024; Prasad et al., 2021; Qi et al., 2023; Sanchez-Segado et al., 2025).

This review therefore does not treat substitution of natural gas by electricity or hydrogen as a drop-in change. Heat-transfer mode, combustion products, local oxygen potential, alkali volatilization, and the allowable temperature profile may change concurrently. Comparative industrial-heating assessments point to several decarbonization pathways, but the chemistry-

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specific validation gap remains material (Bolson et al., 2026; Diesing et al., 2025a; Leicher et al., 2024; Pisciotta et al., 2022).

Table 1 summarizes the process boundaries and evidence categories; Table 2 compares energy carriers; Table 3 identifies heat recovery opportunities; Table 4 sets out scenario-assessment criteria; and Table 5 presents verification requirements. The integrated heat network is introduced in Figure 1, the scenario comparison architecture in Figure 2, and the staged implementation logic in Figure 3. Together they enable a comparison on an equivalent product-output and chromium-conversion basis rather than merely on burner efficiency.

2. Review Scope and Technology Assessment Framework

2.1 Evidence taxonomy and selection logic

The documentary starting point was a REV7 compilation containing 133 bibliographic records; this number represents the supplied search corpus, not a verified count of studies meeting predefined eligibility criteria. For critical synthesis, an author-developed evidence taxonomy separates D (direct evidence: chromite combined with an alkaline reagent under oxidizing conditions to produce chromate-containing phases, or a directly corresponding commercial process), A (analog or contextual evidence, including other industrial kilns and burners, reductive chromite processing, and ferrochrome hydrogen-reduction studies), and G (general methods, reviews, and cross-sector assessments). This classification governs the strength of inference: hydrogen performance in glass furnaces or other rotary-kiln operations can inform design hypotheses but cannot establish chromite-to-chromate conversion performance (Daurer et al., 2025; Gołdasz et al., 2024; Kodanli et al., 2025; Qasim et al., 2025).

The starting REV7 working compilation contained 133 bibliographic records, whereas the reference list in the evaluated manuscript contains 127 entries. The record-level disposition of the difference of six cannot be reconstructed reliably from the available documentation. Accordingly, no retrospective flow diagram or unverified exclusion reasons are reported. The

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final reference list should be understood as the set actually cited in this critical narrative review, not a reproducible systematic-review screening result.

This is a critical narrative review rather than a PRISMA-compliant systematic review. The supplied records were interpreted by process relevance, evidence class, and the extent to which the reported operating boundaries permit transfer to chromite roasting; no reproducible database-by-database search log, independent dual screening, formal risk-of-bias scoring, or statistical meta-analysis was available. Therefore, the corpus must not be presented as exhaustive. A defensible comparison requires a common basis for chromium recovery, feed grade and particle-size distribution, alkali dosage, oxygen availability, and saleable product output. Sources missing these descriptors may support methodological or equipment feasibility discussions, but should not be used to calibrate chromite conversion or claim a superior industrial pathway.

The specific contribution is a chemistry-constrained, common-boundary comparison of conventional fuels, hydrogen-containing combustion, electrification, hybrid heating, and waste-heat recovery for oxidative chromite-to-chromate roasting. Studies of reductive chromite processing can inform phase and transport questions but do not validate oxidative sodium chromate yields. The scarcity of direct coupled energy-and-conversion studies prevents a universal technology ranking.

Table 1. Evidence classes and comparison boundaries for fuel and heat-recovery assessment.

Class	Basis	Permitted inference	Limitation
D—direct	Chromite + alkali + oxidizing atmosphere → chromate product	Roasting chemistry and conversion response	Often laboratory-specific
A—analog	Other furnaces/burners; reductive chromite; ferrochrome reduction	Thermal design and engineering hypotheses	Different feed and atmosphere
G—general	Reviews, models, and integrated assessments	Evaluation procedure and screening criteria	No process-specific validation

Note. Classification devised for this review. A qualitative evidence class does not replace experimental replication or independent verification.

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The evidence hierarchy makes a key distinction: industrial readiness of a burner or heat exchanger does not establish readiness of an integrated chromite-oxidation flowsheet. Therefore, process-specific technology readiness level (TRL) terminology is reserved for demonstrably scaled integrated configurations, and no unsupported numerical TRL is assigned (Diesing et al., 2025b; Pereira, 2026c; Vissa et al., 2025).

2.2 Comparable system boundaries

For comparisons across energy carriers, useful thermal duty and specific purchased energy should be reported separately. Electrical demand must include auxiliaries, and any avoided heat input should be checked against the resulting chromium recovery and process emissions. Suggested performance indicators are screening requirements rather than quantitative results; industrial rankings remain provisional until the mass, chromium, sodium, oxygen, and enthalpy balances close on matching operating periods.

The minimum gate-to-gate boundary includes drying, feed heating, alkali decomposition or reaction, chromite oxidation, exhaust-gas transport, air supply, off-gas abatement, and cooling. A broader cradle-to-gate assessment also includes fuel production, electricity generation, oxygen manufacture (if used), additives, and residuals management. Both bases should report energy per tonne of dry feed and per tonne of sodium chromate equivalent at constant yield (Chen et al., 2024; Dubec et al., 2026; Oh et al., 2024; Turek et al., 2024).

For reproducible comparisons, the roasting-stage chromium conversion is $X_{Cr,roast}$ (%) = 100 $n_{Cr,soluble\ chromate\ after\ roasting}$ / $n_{Cr,feed}$, where both quantities refer to elemental Cr moles and the soluble-chromate fraction is determined by a declared analytical leaching/speciation protocol. The final product recovery is $R_{Cr,product}$ (%) = 100 $n_{Cr,in\ saleable\ product}$ / $n_{Cr,feed}$ and must be reported separately; the first ratio is not a substitute for the second. Sodium utilization may be reported as U_{Na} (%) = 100 $n_{Na,in\ target\ saleable\ Na_2CrO_4}$ / $n_{Na,fresh\ reagents}$, provided recycled sodium is reported separately and the

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numerator is placed on a consistent product-equivalent basis. In parallel, define elemental balance closure for i ∈ {Cr, Na} as C_i (%) = 100 (Σ n_i,out)/(Σ n_i,in), with all recycle flows and stock changes included within the declared boundary. These equations specify reporting metrics; they do not imply that full analytical datasets are available in the published literature.

3. Thermal Demands and Combustion Requirements

3.1 Heat and reaction requirements

A first-principles duty model separates sensible heating of ore and reagent, reaction enthalpy, moisture evaporation, wall and shell losses, gas sensible heat, and unconverted or bypassed solids. For a steady boundary, the fuel-plus-electric input equals useful reaction and sensible duties, exhaust and surface losses, and other losses after crediting recovered heat. Reporting one “specific consumption” value without the feed moisture, recycle rates, and product basis can disguise major differences between operating lines (Bisht et al., 2024; Kodanli et al., 2025; Özkan et al., 2024; Poggianti et al., 2024; Qasim et al., 2025).

The thermodynamic function of oxygen must be kept distinct from its combustion function: burner stoichiometry alone does not prove that sufficient oxygen penetrates the chromite–alkali bed. More excess air can improve bulk oxygen supply while increasing flue-gas heat loss and potentially modifying bed temperature. Tests should therefore measure both exhaust oxygen and conversion across the solids residence-time distribution (Mvita et al., 2024; Qi et al., 2023; Sanchez-Segado et al., 2025).

Define the combustion excess-air ratio λ_comb = $n_{O_2,\text{air supplied to burner}}$ / $n_{O_2,\text{stoichiometric}}$ for complete fuel combustion. Oxygen for chromite oxidation is an additional process demand, and λ_comb does not alone establish the bed oxygen potential. The oxygen balance should identify combustion air, supplemental process oxidant, oxygen enrichment, ingress, reaction consumption, residual O_2, and off-gas flow, with wet/dry reporting basis and uncertainties stated. Oxygen profiles, residence-time distribution, bed-

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temperature maps, hot/cold zones, and conversion should be measured together whenever technically feasible. A representative elemental oxygen-balance expression is $\Sigma n_{O,in} - \Sigma n_{O,out} - \Delta n_{O,inventory} = 0$, where chemical oxygen is counted consistently in gas and condensed phases.

With a consistent enthalpy reference and no double counting of heat circulating within the system, the steady-state thermal balance can be expressed as $Q_{fuel} + W_{electric} + H_{feed,in} + H_{air,in} = \Delta H_{reactions} + Q_{sensible,products} + Q_{evaporation} + Q_{offgas} + Q_{surface} + Q_{other}$. A recovered-heat stream crossing an explicitly chosen sub-boundary may be entered as an internal transfer, but must cancel at plant-wide boundary level. Useful thermal duty is the reaction, drying, and feed-heating duty required to meet the verified product specification, whereas purchased final energy comprises delivered fuel on a stated LHV/HHV basis and metered electricity including auxiliaries. Report $E_{feed} = E_{purchased}/m_{dry\text{-}feed}$ and $E_{product} = E_{purchased}/m_{saleable\text{-}Na_2CrO_4\text{-}equivalent}$, together with the independently measured chromium conversion, sodium utilization, energy-balance residual, and propagated uncertainty. Any heat recovery benefit must be adjusted for additional fan/pump electricity and downtime.

3.2 Thermal gradients and scale-dependent performance

In rotary equipment, radiation, convection, contact with refractories, particle-bed mixing, and residence-time distribution interact. Replacing a luminous flame with indirect electric heating redistributes local fluxes even when the nominal furnace setpoint is unchanged. Literature on rotary kiln modeling and shell losses provides methods for estimating gradients; its numerical output should not be transferred to chromite without geometry and feed calibration (Gull et al., 2025; Ma et al., 2025a; Poggianti et al., 2024; Qasim et al., 2025; Zhou et al., 2025).

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4. Conventional Fuel Options

4.1 Natural gas

Natural gas is a practical benchmark because it offers pipeline delivery, burner control, and a stable supply. Its low particulate and sulfur burdens compared with some solid fuels simplify furnace-gas handling, but its fossil CO_2 remains significant. The relevant comparison is not only lower heating value (LHV), but flame emissivity, gas residence time, air ratio, transfer to the solids, and the effect of flue-gas volume on heat recovery (Bisht et al., 2024; Jacas-Portuondo et al., 2025; Pisciotta et al., 2022).

4.2 Coal, coke, and other solid fuels

Solid fuels may offer supply or price advantages and high radiant intensity, but ash chemistry, sulfur, heterogeneous burnout, and local reducing zones can complicate processes that require chromite oxidation. Mineral ash can contribute Si, Al, Ca, and Fe to deposits or reaction mixtures, altering alkali availability. Other coal-fired rotary kilns have examined co-firing or hydrogen lancing, but these results support only a bounded transferability hypothesis (Baqain et al., 2024; Colin et al., 2025; Ma et al., 2025a).

4.3 Fuel oils and liquid fuels

Fuel oils offer stored energy and operational flexibility but may increase sulfur oxides, particulates, atomization, and maintenance requirements. Steam-assisted liquid-fuel burner studies establish possible control approaches, not chromite-specific conversion outcomes. Screen a fuel-oil option alongside refractory fouling, gas treatment, tankage, and burner turndown (Kopyev et al., 2024; Pereira, 2026a).

Table 2. Qualitative screening of candidate heat carriers for oxidative roasting.

Carrier	Principal potential	Main process risk	Evidence status
Natural gas	Controllable flame, established logistics	Direct fossil CO_2 and flue-gas heat losses	Industrial combustion analogue

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Carrier	Principal potential	Main process risk	Evidence status
Coal/coke	Potential cost and radiant heat advantages	Ash, sulfur, incomplete burnout, reducing pockets	Kiln analogue
Fuel oil	Storage and dispatch flexibility	SO_x, deposits, atomization	Burner analogue
H_2/NG blend	Lower direct fuel-carbon intensity	NO_x, flame shape, hydrogen sourcing	Pilot/burner analog
Direct electricity	No on-site fuel combustion	Heat-flux distribution, grid footprint	Cross-sector analogue
Hybrid heat	Retains combustion controllability	System complexity and capital cost	Conceptual integration

Note. All entries are qualitative. Fuel rankings must use actual supplier certificates, emissions factors, oxygen balance, and equivalent chromium conversion; no universal quantitative fuel property has been assumed.

The table emphasizes that the cheapest delivered energy carrier cannot automatically be the best process choice. A defensible decision retains a conversion floor and emission limits as constraints before optimizing lifetime cost.

5. Alternative Fuels and Low-Carbon Energy Carriers

5.1 Hydrogen and hydrogen–natural gas blends

Hydrogen blending can reduce direct CO_2 from oxidizing the fuel carbon, but the reduction is not proportional to volumetric blend percentage because hydrogen and methane have different volumetric energy contents. Experimental and computational studies of flame geometry, NO_x formation, heat flux, and oxy-fuel conditions demonstrate why pressure regulation, burner design, and mixing must be requalified instead of assuming direct substitution (Aliyu et al., 2024; Ambrazevičius et al., 2025; Barreiro et al., 2024; Dell'Agli et al., 2026; Dzurňák et al., 2026; Florean et al., 2024; Guo et al., 2025; Lan et al., 2024; Le et al., 2025; Lim et al., 2024; Lopez-Ruiz et al., 2024; Madhu et al., 2025; Pan et al., 2023; Pinto et al., 2025; Ravotti et al., 2026; Salcı et al., 2025; Schwarz et al., 2024a; Schwarz et al., 2024b; Swaminathan et al., 2023; Swaminathan et al., 2024; Weidinger et al., 2025; Zhou et al., 2026).

Several furnace and kiln studies explore hydrogen addition and low-NO_x strategies, yet an oxidizing chromite environment places an additional burden on oxygen supply to the bed.

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Hydrogen production emissions, purity, storage, flame stability, and flame-monitoring capability must be included in the boundary. Numerical flame studies should be linked to measured heat fluxes and solids conversion in any demonstration (Colin et al., 2025; Daurer et al., 2025; Dostiyarov et al., 2024; Gołdasz et al., 2024; Liu et al., 2026a; Shahabuddin et al., 2024; Soroka et al., 2025; Tomozawa, 2025).

For hydrogen–natural gas blending, report hydrogen volume and molar fractions at a declared reference pressure and temperature; for an ideal gas mixture, these fractions are equivalent. Report the hydrogen energy fraction separately as $f_{H_2,LHV} = (y_{H_2} \times LHV_{H_2,molar})/(\Sigma_j\ y_j \times LHV_{j,molar})$. Include total burner thermal input, fuel composition, hydrogen production route and upstream kg CO_2e per kg H_2, delivery compression and storage, flame stability, heat-flux pattern, NO_x, and turndown. A volumetric substitution percentage is not a direct CO_2 reduction percentage.

5.2 Biomass-derived gas, ammonia, and alternative carriers

Low-carbon classification is contingent on verifiable upstream carbon accounting and suitable fuel quality. Variable heating value, contaminants, alkali interactions, combustion stability, and supply availability can offset an apparent fuel advantage. Ammonia combustion introduces fuel-nitrogen management; waste-derived gas faces gas-cleaning and availability barriers. Accordingly, the present evidence does not support an industrial chromite-roasting performance claim for either option (W. Chen et al., 2025; Pereira, 2026b; Tomozawa, 2025).

6. Fuel Properties and Combustion Performance

6.1 Fuel certification and burner criteria

An actionable fuel specification requires LHV and higher heating value (HHV) on declared bases, elemental composition, moisture and ash, sulfur and nitrogen, impurity limits, density, Wobbe index for gases, dynamic supply pressure, viscosity for liquids, and ash fusion indicators for solids. Each should be paired with permissible operating windows for flame

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temperature, excess oxygen, turndown, emissions, and solids conversion. Combustion studies confirm that nominal burner rating is insufficient to predict process transfer efficiency (Ahn, 2024; Di Nardo et al., 2025; Dostiyarov et al., 2024; Gołdasz et al., 2024; Lan et al., 2024; Pinto et al., 2025).

6.2 Emissions and atmosphere control

Thermal NO_x can increase when flame temperature and oxygen availability are elevated; changing equivalence ratio to reduce NO_x may nevertheless alter oxygen provision to the roasting charge. Oxy-fuel retrofit studies additionally highlight that dilution and radiation vary with furnace-gas composition. SO_2, particulate, and potential Cr(VI)-containing dust should be controlled by a separate, composition-informed abatement design rather than inferred from the fuel substitution itself (Ahn, 2024; Baqain et al., 2024; Barreiro et al., 2024; Geum et al., 2024; Guo et al., 2025; Le et al., 2025; Pan et al., 2023; Ravotti et al., 2026; Schwarz et al., 2024a).

7. Waste-Heat Recovery Opportunities

7.1 Exhaust-gas and hot-solids heat recovery

Recoverable energy has both quantity and quality: high-temperature exhaust may preheat combustion air or process feed, whereas lower-grade sources may serve drying, water heating, or ancillary processes. The exhaust stream requires assessment for entrained alkaline dust, possible chromium compounds, corrosion, and exchanger cleanability. Kiln and other industrial heat-recovery studies offer relevant exchanger models, but reported savings must not be copied into chromite scenarios without temperature, mass-flow, and fouling data (Bialik et al., 2024; Blaszczuk et al., 2026; Cho et al., 2024; Geum et al., 2024; Hodroj et al., 2024; Kosmadakis, 2024; Ma et al., 2025a; Mahmoudkhani et al., 2025; Poggianti et al., 2024; Tola et al., 2026; Turek et al., 2024; Zima et al., 2026).

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Hot roasted solids offer a second opportunity, provided that controlled cooling maintains product quality and dust containment. Shell heat recovery may appear attractive, but low heat-transfer coefficients, irregular surface temperatures, mechanical access, and the primary purpose of refractory insulation restrict practicality. Thermoelectric shell systems can be investigated as niche electricity-recovery technologies, not presumed large reductions in furnace fuel demand (Gull et al., 2025; Kumar et al., 2026; Ma et al., 2026; Tola et al., 2026; Xiong et al., 2025).

7.2 Thermal upgrading, heat pumps, and power cycles

High-temperature heat pumps, absorption transformers, and thermodynamic cycles can increase the value of industrial waste heat; their applicability depends on the source/sink temperature approach, thermal lift, operating hours, and electrical carbon intensity. A heat pump with a 200 °C delivery capability does not automatically satisfy a substantially hotter roasting bed, but may serve drying, preheating, or utilities. Cement and other process industries provide the appropriate analog evidence (Ahmad et al., 2026; Ayou et al., 2025; Bellos et al., 2025; Fisher et al., 2024; Hu et al., 2024; Kasaeian et al., 2025; Khanmohammadi et al., 2025; Kitanovski et al., 2025; Liu et al., 2024; Liu et al., 2026b; Manalac et al., 2025; Niknam, 2025; Obstawski et al., 2025; Pan et al., 2025; Park et al., 2026; Pimm et al., 2023; Rahbari et al., 2025; Sun et al., 2023; Tang et al., 2026; Vieren et al., 2023; Villa et al., 2025; Wang et al., 2025; Wu et al., 2025).

Where electricity generation is considered, a low-grade waste stream may yield modest net power after parasitic loads and seasonal duty changes. Thermal recovery should therefore prioritize direct, process-compatible use before power generation, unless exergy analysis and site-specific economics demonstrate the reverse (Fisher et al., 2024; Kasaeian et al., 2025; Kumar et al., 2026; Wang et al., 2025; Zima et al., 2026).

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Table 3. Candidate heat-recovery interventions and feasibility gates.

Source	Potential sink	Principal constraint	Required measurement
Cleaned hot off-gas	Air/feed preheating	Dust, dew point, corrosion	Flow, composition, time series
Hot roasted solids	Feed or secondary air	Dust containment, solids handling	Discharge temperature and cooling rate
Kiln shell	Low-grade utility or TEG	Surface gradients and accessibility	Mapped external heat flux
Low-grade utility losses	Heat pump/heat transformer	Temperature lift, duty coincidence	Source/sink temperature profiles
High-grade excess gas heat	Power or thermal storage	Net cycle efficiency and utilisation	Year-round heat availability

Note. These are opportunities, not commitments of recoverable energy. Thermal and chemical compatibility, exchanger fouling, and net parasitic demand require design validation.

As Table 3 implies, thermal cascade quality is more meaningful than a gross heat-loss inventory. Temperature overlap and operating simultaneity determine whether two streams can actually exchange heat.

Net recovered duty should be calculated from time-resolved source/sink mass-flow and enthalpy data after accounting for availability, duty coincidence, minimum approach temperature, exchanger fouling, pressure drop, fan and pump electricity, cleaning frequency, isolation, and emergency bypass. Roasted-solids heat recovery requires confirmation of phase stability, downstream leachability, particulate containment, and product quality. Report heat-pump source and sink temperatures, lift, coefficient of performance (COP = delivered heat / electrical energy consumed), and the electrical emissions factor; a heat pump is not presumed suitable for the roasting-bed duty.

8. Heat Integration and Pinch Analysis

8.1 Pinch targeting and energy balances

Pinch analysis should begin with measured time-resolved heat-source and sink streams, not simply design-point temperatures. Composite curves establish theoretical minimum heating and cooling utilities under a declared minimum temperature approach (ΔTmin), while

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exchanger network synthesis introduces fouling, pressure drop, controllability, and space constraints. Refinery and industrial examples demonstrate the framework but are not validation of a chromite-specific exchanger network (Alhajri et al., 2021; Andayesh et al., 2023; Atuonwu, 2025; Boldyryev et al., 2025a; Boldyryev et al., 2025b; Ding et al., 2024; Gilani et al., 2025; Guo et al., 2026; Lei et al., 2024; Pan et al., 2025; Walmsley et al., 2024; Zhi et al., 2024).

A minimum-cost network is not necessarily optimal if it couples fluctuating units, increases downtime risk, or compromises dust-removal maintenance. Digital monitoring and advanced control can improve duty estimation and tracking while remaining dependent on calibrated sensors, material balances, and representative disturbance scenarios (Y. Chen et al., 2025; Dai et al., 2025; Jacas-Portuondo et al., 2025; Qi et al., 2025; Tang et al., 2025).

Pinch screening must declare ΔT_{min}, the temperature approach for the stream set and corresponding operating mode. Time-varying composites and theoretical minimum utility targets must be followed by a physical exchanger-network appraisal covering mechanical footprint, dust/corrosion, maintenance isolation, controls, emergency bypass, and parasitic power. Exergy-quality and temporal-coincidence checks should precede claims of achievable savings.

8.2 Integrated heat network

Figure 1 maps the preferred conceptual sequence of air or feed preheating, gas treatment-compatible recovery, and optional thermal storage. No arrow implies a confirmed retrofit: gas cleaning sequence, corrosion risk, heat-exchanger bypass, and emergency operation must be engineered.

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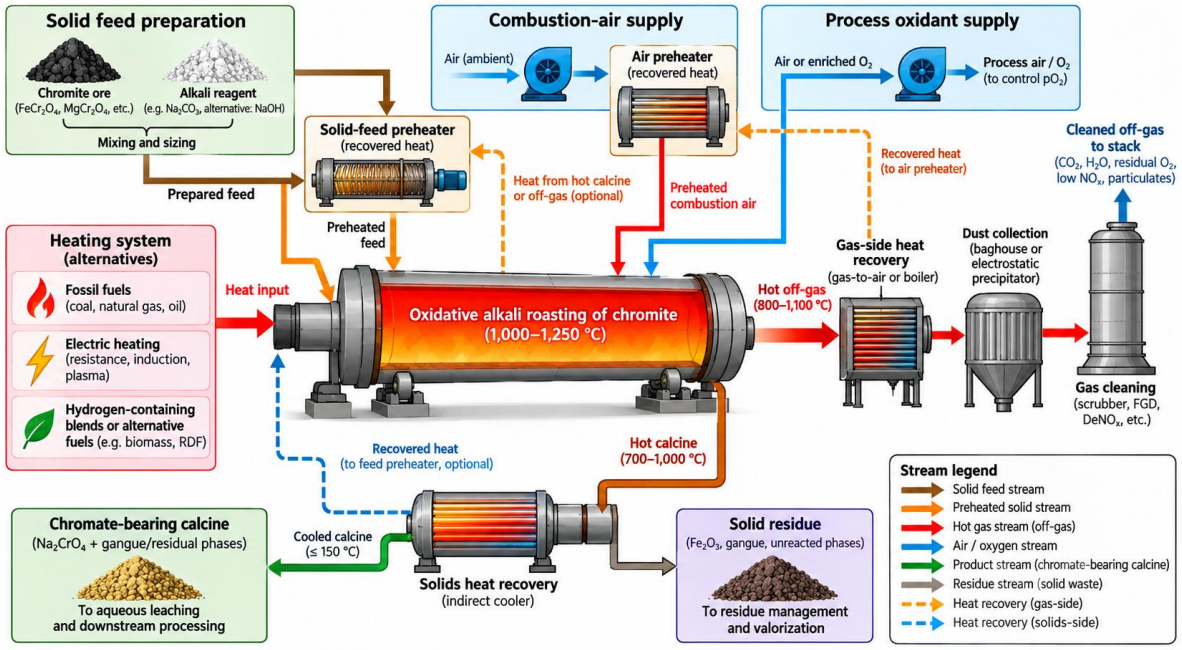

Figure 1. Conceptual waste-heat recovery architecture linking oxidative roasting, exhaust heat, and feed/air preheating.
Note. Original diagram developed for this review, informed by general heat-integration principles; it is not adapted from any single published figure and contains no measured energy flows.

The main design implication is to avoid recovering energy in ways that cool gases below safe transport conditions or reintroduce chromium-bearing dust into clean material circuits. Heat recovery should be integrated with the environmental control architecture, not designed as an isolated energy project.

9. Electrification and Hybrid Heating Systems

9.1 Direct, indirect, and hybrid heating

Direct resistance, indirect electrically heated walls, induction-assisted systems, and hybrid burners can decouple thermal input from fossil combustion. Their suitability differs substantially with particle conductivity, refractory heat transfer, bed geometry, oxygen delivery, peak-power demand, and temperature control. Electrified kilns and furnace models from magnesite, cement, and steel applications establish plausible configurations but not

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chromium oxidation equivalence (Asar et al., 2025; Bhardwaj et al., 2024; Knorr et al., 2025; Leicher et al., 2024; Madeddu et al., 2020; Masuku et al., 2024; Muñoz-Maldonado et al., 2023; Peppas et al., 2026; Quevedo Parra et al., 2023; Vissa et al., 2025).

Hybrid heating retains an oxidizing-gas circuit while shifting some sensible heating to low-carbon electricity. Its advantages can include staged retrofit, flexible dispatch, and operating redundancy; drawbacks include dual systems, electricity-demand charges, and novel heat-flux patterns. A future proof of concept should match not merely output temperature but the bed's thermal history and chromate selectivity (Bolson et al., 2026; Diesing et al., 2025a; Knorr et al., 2025; Leicher et al., 2024; Madeddu et al., 2020; Muñoz-Maldonado et al., 2023; Peppas et al., 2026; Vissa et al., 2025).

Qualification of electrical or hybrid heating should include installed and peak MW, annual metered MWh, electrical load factor, grid-connection upgrades, transformer and standby capacity, ancillary power, backup strategy, the hourly or marginal grid-emissions factor where decision-relevant, and product-equivalent energy intensity. Local furnace setpoint alone cannot prove equivalence of solids temperature–time histories, oxygen profiles, or chromium yield.

9.2 Thermal storage and flexibility

Thermal batteries, pumped thermal storage, and integrated control may moderate electricity price fluctuations, although the extra storage cycle introduces losses and capital expenditure. Their feasibility depends on cycling frequency and permissible temperature variation rather than installed storage capacity alone (Asar et al., 2025; Ma et al., 2025b; Meng et al., 2026; Tang et al., 2025).

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10. Carbon-Emission Reduction Potential

10.1 Consistent emissions accounting

A fuel switch should be evaluated using both plant-direct emissions (Scope 1) and electricity-related emissions (Scope 2), with upstream fuel, additives, and logistical impacts reported separately where the boundary includes them. A carbon-free furnace stack is not equivalent to a zero-carbon product when grid electricity or hydrogen production is emissions intensive. Allocation of shared heat-recovery benefits must be declared to prevent double counting (W. Chen et al., 2025; Chen et al., 2024; Diesing et al., 2025a; Dubec et al., 2026; Madeddu et al., 2020; Markussen et al., 2025; Niknam, 2025; Pisciotta et al., 2022).

Scenario comparisons should retain a common product functional unit and constant chromium yield. If one option lowers fuel consumption but increases residual chromite or alkali use, an apparent per-tonne-feed saving may vanish per tonne of saleable sodium chromate. Uncertainty analysis should consider hourly electricity emissions, fuel certificates, system utilization, heat recovery, and conversion sensitivity (Bolson et al., 2026; Diesing et al., 2025b; Markussen et al., 2025; Oh et al., 2024; Pisciotta et al., 2022).

Define cradle-to-gate GHG intensity as I_GHG = (GHG_Scope1 + GHG_Scope2 + included upstream GHG − valid non-duplicated external credits)/m_saleable-Na_2CrO_4-equivalent, expressed in kg CO_2e t^{-1}, with all boundary choices and emission factors disclosed and the same recovery and product specification enforced. Do not count internal heat reuse as an avoided purchased input more than once. Report NO_x, SO_x, particulates, Cr(VI)-bearing dust, residues, and effluents as independent compliance constraints, even where GHG intensity declines.

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10.2 Comparable scenarios

Figure 2 shows a sequence for comparing baseline firing, heat-recovery-first modification, and hybrid electricity with exactly the same conversion and product specification gates. The figure is a comparison protocol; it does not plot invented energy savings or carbon reductions.

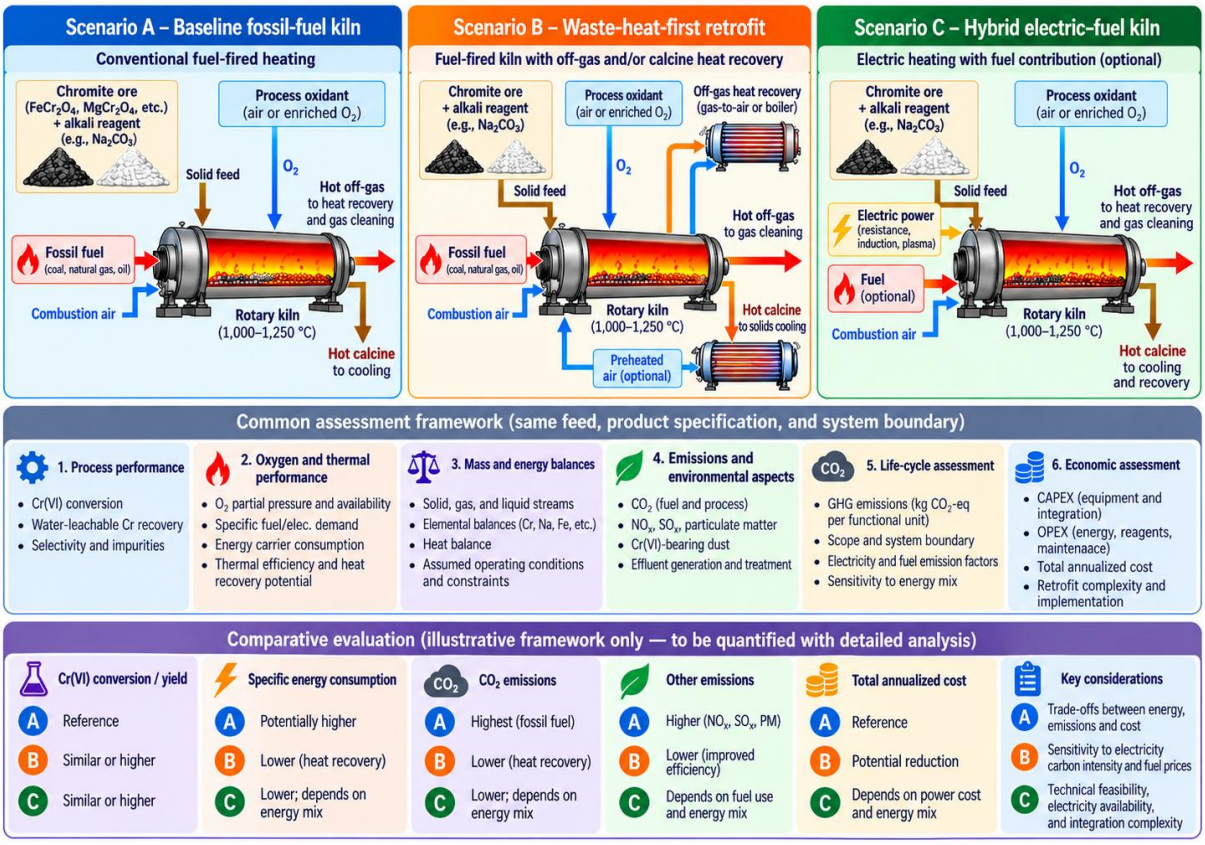

Figure 2. Decision structure for baseline, heat-recovery-first, and hybrid-heating scenarios.
Note. Original conceptual comparison by the author; pathways are hypotheses requiring harmonized measurements, not externally published quantitative scenarios.

A lower-carbon scenario is feasible only if measured operations satisfy simultaneous chromate yield, gas-control, thermal-performance, availability, and environmental thresholds. This multi-constraint definition prevents emissions-only optimization from displacing a technical burden into product losses or waste treatment.

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Table 4. Normalized multi-criteria scenario comparison and reporting requirements.

Indicator	Reporting basis	Critical qualification
Thermal efficiency	Useful duty / purchased heat	Fixed boundary and operation
Specific final energy	GJ per t dry feed and product	Feed moisture and conversion held constant
Chromium conversion	Moles chromium in target chromate/feed Cr	Measured speciation and reconciliation
GHG intensity	kg CO_2e per t product	Scopes and factors disclosed
NO_x, SO_x, particulates	Mass per t product and legal units	Control configuration stated
Economics	NPV / lifecycle cost with uncertainty	Local energy tariffs and capital costs
Availability	Annual net operating hours	Maintenance and reliability included
Sodium utilization and closure	U_Na (%) and C_Na (%)	Na in fresh/recycled reagent, product, residue, dust, and liquor
Chromium closure	C_Cr (%)	Cr in feed, calcine/product, dust, residue, and effluent
Thermal balance uncertainty	Energy residual (%) ± uncertainty	Define enthalpy reference and avoid recovery double credit
Oxidant balance	λ_comb and separate oxidant/O_2 flows	Do not use stack O_2 as proxy for bed oxidation
Electric power demand	Peak MW, MWh, load factor	Include auxiliaries and power-system upgrade

Note. No values are reported because REV7 does not contain a harmonized plant dataset for these indicators. Rows are mandatory comparisons, not estimated outcomes.

Table 4 defines the minimum data needed for a defensible ranking. A cross-sector scenario may clarify parameter sensitivity but must not be relabeled as a chromite demonstration.

11. Technical, Economic, and Operational Trade-Offs

11.1 Retrofit reliability, economics, and environmental control

Capital costs should cover burners or electric heaters, electrical infrastructure, refractory change, heat exchangers, ductwork, gas cleaning, controls, storage, and shutdown requirements. Operating costs include energy, oxygen or combustion air, fan power, maintenance, reagents, ash handling, residue treatment, and losses caused by conversion deterioration. Conventional net-present-value calculations are insufficient without deployment

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risk and operational reliability, especially when feed mineralogy varies (Bisht et al., 2024; Diesing et al., 2025b; Ding et al., 2024; Jacas-Portuondo et al., 2025; Markussen et al., 2025; Özkan et al., 2024; Pereira, 2026c).

Chromium-bearing residues and process effluents remain a critical boundary condition. Studies of chromate and chromium oxide production show distinct process objectives and mechanisms; they must not be conflated with energy-only roasting performance. Environmental design should monitor Cr(VI) deportment, captured dust management, leachability, and treatment responsibilities when modified gas flow changes the capture burden (Li et al., 2024; Mu et al., 2024; Pereira, 2026d; Prasad et al., 2021; Qi et al., 2023; Sanchez-Segado et al., 2025; Tian et al., 2025; Zhong et al., 2026).

Plant availability is A (%) = 100 t_net operating / t_scheduled, with scheduled and unplanned downtime distinguished and the effect of heat-exchanger cleaning, refractory replacement, dual-heater servicing, and commissioning explicitly recorded. Economic comparison should evaluate lifecycle cost or NPV inclusive of process-conversion losses, burners, electric equipment, grid connections, storage/compression where applicable, gas cleaning, controls, refractory impacts, retrofit outages, ramp-up, maintenance, and uncertainty; perform sensitivity to fuel/electricity price, emissions factors, hydrogen cost, and chromium yield.

11.2 Research gaps and experimental verification

The main gap is a common, experimentally reconciled baseline. A pilot program should vary one thermal variable at a time after characterizing the feed, while documenting oxygen profile, temperature gradients, residence time, chromate yield, sodium recovery, soluble impurities, NO_x, and particulate entrainment. Measure kiln shell losses, off-gas thermal states, and controllability during stable runs and realistic disturbances (Dai et al., 2025; Mvita et al., 2024; Qasim et al., 2025; Qi et al., 2025; Tang et al., 2025).

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Table 5. Minimum verification program before technology selection.

Gate	Evidence required	Failure criterion
Feed baseline	Mineralogy, Cr assay, PSD, moisture, alkali ratio	Non-comparable feed batches
Process response	Temperature, O_2, residence distribution, Cr(VI) yield	Yield or quality degradation
Thermal closure	Calibrated fuel/power, gas/solid enthalpy	Unclosed material or heat balance
Environmental controls	Stack testing, dust speciation, gas cleaning	Regulatory noncompliance
Scale-up	Continuous demonstration, availability, fouling	Unacceptable instability
Decision basis	CAPEX, OPEX, CO_2e, uncertainty	No robust advantage over baseline

Note. Proposed test matrix for this review, not a quotation of measured study results. Product quality and occupational/environmental safety are binding constraints.

Table 5 turns the literature limitations into falsifiable operating gates. Successful heater testing without confirmed ore conversion, material handling, and emissions performance is insufficient to claim deployment readiness.

11.3 Staged industrial implementation

Figure 3 proposes a sequence that first establishes mass and energy balances, then captures low-risk heat integration and control improvements, and only then evaluates hybrid heat and low-carbon fuels. The sequence is conditional: plants with exceptionally low-carbon electricity and a suitable replacement cycle may rationally consider electrification earlier.

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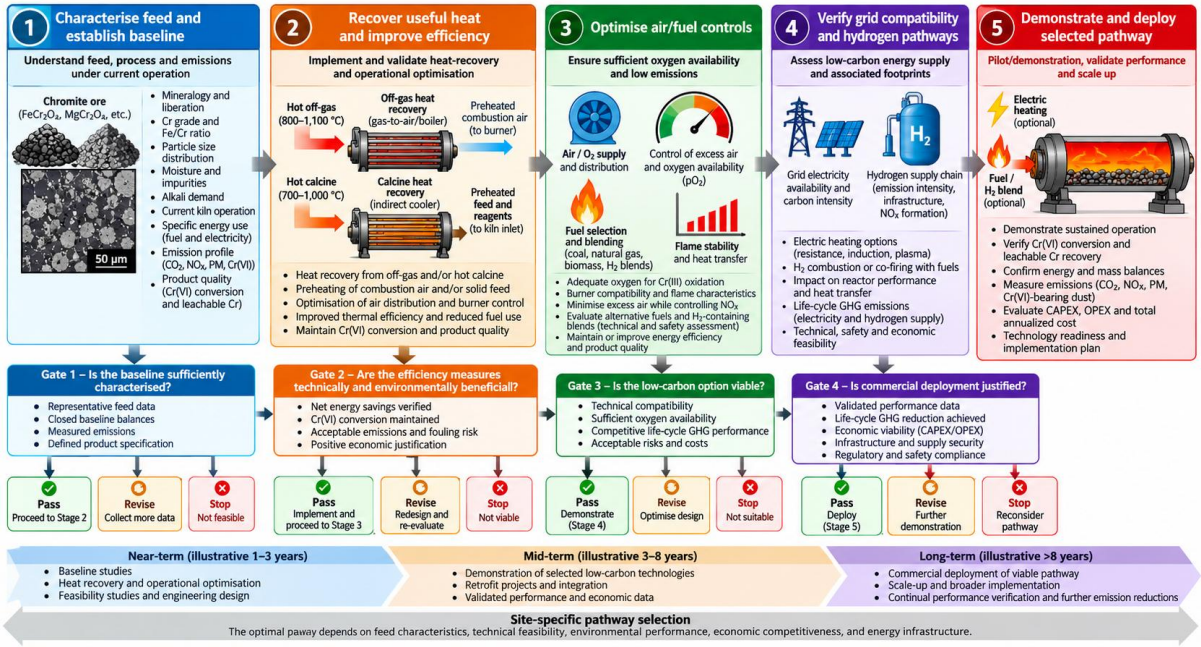

Figure 3. Staged, evidence-gated roadmap for lowering energy demand and greenhouse-gas emissions in chromite oxidative alkali roasting.
Note. Original schematic proposed in this review; not adapted from an external source. Direction indicates assessment sequence, not a universal technology ranking.

Investment decisions should follow the outcomes of these gates. In particular, hydrogen blending is not a necessary transition stage if electric options better satisfy the local power mix and thermal constraints, and recovered heat should not justify the installation of oversized heat-exchange surfaces without reliable demand matching.

12. Conclusions and Future Research

The preferred pathway cannot be determined from fuel heating value or nominal furnace efficiency alone. For oxidative alkali roasting of chromite, oxygen availability, temperature distribution, chromium conversion, alkali balance, and safe handling of chromium-bearing materials must constrain energy-system changes. A heat-recovery-first program supported by measured mass and energy balances offers a defensible initial route to reduce purchased energy without prematurely changing the primary heat-transfer mechanism.

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Hydrogen co-firing, direct electrification, and hybrid systems can be promising but remain conditional for this specific process. Their relative environmental performance depends on energy sourcing and their operational suitability depends on demonstrated heat transfer, emissions, and stable conversion. The central research priority is a directly comparable pilot dataset that reports chromate recovery, energy intensity, flue-gas conditions, operating stability, and life-cycle carbon on a consistent product basis. The conceptual assessment framework and verification gates developed here support future industrial screening, but do not substitute for such validation.

Declarations

Funding. Funding information has not been verified from the materials available for this revision. A definitive declaration must be supplied by the author before submission.

Conflict of interest. The author must confirm the final disclosure of financial and nonfinancial interests before submission; no declaration is inferred from the manuscript.

Data availability. No new experimental datasets were generated for this critical review. The literature dataset and bibliographic metadata require final source-by-source verification before submission.

Author contributions. The sole author performed conceptualization, literature synthesis, critical analysis, visualization oversight, and manuscript preparation.

Declaration of generative AI and AI-assisted technologies. The author must verify whether and how AI tools were used for language editing, figures, or drafting, and provide a journal-compliant disclosure before submission. Scientific responsibility remains with the author.

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