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Cyanidation Leaching of Gold: A Critical Review of Chemistry, Kinetics, Mineralogical Controls, Process Integration, Industrial Performance, and Future Directions

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Abstract

Cyanidation remains the reference hydrometallurgical route for gold extraction because the dicyanoaurate complex is highly stable under alkaline, oxidizing conditions and because the process integrates with mature adsorption, precipitation, and electrowinning circuits. This critical review examines the process as a coupled system rather than as an isolated leaching reaction. It evaluates interfacial chemistry, mixed-potential behavior, mass transfer, mineralogical accessibility, cyanicide reactions, preg-robbing, pretreatment, operating-variable interactions, gold recovery, cyanide recycling, detoxification, and industrial scale-up. Particular emphasis is placed on why nominally similar laboratory extractions frequently diverge at plant scale: feed variability, oxygen-transfer limitations, competing metal complexes, solution recycle, carbon performance, and water chemistry alter the effective operating window. The review also compares conventional cyanidation with intensified and hybrid routes, including glycine–cyanide systems and alternative lixiviants. A mineralogy-to-flowsheet framework is proposed that evaluates recovery, reagent demand, water closure, residue quality, and process risk simultaneously. The synthesis shows that the principal opportunity is not a universal replacement of cyanide but a more selective use of cyanide within integrated, mineralogy-informed, recycle-oriented flowsheets that minimize total environmental and economic burdens while preserving high gold recovery.

Keywords: gold cyanidation; dicyanoaurate; refractory gold; preg-robbing; cyanide detoxification; process integration

Highlights

• Links cyanidation chemistry, mineralogy, kinetics, and plant-scale transport constraints.

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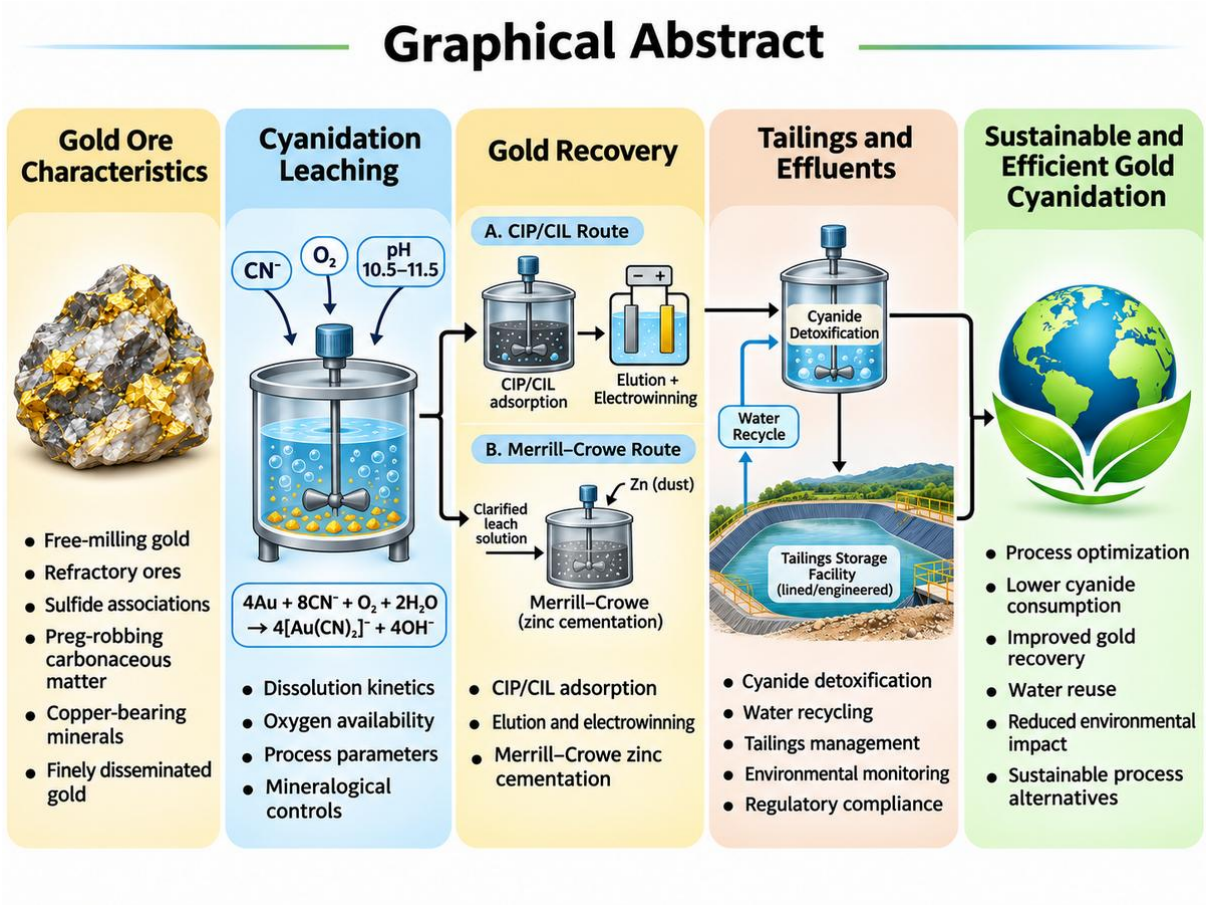
• Distinguishes leach extraction from integrated recovery, recycle, and detoxification performance.
• Compares conventional, intensified, and hybrid routes for complex and refractory gold feeds.
• Proposes a mineralogy-to-flowsheet framework for lower reagent, water, and residue burdens.

Graphical abstract



Graphical abstract. Integrated view of ore characteristics, cyanide leaching, gold recovery, tailings management, and sustainable process improvement.
Note. Visual synthesis prepared for this review. The provenance and reuse permissions of individual graphical assets require confirmation before publication.

1. Introduction

Cyanidation remains the benchmark technology for primary and secondary gold recovery because it combines a strong thermodynamic driving force for $[Au(CN)_2]^-$ formation with a

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process envelope that can be controlled at industrial scale. The mature process family includes agitation leaching, carbon-in-leach (CIL), carbon-in-pulp (CIP), carbon-in-column (CIC), heap leaching, Merrill–Crowe precipitation, electrowinning, and multiple cyanide-recovery strategies. Yet maturity should not be confused with simplicity: cyanide recycle, trace-element deportment, sulfide oxidation, copper complexation, carbon fouling, and solution chemistry couple upstream and downstream operations, so plant performance is governed by the whole circuit rather than by bottle-roll extraction alone (Adams, 2013; Adams, 2016b; Azizi et al., 2014; Celep et al., 2014; Dai et al., 2010; Dai et al., 2012a; Fleming, 2016; Khalid & Larachi, 2017; Kyle et al., 2012; Lapidus & Millard, 2016; Muir, 2011; Pereira, 2026c; Quilaqueo et al., 2020; Rohner & Millard, 2016; Staunton, 2016; Xie et al., 2014; Zhang et al., 2019).

The challenge has intensified as operations treat lower-grade and more mineralogically complex ores. Gold may be liberated, encapsulated in pyrite or arsenopyrite, associated with tellurides or silver minerals, adsorbed by native carbon, or accompanied by copper, arsenic, antimony, and other cyanide-reactive components. These features can change both the accessible gold inventory and the stoichiometric demand for oxygen and cyanide, while pretreatment can create new surface films or soluble species that alter subsequent leaching. Consequently, critical evaluation requires explicit distinction between intrinsic dissolution chemistry, mineralogical liberation, reagent competition, and transport-limited plant behavior.

The structure of this review is summarized by the visual and quantitative elements embedded throughout the manuscript. Figure 1 presents the interfacial reaction sequence and rate controls, Figure 2 links mineralogical classes to pretreatment and recovery choices, Figure 3 integrates leaching with recovery, recycle, and detoxification, and Figure 4 condenses the final decision hierarchy. Table 1 defines the evidence classes and review logic, Table 2 summarizes the main chemical and operating variables, Table 3 compares mineralogical constraints and responses, Table 4 contrasts gold-recovery and cyanide-management routes,

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and Table 5 identifies scale-up gaps and research priorities. These elements are used as analytical devices, not as stand-alone summaries.

The objective is therefore to reassess cyanidation as an integrated hydrometallurgical system, identify conditions under which common operating heuristics break down, and establish a decision framework for choosing direct cyanidation, pretreatment-assisted cyanidation, intensified operation, hybrid lixiviant systems, or alternative routes. The focus is on evidence relevant to chemistry, kinetics, mineralogical controls, process integration, industrial performance, environmental management, and future translation.

2. Review methodology and literature scope

Scope and reproducibility limitation. The assembled bibliography covers mechanistic, laboratory, pilot, industrial, and environmental evidence, but no reproducible database-by-database search log, deduplication record, or study-level quality scores accompanied the manuscript. Accordingly, the evidence classes in Table 1 are interpretive categories rather than formal risk-of-bias ratings. Claims about industrial transferability are treated as conditional on ore mineralogy, solution chemistry, recycle regime, and available plant operating data.

The review draws on a consolidated bibliography of 150 entries assembled for this study; this number describes the supplied corpus rather than the yield of a documented systematic database search. The literature spans fundamental electrochemistry, refractory-ore mineralogy, pretreatment, adsorption and recovery, cyanide recycle, tailings treatment, process control, industrial practice, and emerging lixiviants. Journal articles and authoritative technical chapters were prioritized, while preprints were excluded from the supplied corpus. Because database search histories, screening counts, and exclusion records were not available, the synthesis is presented as a critical narrative review, not as a systematic review or a PRISMA-compliant evidence inventory. Evidence is interpreted by process function rather than by publication sequence, and apparent disagreements are examined against differences in feed mineralogy,

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particle size, solution composition, oxidant supply, residence time, and downstream recovery configuration.

Table 1 presents the evidence classes used to avoid conflating laboratory chemistry with industrial performance. This distinction is critical because a reagent or pretreatment may increase batch extraction but become unattractive when considering oxygen transfer, solid–liquid separation, carbon loading, cyanide recycle, water closure, or residue handling.

Table 1. Evidence classes used in the critical review and their principal interpretive limitations.

Evidence class	Typical scale	Primary value	Main limitation
Fundamental	Electrochemical/molecular	Mechanism, speciation, mixed potential	May not represent reactive gangue or hydrodynamics
Bench leach	Bottle / stirred vessel	Relative extraction and reagent response	Strong sensitivity to grind, slurry chemistry, and oxygen transfer
Pilot / semi-pilot	Continuous or larger batch	Residence-time and recycle effects	Feed campaign may be too short to capture long-term variability
Industrial	CIL/CIP, heap, pressure oxidation, roasting	Integrated mass balance and operability	Commercial data often aggregated or incomplete
Environmental / residue	Tailings, wastewater, field systems	Fate, toxicity, detoxification, water closure	Site-specific chemistry limits direct transfer

Note. Prepared by the author based on the evidence classes represented in the consolidated literature corpus.

The review therefore uses a hierarchy of interpretation: first, whether a mechanism is chemically plausible; second, whether it is observed in mineral-bearing systems; third, whether the effect persists under continuous operation; and fourth, whether the effect improves integrated recovery, reagent use, residue quality, and process robustness. This hierarchy matters especially when comparing conventional cyanidation with pretreatment or alternative-lixiviant studies, where laboratory success can mask downstream penalties.

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3. Chemical and electrochemical fundamentals

3.1. Speciation, mixed potential, and interfacial sequence

The Elsner reaction conventionally represents gold dissolution in alkaline cyanide, but the practical rate emerges from coupled anodic gold oxidation and cathodic oxidant reduction. Cyanide stabilizes dissolved gold as $[Au(CN)_2]^-$, while dissolved oxygen typically supplies the cathodic reaction. The resulting mixed potential depends on dissolved oxygen, cyanide activity, pH, surface state, and the presence of sulfide-derived or metal-derived species. Recent mechanistic and electrochemical studies reinforce that the apparent rate can shift between interfacial and transport control and that lead, sulfide, silver, and other species may alter surface kinetics or passivation (Andrianandraina et al., 2022; Aromaa et al., 2015; Azizi et al., 2010; Azizi et al., 2012; Bas et al., 2017; Birich et al., 2019; Deschênes, 2016; Karimi et al., 2010; Khalid et al., 2018; Larrabure & Rodríguez-Reyes, 2021; Li et al., 2020a; Ma et al., 2026; Matar et al., 2026; Nicol, 2025; Nicol, 2026; Nourmohamadi & Rezai, 2022; Ruan, 2020; Xia et al., 2022).

For alkaline cyanidation with oxygen as the electron acceptor, the balanced anodic and cathodic half-reactions are:

$$Au(s) + 2\ CN^-(aq) \rightarrow [Au(CN)_2]^-(aq) + e^-$$

$$O_2(aq) + 2\ H_2O(l) + 4\ e^- \rightarrow 4\ OH^-(aq)$$

Combining four anodic reactions with the cathodic reaction gives the balanced overall Elsner reaction:

$$4\ Au(s) + 8\ CN^-(aq) + O_2(aq) + 2\ H_2O(l) \rightarrow 4\ [Au(CN)_2]^-(aq) + 4\ OH^-(aq)$$

These idealized equations conserve Au, C, N, O, and H atoms and electric charge. They describe the net oxygen-reduction pathway rather than a universal kinetic mechanism; the actual rate depends on surface state and mass transfer.

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Figure 1 represents these dependencies as a sequence from cyanide adsorption through electron transfer, complex formation, desorption, and diffusion. The figure emphasizes that none of these steps is rate-limiting across the entire operating range; a plant can shift from cyanide limitation to oxygen limitation or surface passivation as solution composition and ore reactivity evolve.

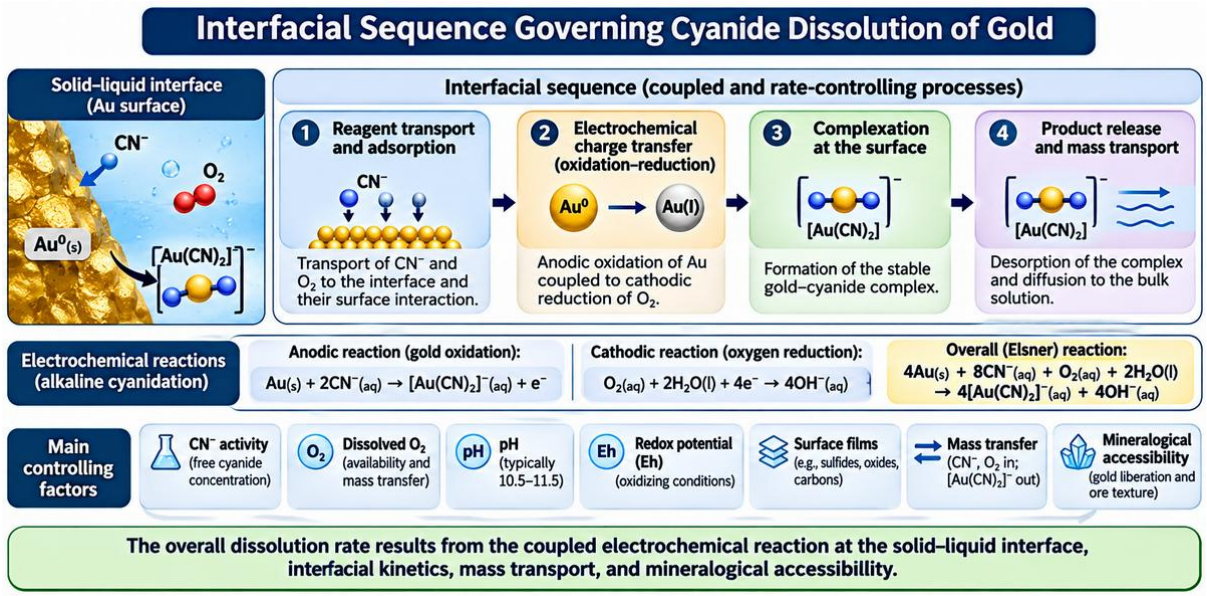

Figure 1. Interfacial sequence and coupled variables controlling the cyanide dissolution rate of gold.
Note. Conceptual synthesis for this review, developed from the mechanistic and electrochemical literature cited in Section 3.

As shown in Figure 1, increasing free cyanide does not guarantee a proportional rate increase when oxygen transfer or surface accessibility is limiting. Conversely, increasing dissolved oxygen can be ineffective where copper consumes cyanide or where passivating films restrict interfacial reaction. A critical interpretation therefore requires paired measurement of free cyanide, dissolved oxygen, pH/Eh, and reactive mineralogy rather than reliance on a single nominal reagent concentration.

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3.2. pH, cyanide stability, and competing complexes

Industrial cyanidation is operated in strongly alkaline media to suppress hydrogen cyanide volatilization and maintain CN^- as the dominant ligand. Lime remains a common pH-control reagent, but alkalinity also affects calcium and carbonate chemistry, sulfate accumulation, recycled process water, and dissolved metals, which can change ionic strength, precipitation, and carbon adsorption behavior. Copper and iron cyanide complexes are particularly important because they redistribute cyanide among species with different reactivity and recoverability. Thus, “free cyanide concentration” is an incomplete descriptor unless you also understand the metal-cyanide inventory and water chemistry.

4. Kinetics, mass transfer, and operating variables

Cyanidation kinetics are often reported as if controlled by a single intrinsic rate constant. Still, plant data are better interpreted as the product of accessible gold area, reaction kinetics, oxygen and cyanide transport, slurry rheology, and residence-time distribution. Grinding can increase exposed surface area and accelerate dissolution, yet excessive fines increase viscosity, hinder oxygen dispersion, alter carbon–slurry contact, and complicate solid–liquid separation. Agitation, dissolved oxygen, oxidant addition, pressure, ultrasound, and model-based control can therefore improve apparent kinetics through different mechanisms (du Plessis et al., 2021; Hulbert & Aldrich, 2016; Jia & You, 2021; Khosravi et al., 2017; Liu et al., 2022; Meretukov, 2025; Nunan et al., 2017; Smith, 2016; Surimbayev et al., 2024; Thomas, 2016a; Welman-Purchase & Hansen, 2023a; Ye et al., 2017; Yu et al., 2020; Zhang et al., 2015).

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Table 2 summarizes the principal variables and why each shows a practical optimum rather than a monotonic benefit. Reported industrial ranges should be treated as starting envelopes, because ore-specific cyanicide demand and oxygen uptake can shift the optimum significantly.

Table 2. Principal operating variables, expected effects, and practical constraints in gold cyanidation.

Variable	Typical operating consideration	Expected benefit	Critical constraint
Free cyanide	Controlled residual rather than maximum dose	Maintains Au complexation and dissolution	Cu, Zn, Fe, S species increase consumption
pH/alkalinity	Strongly alkaline operation	Suppresses HCN and stabilizes CN^-	Very high alkalinity can alter kinetics and scaling
Dissolved oxygen	Air, oxygen enrichment, or selected oxidants	Raises cathodic reaction rate	Mass transfer and ore oxygen demand can dominate
Particle size	Liberation balanced against rheology	Exposes locked gold	Ultrafines raise viscosity and downstream costs
Pulp density	Selected for throughput and gas transfer	Higher solids increase volumetric productivity	High solids reduce oxygen and reagent transport
Residence time	Matched to slowest economically recoverable fraction	Raises final extraction	Long tails in kinetics reduce marginal value
Temperature	Usually near ambient in conventional circuits	Can accelerate reaction	May increase cyanide loss and side reactions

Note. Prepared by the author from the process ranges and mechanistic relationships synthesized in this review.

The most transferable kinetic insight is therefore not a universal activation energy or reagent optimum, but the need to identify the controlling resistance under the actual slurry chemistry. Tests that vary cyanide while holding oxygen poorly controlled can misattribute mass-transfer effects to chemical kinetics; similarly, oxidant tests performed on one grind size may not translate to another because liberation and gas–liquid transfer change simultaneously.

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5. Mineralogical controls and pretreatment

5.1. Refractory sulfides, preg-robbing, and cyanicide minerals

Mineralogy is the central boundary condition for cyanidation. Gold encapsulated in pyrite, arsenopyrite, or other sulfides can remain physically inaccessible; carbonaceous matter can adsorb dissolved $[Au(CN)_2]^-$; copper minerals can consume cyanide and alter adsorption; and arsenic-, antimony-, tellurium-, lead-, and silver-bearing phases can change both surface chemistry and downstream deportment. The literature consistently shows that these effects are not adequately represented by head grade alone, and that diagnostic mineralogy should distinguish liberated gold, locked gold, preg-robbing capacity, reactive sulfides, and cyanicide phases (Asamoah et al., 2018; Asamoah et al., 2021; Baron et al., 2016; Bas et al., 2012; Bas et al., 2015; Bidari & Aghazadeh, 2018; Celep et al., 2011a; Celep et al., 2011b; Celep et al., 2015; Chryssoulis & McMullen, 2016; Eksteen & Oraby, 2015; Ellis & Deschênes, 2016; Fleming, 2010b; Hu et al., 2017; Kanayev et al., 2016; Karimi Darvanjooghi et al., 2024; Konadu et al., 2020; Kyle et al., 2015; Li et al., 2020b; Lin et al., 2022; Lunt & Briggs, 2016b; Medina & Anderson, 2020; Mendoza & Lapidus, 2017; Miller & Brown, 2016a; Miller et al., 2016b; Msumange et al., 2023; Muir, 2012; Oraby & Eksteen, 2016; Pereira & Barbosa, 2017; Pereira et al., 2019; Pereira, 2025; Pereira, 2026a; Pereira, 2026b; Piervandi, 2023; Thomas & Cole, 2016b; Yazici et al., 2014; Yazici et al., 2015; Zhang et al., 2020; Zhang et al., 2021b; Zheng et al., 2016; Zhou & Gu, 2016).

Figure 2 converts these mineralogical observations into a flowsheet logic. The central principle is that pretreatment should target the limiting mechanism: liberation for encapsulated

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gold, oxidation for refractory sulfides, carbon management for preg-robbing, and selective removal or complex-management for high cyanicide ores.

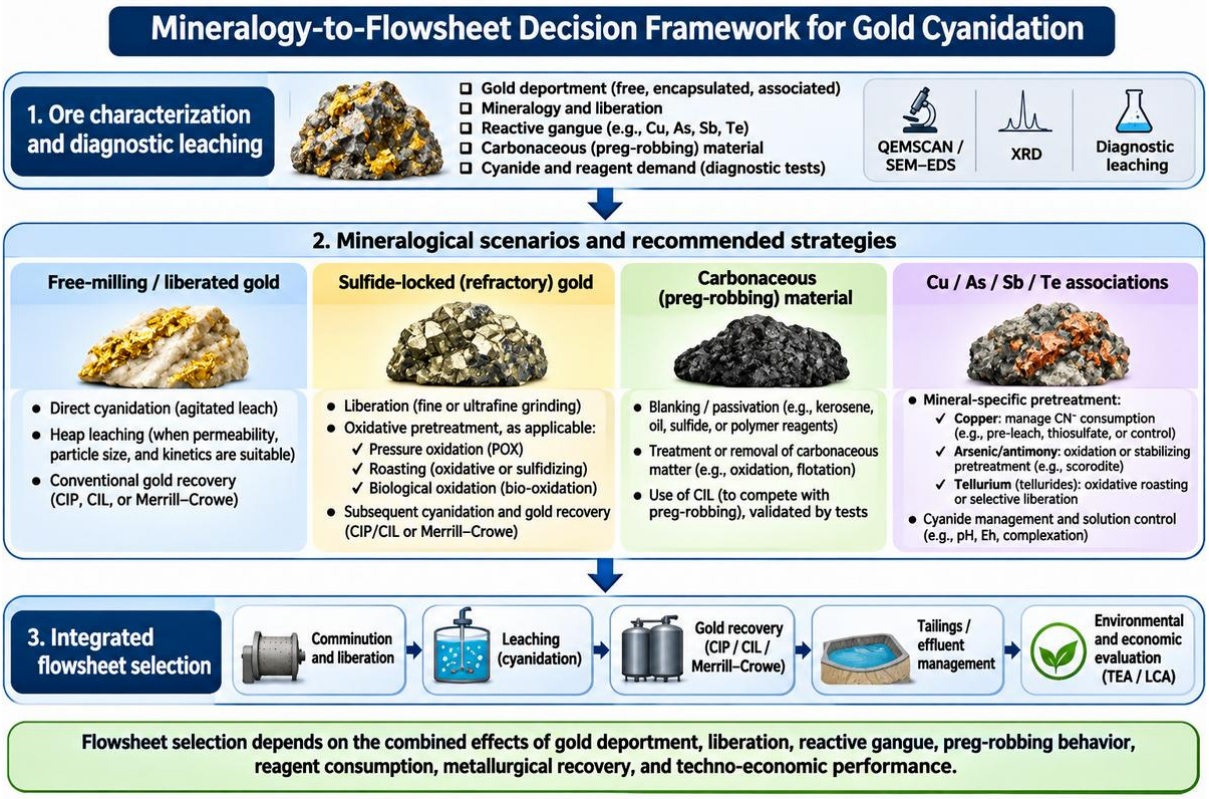

Figure 2. Mineralogy-to-flowsheet decision framework for selecting direct cyanidation or pretreatment-assisted routes.
Note. Conceptual synthesis prepared for this review from the mineralogical and pretreatment studies discussed in Section 5; graphical-asset provenance requires confirmation.

Figure 2 also highlights why a single “refractory” label is insufficient. Two ores with equally low direct-cyanidation recovery may require fundamentally different interventions: ultrafine grinding can expose submicroscopic gold without removing preg-robbing carbon, whereas oxidation can destroy sulfide matrices but generate iron phases or soluble species that

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alter subsequent cyanidation. Pretreatment evaluation must therefore include the chemistry of the treated residue, not only increased gold exposure.

5.2. Pretreatment options and secondary effects

Roasting, pressure oxidation, biological oxidation, alkaline or acid conditioning, ozonation, and ultrafine grinding appear in the literature as routes to improve cyanide accessibility. Their benefits are ore-dependent and must be weighed against secondary effects such as basic iron sulfate formation, residual sulfur species, acid or alkali neutralization demand, arsenic stabilization, carbon destruction, and changes in particle-size distribution. The strongest industrial cases link the pretreatment mechanism to mineralogical characterization and downstream cyanidation behavior rather than assessing it only by pre- and post-treatment extraction.

Table 3 summarizes the dominant mineralogical constraints and the corresponding process responses. The table should be read as a decision aid rather than as a prescriptive matrix, because mixed ores frequently express several constraints simultaneously.

Table 3. Mineralogical constraints, diagnostic indicators, and process responses relevant to cyanidation.

Constraint	Diagnostic indication	Likely cyanidation impact	Potential response
Sulfide encapsulation	Au within pyrite/arsenopyrite; low liberation	Slow or incomplete extraction	BIOX, POX, roasting, UFG, or combinations
Preg-robbing carbon	High preg-robbing index / organic carbon	Re-adsorption of $[Au(CN)_2]^-$	CIL strategy, carbon blinding, oxidation, competitive adsorption control
Copper minerals	High cyanide-soluble Cu	High cyanide consumption and copper(I) cyanide complexes formation	Selective pre-leach, ammonia/glycine-assisted systems, cyanide recovery
As/Sb/Te-bearing phases	Refractory mineral association and toxic trace elements	Passivation, slow kinetics, residue-management burden	Mineralogy-specific oxidation or alkaline conditioning

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Constraint	Diagnostic indication	Likely cyanidation impact	Potential response
Fine locked gold	Submicroscopic inclusions	Low accessible surface area	Fine/UFG grinding with rheology control
High silver association	Electrum or silver minerals	Altered kinetics and recovery route	Adjust residence time, recovery circuit, and precipitant/adsorbent strategy

Note. Prepared by the author from the mineralogical and pretreatment literature cited in Section 5.

The critical implication from Table 3 is that pretreatment selection cannot be optimized against extraction alone. It must be evaluated against reagent carryover, solid–liquid behavior, carbon performance, solution recycle, detoxification requirements, and residue stability. This integrated view explains why some highly effective laboratory pretreatments have limited industrial uptake.

6. Process control, water chemistry, and plant integration

Industrial cyanidation operates as a dynamic system in which feed grade, grind, sulfide content, soluble copper, alkalinity, and process-water composition vary continuously. Conventional control based on pH and free cyanide is increasingly supplemented by dissolved oxygen, online analyzers, soft sensors, hybrid models, and economic model-predictive control. However, model quality depends on whether the measured variables adequately represent hidden state variables such as mineral reactivity, carbon activity, residence-time distribution, and solution recycle. Process simulation and hybrid modeling studies demonstrate the value of dynamic control, while also showing that poorly characterized feed variability can dominate prediction error.

Water recycling is especially important. Recirculation reduces freshwater demand and can recover residual cyanide, but it also accumulates thiocyanate, sulfate, metal-cyanide species, dissolved salts, and degradation products. These species can affect leaching kinetics, carbon adsorption, scaling, and detoxification demand. Consequently, cyanide recycle should be

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assessed as part of a water-quality control strategy rather than as an isolated reagent-saving measure.

7. Gold recovery, cyanide recovery, and downstream coupling

Leaching and recovery are inseparable in CIL/CIP circuits because the dissolved gold concentration profile determines adsorption driving force, while activated-carbon inventory, fouling, attrition, and competing species influence the apparent benefit of faster leaching. Merrill–Crowe remains advantageous for suitable clarified solutions and precious-metal compositions, whereas electrowinning is commonly integrated with carbon elution. Ion-exchange and resin systems broaden the recovery toolbox, particularly where carbon selectivity or solution chemistry is unfavorable. The relevant literature also shows that recovery performance is affected by copper and iron cyanide complexes, thiocyanate, surfactants, and solution composition (Alaei et al., 2020; Botz et al., 2016; Browner & Davidson, 2010; Costello, 2016; Dai et al., 2012b; Donato & Overdevest, 2016; Fleming et al., 2011; Jeffrey et al., 2010; Karppinen et al., 2024; Kotze et al., 2016; Martínez-Mendoza et al., 2020; Mekuto et al., 2016; Parga Torres et al., 2024; Sceresini & Breuer, 2016; Tauetsile et al., 2019; Vargas et al., 2022; Walton, 2016; Wang et al., 2021; Williams, 2016; Yin et al., 2011).

Table 4 compares the major recovery and cyanide-management routes. No single route is universally superior; selection depends on solution grade, silver content, suspended solids, copper load, water balance, and the value placed on cyanide recycle.

Table 4. Comparison of gold-recovery and cyanide-management routes used or proposed for cyanidation circuits.

Route	Best suited to	Principal advantage	Principal limitation/coupling
CIL/CIP	Slurries from agitated leaching	High throughput without full clarification	Carbon fouling, preg-robbing competition, Cu/SCN effects

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Route	Best suited to	Principal advantage	Principal limitation/coupling
CIC	Clarified or low-solids solutions/heaps	Simple adsorption polishing	Requires solids control and carbon management
Merrill–Crowe	High-grade or silver-bearing clarified solutions	Efficient precipitation and Ag co-recovery	Clarification and deaeration required
Electrowinning	Concentrated eluates	Direct metal recovery	Depends on upstream concentration and impurity control
Ion exchange / RIP/RIS	Selected solution chemistries	Potential selectivity and alternative elution options	Resin poisoning, competing anions, and mechanical handling
Cyanide recovery	Tailings or barren solutions	Reduces fresh NaCN demand and discharge load	Requires control of volatile/metal-bound cyanide and recycle impurities

Note. Prepared by the author from the recovery, adsorption, resin, precipitation, and cyanide-recycle studies cited in Section 7.

The key process-integration lesson from Table 4 is that the economic value of a leaching improvement depends on whether the additional dissolved gold can be recovered without proportionally increasing carbon inventory, elution frequency, zinc consumption, electrowinning load, or cyanide-treatment demand. Integrated optimization should therefore use recovered bullion and net reagent consumption as primary response variables, not leach extraction alone.

8. Cyanide detoxification, residues, and environmental management

Environmental performance extends from reagent transport and HCN control to tailings storage, metal-cyanide stability, thiocyanate degradation, water recycling, and long-term residue behavior. Researchers have investigated chemical oxidation, SO_2/air-type systems, peroxide-based treatments, adsorption, membrane recovery, biological treatment, photocatalysis, reagent elution, and passive or semi-passive systems. Field and case-study literature also demonstrates that risk depends strongly on site water balance, containment integrity, monitoring, and governance rather than on cyanide concentration alone (Alvillo-

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Rivera & Garrido-Hoyos, 2022; Anning et al., 2019; Ayoo et al., 2024; Ayoo, 2026; Bahrami et al., 2020; Breuer et al., 2011; Breuer et al., 2012; Brüger et al., 2018; Cakiroglu et al., 2025; Castro et al., 2024; Chi et al., 2025; Dong et al., 2021; Fleming et al., 2010a; González-Valoys et al., 2022; Greenwald & Bateman, 2016; Han et al., 2024; Hewitt et al., 2015; Leung & Lu, 2016; Li et al., 2023; Liu et al., 2023; Marshall et al., 2020; Parga et al., 2012; Wates & Götz, 2016; Welman-Purchase et al., 2023b; Xie et al., 2016; Zhang et al., 2021a; Zhang et al., 2026; Álvarez et al., 2013).

Detoxification should be designed around the cyanide speciation entering the treatment step. Free and weak-acid-dissociable cyanide can respond differently from strong metal-cyanide complexes; thiocyanate and ammonia may become the controlling residuals after biological or oxidative treatment. This is why treatment performance should report not only total cyanide removal but also residual species, associated metals, nitrogen compounds, reagent consumption, and the final destination of treated water or solids.

A second critical issue is the potential displacement of environmental burden. Strong oxidation can lower cyanide concentration while increasing sulfate, dissolved metals, or secondary-sludge generation; conversely, cyanide recovery can reduce fresh reagent demand but recycle impurities upstream. The preferred strategy therefore couples source reduction, reagent recovery, targeted detoxification, water reuse, and residue stabilization rather than maximizing end-of-pipe destruction.

9. Industrial configurations, scale-up, and evidence translation

Industrial cyanidation is implemented through several configurations—heap leaching for suitable low-grade ores, agitated CIL/CIP for milled feeds, intensive cyanidation for concentrates, and circuits integrated with roasting, pressure oxidation, or biological oxidation for refractory materials. Ore mineralogy, grade, permeability, grind requirement, capital intensity, water availability, and recovery kinetics govern the choice. Industrial and flowsheet literature shows that equipment residence-time distribution, gas dispersion, solids handling,

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and recycle chemistry create constraints usually absent from small-batch tests (Adams, 2016c; Hammerschmidt et al., 2016; Lunt & Weeks, 2016a; Manning & Kappes, 2016).

Figure 3 emphasizes the recycle loops that convert a nominally linear flowsheet into a coupled system. Barren solution and water return upstream, while detoxification and recovery choices feed back into cyanide speciation, dissolved salts, and carbon performance.

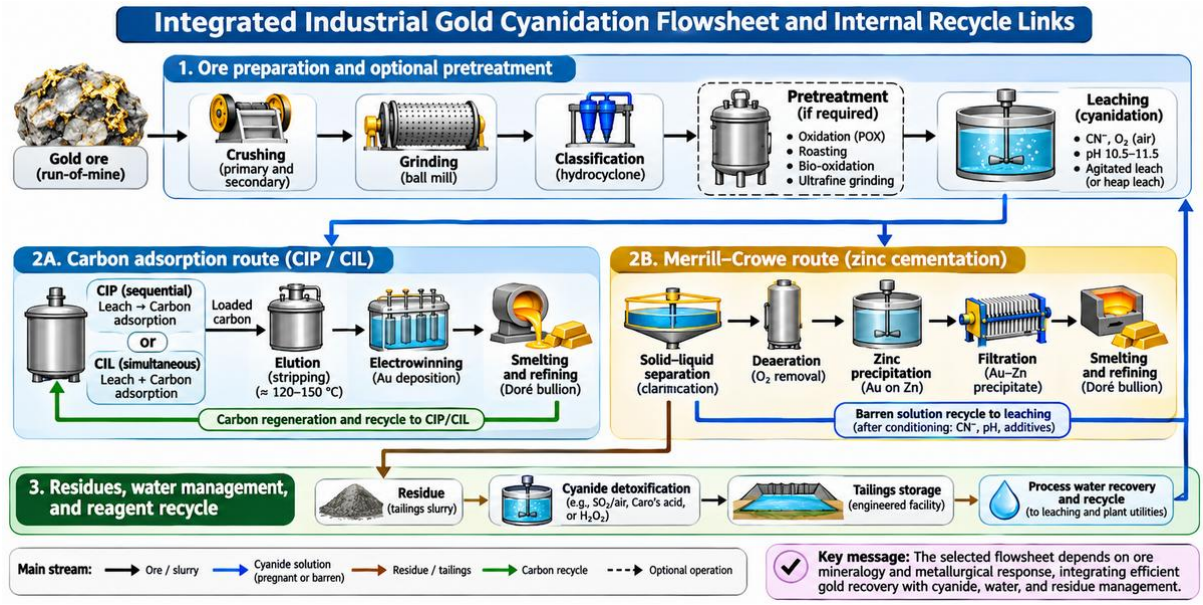

Figure 3. Integrated industrial cyanidation flowsheet showing pretreatment, leaching, recovery, recycle, and tailings-management links.
Note. Conceptual synthesis prepared for this review from the industrial process and flowsheet literature discussed in Sections 7–9; graphical-asset provenance requires confirmation.

Figure 3 illustrates why scale-up should be based on linked mass balances rather than on extraction percentage alone. A laboratory test can reproduce reagent concentrations but not necessarily oxygen-transfer coefficients, carbon inventory, recycle accumulation, or residence-time distribution. Pilot and semi-pilot testing is most valuable when it includes these coupling

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variables and runs long enough for recycled species to approach representative steady-state concentrations.

10. Hybrid systems and alternatives to conventional cyanidation

Alternatives to cyanide are motivated by environmental, regulatory, mineralogical, and selectivity considerations. Thiosulfate, halide/chloride systems, glycine, amino acids, and other lixiviants have demonstrated technically important capabilities, while glycine–cyanide combinations can reduce free-cyanide demand in some copper-bearing ores. Nevertheless, an alternative must be compared across the full flowsheet: reagent stability, oxidant demand, corrosion, solution purification, gold recovery, recycle, impurity management, and residue treatment are as important as leach kinetics (Adams, 2016a; Altinkaya et al., 2020; Aylmore, 2016a; Aylmore, 2016b; Barani et al., 2021; Barani et al., 2022; Oraby & Eksteen, 2015; Zhang et al., 2022).

Hybrid systems are especially attractive when they target a specific cyanidation limitation rather than attempting wholesale replacement. Examples include selective copper removal before cyanidation, cyanide-starved glycine systems, oxidant-assisted cyanidation, or chloride treatment of cyanidation residues. This modular approach preserves mature gold-recovery infrastructure while reducing the particular penalty imposed by copper, refractory phases, or residual gold.

11. Integrated decision framework and research gaps

The evidence reviewed above suggests that future cyanidation research should move from one-factor optimization toward constraint-based flowsheet design. The correct question is not simply how to maximize extraction, but which combination of liberation, oxidation, cyanide concentration, oxygen delivery, recovery method, recycle, and detoxification minimizes total cost and environmental burden at the required recovery. Figure 4 summarizes this hierarchy.

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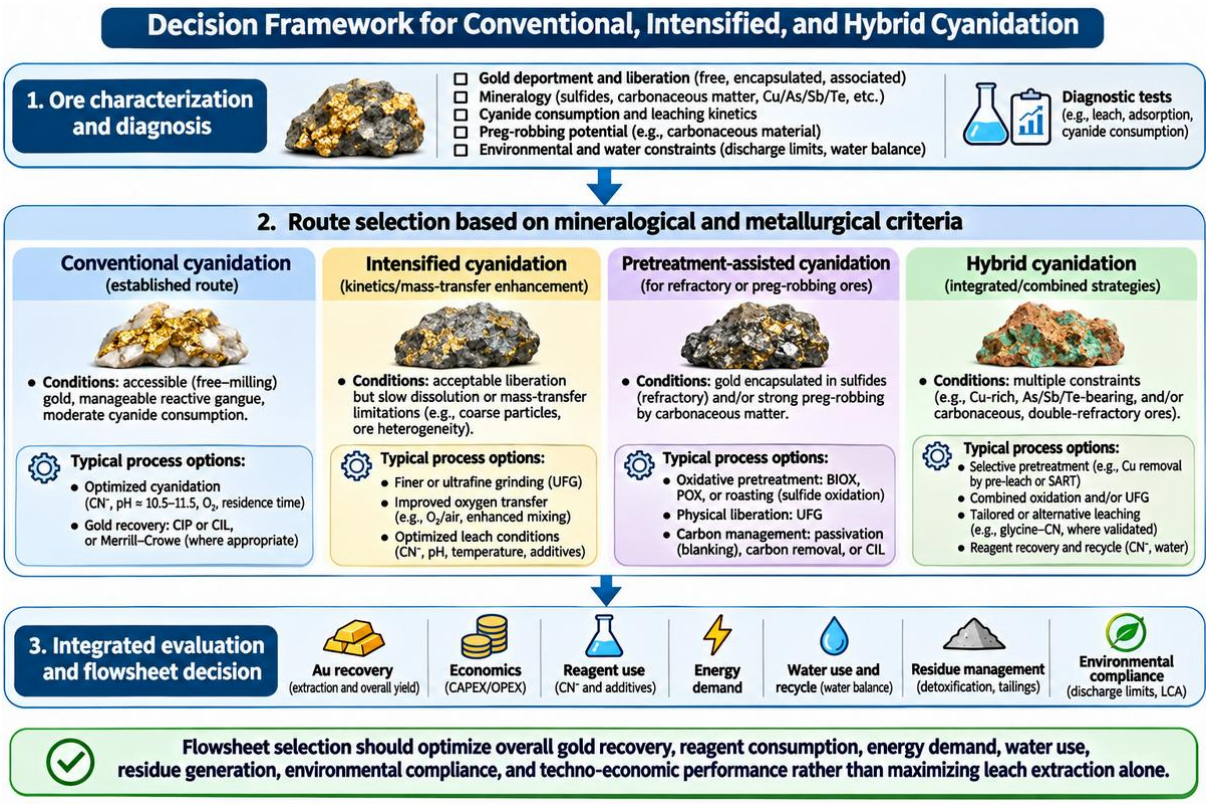

Figure 4. Decision hierarchy for selecting conventional, intensified, pretreatment-assisted, or hybrid cyanidation routes.
Note. The author developed it as an integrated synthesis of the evidence discussed in this review.

As Figure 4 indicates, flowsheet selection begins with mineralogical accessibility and cyanicide demand, then adds recovery and environmental constraints. This approach discourages the common practice of transferring a single optimum cyanide concentration or residence time from one ore to another. It also provides a basis for integrating geometallurgy and process control: if ore classes are defined by gold occurrence, reactive gangue, and preg-robbing behavior, control targets can change proactively with feed type rather than reactively after recovery loss.

Table 5 identifies the research gaps that most directly limit translation from laboratory studies to industrial value. The most persistent gaps concern standardized reporting of solution

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chemistry, long-duration recycle effects, quantitative mineralogical descriptors, coupled gas–liquid–solid transport, and economic/environmental metrics that are measured on a common basis.

Table 5. Priority research gaps for advancing cyanidation performance and sustainability.

Gap	Why it matters	Recommended evidence
Integrated speciation reporting	Free cyanide alone cannot represent Cu–Fe–SCN^- speciation	Full cyanide species, dissolved metals, pH/Eh, ionic strength
Mineralogy-linked kinetics	Head grade masks accessibility and reactive gangue	Automated mineralogy, gold deportment, liberation, preg-robbing index
Oxygen-transfer quantification	DO setpoint does not define transfer capacity	kLa, oxygen uptake rate, slurry rheology, gas dispersion
Long-duration recycle tests	Impurities accumulate slowly	Continuous pilot campaigns with water and cyanide recycle
Recovery-coupled leach testing	Extraction gains may not translate to bullion	CIL/CIP or recovery testing in parallel with leaching
Comparable sustainability metrics	Burden can shift between leach and detox steps	Reagent, energy, water, residue, and emissions per recovered Au
Scale-up uncertainty	Laboratory optimums can be non-robust	Feed variability scenarios, dynamic models, industrial validation

Note. Prepared by the author as a synthesis of the limitations identified across the literature reviewed in this manuscript.

A final gap is the need for transparent negative results. Studies often report the best extraction condition, whereas industrial design also needs to know where performance deteriorates: the onset of passivation, the cyanide concentration beyond which no kinetic benefit occurs, the impurity load that reduces carbon capacity, or the recycle ratio that causes scaling or detoxification instability. Reporting these boundaries would make the literature substantially more useful for design and control.

12. Conclusions

Gold cyanidation remains a robust and adaptable technology, but its future performance depends on treating it as an integrated chemical, mineralogical, and process-control system.

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The dissolution reaction is only one component of the overall recovery chain. Gold accessibility, sulfide reactivity, preg-robbing, copper and trace-element chemistry, oxygen transfer, slurry hydrodynamics, activated-carbon behavior, solution recycle, and tailings treatment collectively define the effective operating window.

A defensible route to higher recovery and lower reagent consumption is mineralogy-informed flowsheet selection coupled with dynamic control of cyanide, oxygen, alkalinity, and recycle chemistry. Pretreatment is justified when it removes a clearly identified limitation. At the same time, hybrid lixiviant systems are most promising when they selectively reduce cyanide demand or address difficult impurities without creating larger downstream penalties. Future progress should be judged by recovered gold, total reagent and water use, residue quality, process stability, and whole-flowsheet economics rather than by batch extraction alone.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

All literature data used in this review are contained in the cited sources; no new experimental datasets were generated.

Author Contributions

The author performed conceptualization, literature synthesis, critical analysis, writing, and revision of the manuscript.

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