



Preg-Robbing in Refractory Gold Ores: A Critical Review of Mineralogical Controls, Pretreatment Strategies and Flowsheet Selection

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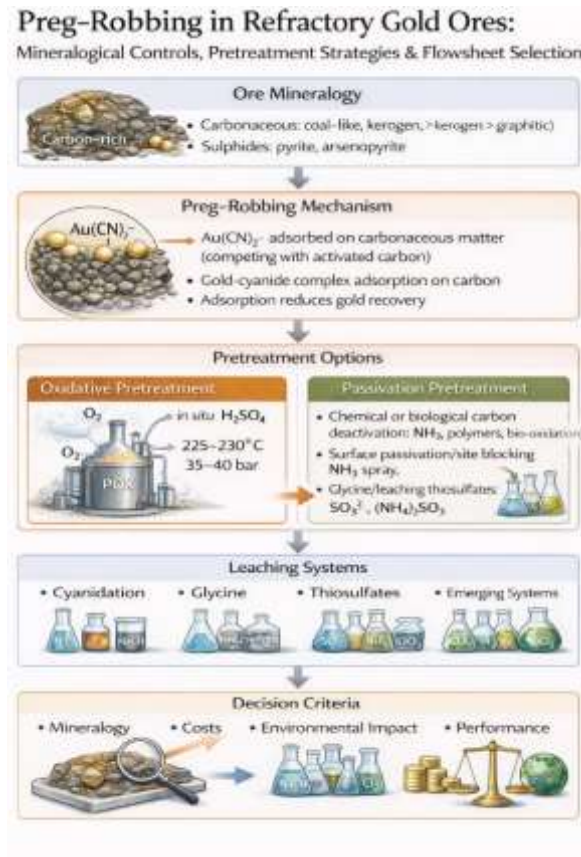
ABSTRACT: Preg-robbing remains a major constraint in the processing of refractory gold ores, particularly those containing carbonaceous matter, fine clays, and iron-bearing phases capable of adsorbing dissolved gold during leaching. This review critically evaluates advances reported between 2020 and 2025, focusing on the mineralogical controls of preg-robbing, its interaction with gold dissolution chemistry, and the effectiveness of current mitigation strategies. Gold adsorption is governed by carbon structure, surface functional groups, sulfide associations, and textural features that control accessibility, determining whether adsorption is reversible or irreversible and, consequently, whether conventional recovery routes remain viable. Pretreatment options, including roasting, pressure oxidation, bio-oxidation, chemical passivation, and selective removal of reactive phases, are assessed in terms of metallurgical performance, operational complexity, energy demand, and environmental impact. The review also examines alternative lixivants such as thiosulfate, glycine, and ammonia-based systems, highlighting their potential to reduce sensitivity to carbonaceous matter while emphasizing their dependence on mineralogy and process control. Rather than proposing a universal solution, the analysis defines decision-oriented criteria for flowsheet selection based on mineralogical and operational constraints, identifying the conditions under which specific approaches are technically robust and economically justified. Key research gaps are highlighted, particularly in the quantitative characterization of adsorption capacity and kinetics, and in the integration of mineralogical data into predictive process design frameworks.

KEYWORDS: Alternative lixivants, Carbonaceous matter, Flowsheet selection, Gold adsorption, Hydrometallurgy, Preg-robbing, Refractory gold ores, Pretreatment technologies.

Highlights

- Preg-robbing is controlled by complex mineralogical factors beyond total carbon content.
- Carbonaceous matter, clays, and sulfide surfaces play distinct roles in gold adsorption.
- Conventional pretreatments remain effective but face energy and environmental constraints.
- Cyanide-free lixivants show potential yet remain highly sensitive to preg-robbing behavior.
- Mineralogy-driven flowsheet selection is essential for processing preg-robbing gold ores.

Graphical abstract



1. INTRODUCTION

Preg-robbing ores remain a major operational challenge for gold plants. The issue extends beyond slow leaching or incomplete liberation. Reactive carbonaceous matter actively removes dissolved gold from solution, competing with activated carbon and causing irreversible losses (Ng, Wang, & Chen, 2022). This behavior is increasingly common as processing shifts toward carbon-bearing and polymetallic deposits (Nwaila et al., 2020).

Preg-robbing must be distinguished from classical refractoriness. In sulfide ores, gold is physically encapsulated in pyrite or arsenopyrite and becomes accessible only after oxidation or fine grinding (Asamoah et al., 2021). In preg-robbing systems, adsorption introduces an additional barrier. Reactive carbonaceous phases remove dissolved gold complexes from solution, reducing the fraction available for recovery (Ng et al., 2022). Under cyanidation, the dominant species is $Au(CN)_2^-$, which readily adsorbs onto natural carbon surfaces, including graphitic and kerogen-associated structures (Niu, Yang, & Tong, 2020). Similar limitations apply to non-cyanide systems, as adsorption remains controlled by surface chemistry and solution speciation (Arasteh, Khalesi, & Mohseni, 2023).

The industrial relevance of preg-robbing continues to increase. Ore blending windows are narrowing, variability is rising, and plant performance is increasingly constrained by mineralogical factors rather than head grade (Gökdemir, Can, & Harzanak, 2025). Under these conditions, preg-robbing becomes a flowsheet-level risk. It increases reagent consumption, destabilizes CIL/CIP circuits, and compromises reconciliation when carbon activity is not properly characterized (Ocampo-López et al., 2024). Recent studies report significant gold losses associated with both reagent selection and pretreatment conditions, including cases in which pretreatment introduces new solution-phase penalties (Ahmadi & Mohammadnejad, 2025).

Recent work shows two trends: improved diagnostic methods focusing on carbonaceous matter with advanced techniques (Xue et al., 2025), and expanded control strategies such as chemical passivation, flotation, and pretreatment based on mineralogy and economics (Mabwe, 2020; Owusu et al., 2021). Interest in alternative lixiviants like thiosulfate and glycine has increased, driven by cyanide restrictions and their lower interference sensitivity (Vashist et al., 2022).

This review examines the mineralogical and surface-chemical controls on preg-robbing, diagnostic methods that link carbon characteristics to process risk, and pretreatment and leaching strategies for robust flowsheet design. The analysis focuses on causal relationships, failure modes, and decision boundaries defined by ore type, carbon reactivity, and operating constraints (Dyson et al., 2022). The next section outlines the methodology used to ensure that conclusions reflect recent literature rather than legacy assumptions.

2. METHODOLOGY

This review follows the PRISMA 2020 guidelines to ensure transparency and traceability in study selection (Page et al., 2021). The approach combines systematic screening with critical analysis, which is appropriate for process-oriented studies in extractive metallurgy.

The scope covered publications from 2020-2025 on preg-robbing in refractory gold ores, focusing on mineralogical controls, pretreatment, lixivants, and flowsheet implications. It included primary ores, concentrates, and pretreated materials. Studies on artisanal or mercury-based recovery were excluded unless they offered mechanistic insights into gold adsorption or carbon reactivity (Manzila, 2022).

Literature searches were performed using Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. These were complemented by targeted searches in key journals, including *Mining, Metallurgy & Exploration, Minerals Engineering,* and *Hydrometallurgy*. Search terms combined mineralogical and metallurgical descriptors related to preg-robbing, carbonaceous matter, pretreatment, and leaching systems.

Study selection followed a two-stage process. Titles and abstracts were screened to remove irrelevant records. Full texts were then evaluated based on evidence of preg-robbing behavior, mineralogical characterization, and process performance.

Figure 1 summarizes the identification, screening, eligibility, and inclusion stages. It shows how the initial dataset was refined to the studies included in the qualitative synthesis, ensuring consistency with PRISMA requirements (Page et al., 2021).

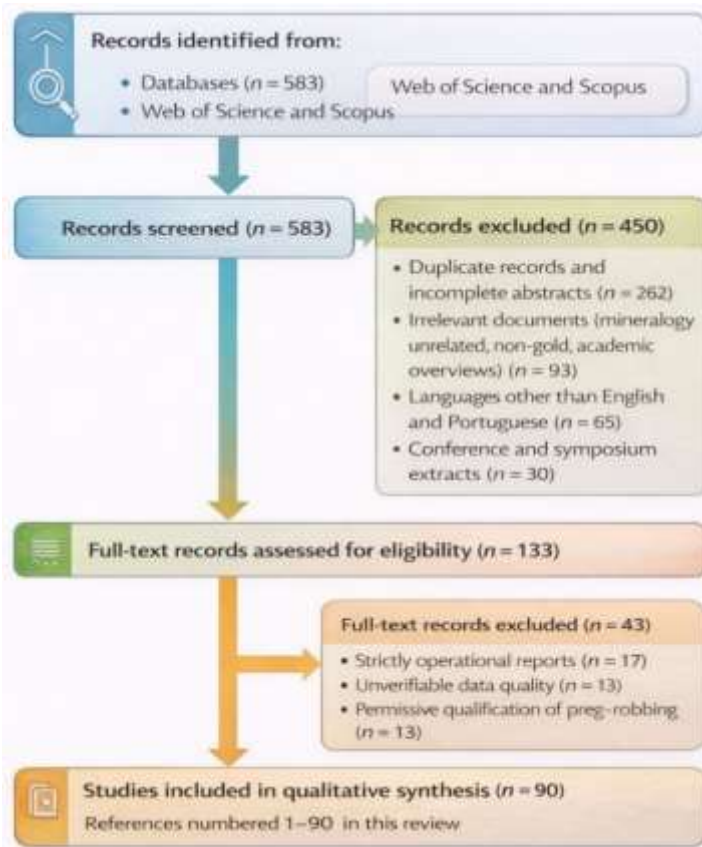


Figure 1. PRISMA 2020 flow diagram of the study selection process. Adapted from Page et al. (2021)



For each study, data were extracted on ore type, characteristics of carbonaceous matter, preg-robbing intensity, pretreatment conditions, leaching system, and metallurgical outcomes. The information was structured into comparative matrices to enable cross-analysis.

The synthesis prioritizes consistency between mineralogical evidence and metallurgical response. Pretreatment routes and alternative lixiviants were assessed in terms of adsorption behavior and circuit integration, rather than as isolated laboratory results (Ng, Wang, & Chen, 2022; Owusu et al., 2021; Vashist et al., 2022).

A formal meta-analysis was not performed due to variability in ore types and reporting metrics. Conclusions were instead based on converging trends across independent studies (Dyson et al., 2022).

The next section applies this framework to examine the mineralogical and surface-chemical characteristics that control preg-robbing behavior

3. MINERALOGICAL DIAGNOSIS OF PREG-ROBBING ORES

Mineralogical diagnosis is the foundation for understanding preg-robbing behavior. Chemical or operational symptoms alone are insufficient. Without identifying the nature, distribution, and surface reactivity of carbonaceous matter, mitigation strategies remain empirical and often ineffective (Ng, Wang, & Chen, 2022).

3.1. Modes of occurrence of carbonaceous matter

Preg-robbing mainly involves reactive carbonaceous matter (RCM), including amorphous organic carbon, kerogen fragments, bitumen phases, humic substances, and disordered carbon (Niu, Yang, & Tong, 2020). Well-crystallized graphite is less reactive unless defects or surface oxidation boost adsorption (Youlton et al., 2021; Lenoir, 2023).

RCM occurs in distinct textural forms. It may be dispersed as fine particles within silicate matrices, concentrated along microfractures, or intergrown with sulfides such as pyrite and arsenopyrite (Asamoah et al., 2021). In some cases, carbonaceous matter forms continuous coatings on gold surfaces, simultaneously limiting access and providing active adsorption sites (Konadu et al., 2020; Zhou et al., 2024).

Adsorption depends on surface chemistry, with oxygen groups like hydroxyl, carboxyl, and carbonyl increasing gold complex affinity via electrostatic and ligand interactions (Ghasemi, Mohammadnejad, & Khalesi, 2022). Structural disorder and high surface area also boost reactivity. These factors clarify why bulk carbon grade alone can't predict preg-robbing severity (Mansurov et al., 2020; Gómez Santiago et al., 2022).

Carbonaceous matter in these systems is heterogeneous in origin, structure, and reactivity. Classification must therefore be based on structural order and surface functionality rather than total carbon content. Table 1 summarizes the principal carbonaceous forms reported in refractory gold ores and their relative contribution to preg-robbing.

Table 1. Classification of carbonaceous matter associated with preg-robbing behavior. Adapted from Niu et al. (2020), Asamoah et al. (2021), Lenoir (2023), and Zhou et al. (2024).

Carbonaceous material	Typical origin	Degree of structural order	Surface reactivity	Preg-robbing relevance
Amorphous organic carbon	Sedimentary / diagenetic	Very low	Very high	Dominant
Kerogen fragments	Sedimentary basins	Low	High	High
Bitumen-derived carbon	Hydrocarbon alteration	Low–moderate	High	High
Disordered carbon fines	Mechanical/thermal degradation	Low	Moderate–high	Moderate
Graphitic carbon	Metamorphic	High	Low (unless defective)	Low–moderate
Soot-like carbon	Thermal alteration	Very low	Very high	Dominant

Table 1 shows that preg-robbing intensity is governed primarily by structural disorder and surface reactivity rather than by carbon abundance. Amorphous and soot-like carbon exhibits the highest adsorption potential due to its low structural order and high density of reactive sites. In contrast, well-crystallized graphitic carbon is comparatively inert, unless defects or surface oxidation increase its reactivity.

Intermediate forms, such as kerogen and bitumen-derived carbon, display significant adsorption capacity and often dominate preg-robbing behavior in sedimentary systems. Disordered carbon fines, although less reactive, can still contribute to gold losses when present in large surface area fractions.

These distinctions have direct implications for process design. Treating all carbonaceous matter as equally reactive leads to systematic over- or underestimation of preg-robbing severity. Effective classification therefore requires linking mineralogical characterization to adsorption behavior rather than relying on bulk carbon metrics.

3.2. Definition and classification of preg-robbing behavior

To distinguish gold loss mechanisms in carbonaceous ores, it is important to differentiate between irreversible and reversible adsorption, as they have fundamentally different metallurgical implications.

Figure 2 compares preg-robbing and preg-borrowing systems, emphasizing adsorption kinetics, surface reactivity, and competitive interactions with activated carbon in CIL/CIP conditions. This is key for interpreting diagnostic leaching and choosing processing strategies.

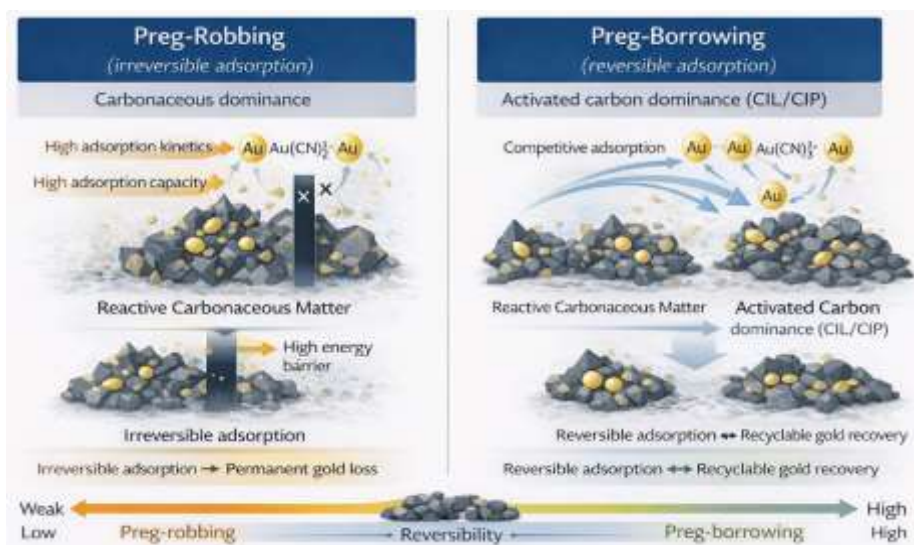


Figure 2. Conceptual representation of preg-robbing and preg-borrowing mechanisms. Adapted from Ng, Wang, and Chen (2022) and Owusu et al. (2021)

Figure 2 highlights the fundamental distinction between preg-robbing and preg-borrowing in carbonaceous gold ores. In preg-robbing systems, dissolved gold complexes (e.g., $\text{Au}(\text{CN})_2^-$) are irreversibly adsorbed onto reactive carbonaceous matter (RCM). This process is governed by rapid adsorption kinetics and strong binding, which prevent desorption under typical leaching conditions. As a result, gold losses are permanent and cannot be recovered through conventional CIL or CIP circuits.

In contrast, preg-borrowing involves reversible adsorption. Gold complexes may temporarily associate with natural carbon surfaces but can be displaced by activated carbon under competitive conditions. The outcome depends on relative adsorption affinity, carbon surface characteristics, and operating variables such as carbon loading and residence time. Recovery remains viable when activated carbon effectively outcompetes natural carbonaceous matter.

This distinction reflects differences in surface chemistry, structural disorder of carbonaceous phases, and solution speciation. It is not merely descriptive. Misclassification of adsorption behavior remains a common source of process failure, particularly when reversible systems are treated as irreversible, or vice versa.



Preg-robbing is therefore defined as the irreversible adsorption of dissolved gold complexes onto natural carbonaceous matter during leaching, leading to permanent gold loss (Ng, Wang, & Chen, 2022). Preg-borrowing, by contrast, describes reversible adsorption, in which gold can be displaced by activated carbon during CIL or CIP processing (Owusu et al., 2021; Konadu et al., 2023).

Quantitative differentiation requires consideration of both adsorption capacity and kinetics. Some ores exhibit limited capacity but fast adsorption, allowing natural carbon to outcompete activated carbon within industrial residence times (Niu et al., 2023; Li et al., 2020). Others display slower kinetics but higher capacity, resulting in cumulative losses along the leach train.

The Preg-Robbing Index (PRI) provides a standardized measure of adsorption behavior (Darteh et al., 2020; Chingwaru, 2024). However, it does not resolve reversibility. Distinguishing irreversible adsorption from competitive but reversible uptake remains essential for reliable flowsheet selection.

3.3. Diagnostic leaching applied to preg-robbing systems

Diagnostic leaching is the most widely used approach for quantifying preg-robbing under controlled conditions. Cyanidation tests performed with and without activated carbon enable direct discrimination between preg-robbing and preg-borrowing responses (Byvaltsev et al., 2025). Simulated CIL/CIP tests extend this analysis by incorporating competitive adsorption under realistic pulp densities and carbon loadings, providing insight into adsorption kinetics and displacement behavior (Cao et al., 2022; Ocampo-López et al., 2024).

More advanced protocols integrate diagnostic leaching with selective pre-oxidation or carbon removal to isolate adsorption mechanisms (Bare et al., 2021; Bampole Lukumu, 2023). These approaches are particularly relevant for complex ores, where carbonaceous matter coexists with fine sulfides or iron oxides that can also influence gold speciation and adsorption (Arasteh et al., 2023).

Despite their practical value, diagnostic leaching methods have inherent limitations. No single test captures the full complexity of adsorption processes, particularly the interplay between kinetics, capacity, and reversibility.

Table 2 summarizes the principal diagnostic approaches, highlighting their objectives, the information they provide, and their limitations. Interpretation requires careful consideration of carbon activity, adsorption kinetics, and test conditions, as these factors strongly influence the apparent preg-robbing response.

Table 2. Diagnostic leaching approaches applied to preg-robbing ores. Adapted from Darteh et al. (2020), Byvaltsev et al. (2025), and Ocampo-López et al. (2024).

Test type	Main objective	Information obtained	Limitation
Cyanidation without AC	Baseline recovery	Total adsorption losses	Overestimates losses
Cyanidation with AC	Competitive adsorption	Preg-borrowing vs robbing	AC quality dependent
Simulated CIL/CIP	Industrial relevance	Kinetics and displacement	Time-consuming
Diagnostic leaching sequence	Mechanism isolation	Reversibility assessment	Requires expertise

Table 2 shows that diagnostic leaching methods differ significantly in their ability to resolve adsorption mechanisms. Cyanidation without activated carbon provides a useful baseline but systematically overestimates gold losses, as it does not account for competitive adsorption. In contrast, tests conducted with activated carbon allow differentiation between preg-robbing and preg-borrowing behavior, although the results are strongly influenced by carbon quality and operating conditions.

Simulated CIL/CIP tests offer greater industrial relevance by incorporating competitive adsorption and residence time effects. These tests provide insight into adsorption kinetics and displacement behavior but are more time-consuming and sensitive to experimental setup. Diagnostic leaching sequences, which combine multiple steps, are the most effective for isolating mechanisms and assessing reversibility. However, they require careful design and expert interpretation.

Taken together, these methods confirm that a single parameter cannot define preg-robbing. Reliable classification depends on integrating test results with mineralogical and surface-chemical data. Failure to do so often leads to misinterpretation of adsorption behavior and, consequently, to inappropriate flowsheet selection

3.4. Mineralogical characterization techniques

Reliable assessment of preg-robbing behavior requires more than bulk mineralogical characterization. Adsorption phenomena are controlled by surface chemistry, structural disorder, and the spatial relationship between carbonaceous matter and gold-bearing phases. A single analytical technique cannot capture these features.

Figure 3 presents an integrated characterization framework that combines spectroscopic, surface-sensitive, and spatially resolved methods to evaluate preg-robbing potential. The objective is not only to describe the ore but to link measurable properties to adsorption behavior and, ultimately, to process selection.

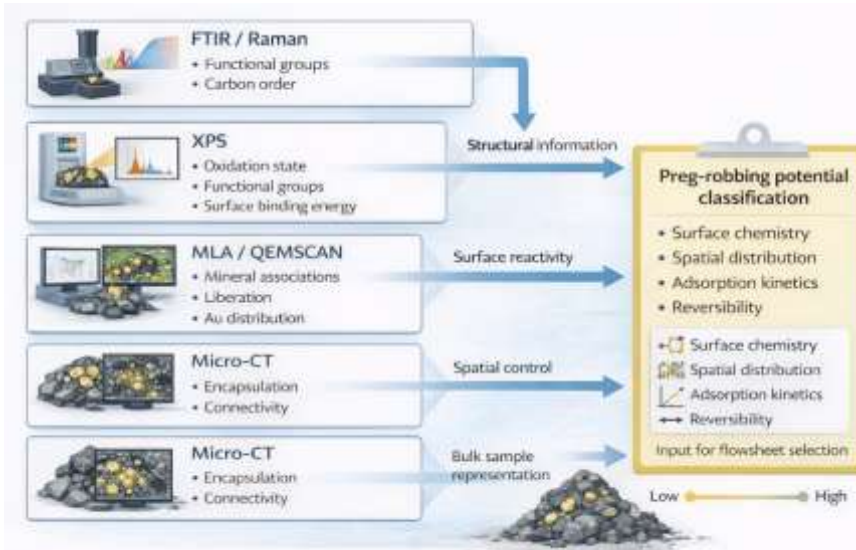


Figure 3. Integrated mineralogical and surface-chemical workflow for diagnosing preg-robbing behavior in refractory gold ores. Adapted from Niu et al. (2020), Garcia Rosales et al. (2024), Lee et al. (2021), and Xue et al. (2025).

Figure 3 shows that preg-robbing classification requires integration of complementary datasets. Isolated measurements are insufficient to capture adsorption behavior. FTIR and Raman spectroscopy identify functional groups and structural disorder, both directly linked to carbon reactivity (Niu, Yang, & Tong, 2020). XPS complements this by resolving oxidation states and surface binding environments associated with adsorption sites (Garcia Rosales et al., 2024; Silva et al., 2025).

Spatially resolved techniques provide a different level of control. MLA and QEMSCAN quantify mineral associations, gold distribution, and liberation (Lee, Gibson, & Ghahreman, 2021). Micro-CT reveals encapsulation and connectivity, which govern access to reactive carbon surfaces and help explain variations in metallurgical response among ores with similar bulk composition (Xue et al., 2025).

Together, these datasets support classification of preg-robbing potential based on surface chemistry, spatial distribution, adsorption kinetics, and reversibility. This classification defines process limits. It directly informs leaching strategy and flowsheet selection.

Without this integration, diagnostic leaching is often misinterpreted. Adsorption behavior is then attributed to bulk composition rather than to reactive carbon characteristics. This leads to inappropriate process choices, unstable operation, and reduced gold recovery in carbonaceous ores.

3.5. Implications for process design

Mineralogical diagnosis constrains process selection. Ores with reversible adsorption can be managed through carbon control and circuit design. When adsorption is irreversible, these measures are insufficient. In such cases, chemical passivation, carbon removal, or oxidative pretreatment becomes necessary before leaching (Owusu et al., 2021).

Alternative lixiviants may be considered in severe systems. Their application, however, depends on prior characterization of carbon reactivity and adsorption behavior (Vashist et al., 2022).



Once mineralogical controls and diagnostic responses are established, attention shifts to pretreatment. The objective is not only gold liberation but suppression of carbon reactivity. Section 4 examines oxidative, thermal, chemical, and hybrid approaches, focusing on their effectiveness, limitations, and integration at the flowsheet level.

4. PRETREATMENT TECHNOLOGIES

Although preg-robbing has a different origin from sulfide refractoriness, many oxidative and physicochemical pretreatment technologies remain applicable, provided that their impact on carbonaceous matter is explicitly considered. In preg-robbing systems, the objective of pretreatment is twofold: to liberate gold and to neutralize or eliminate reactive carbon surfaces. Technologies that achieve only one of these goals often fail at the flowsheet level (Ng, Wang, & Chen, 2022).

4.1. Ultrafine Grinding (UFG)

Ultrafine grinding (UFG) increases gold liberation by reducing particle size and exposing encapsulated or finely disseminated gold. In preg-robbing ores, this effect is not necessarily beneficial. Particle sizes below ~20 μm significantly increase the surface area of carbonaceous matter, which can enhance the adsorption of gold complexes if not properly controlled (Niu, Yang, & Tong, 2020).

Although improved leaching kinetics are often reported after UFG, increases in preg-robbing capacity are frequently observed. This trade-off limits the effectiveness of UFG as a standalone strategy. Its use is only justified when combined with downstream measures that suppress carbon reactivity, such as chemical passivation, oxidative pretreatment, or alternative lixiviants (Owusu et al., 2021).

4.2. Roasting of carbonaceous ores

Roasting is one of the most effective routes for eliminating reactive carbonaceous matter. At 500–700 $^{\circ}\text{C}$, organic carbon oxidizes to CO_2 , removing the adsorption sites responsible for preg-robbing (Zhang et al., 2022; Dong et al., 2025). When properly controlled, roasting can convert highly refractory ores into feed suitable for conventional cyanidation (Wu et al., 2020; Zhang et al., 2025).

This effectiveness comes with significant constraints. Roasting generates CO_2 and SO_2 , and in arsenic-bearing ores, volatile As species, requiring complex gas treatment systems (Amankwah & Ofori-Sarpong, 2020; Li et al., 2022). Temperature control is critical. Overheating can induce sintering or re-encapsulation of gold, reducing overall recovery.

Chloridizing roasting enhances oxidation and improves gold exposure. However, it introduces additional challenges, including corrosion, reagent handling, and process complexity (Hao et al., 2022; Liu et al., 2022; Xiao et al., 2022).

4.3. Pressure Oxidation (POX)

Pressure oxidation (POX) enables near-complete oxidation of sulfide minerals and carbonaceous matter under controlled conditions. In preg-robbing ores, it is often the most robust pretreatment option, as it combines gold liberation with suppression of carbon reactivity (Dyson et al., 2022).

Typical conditions (190–230 $^{\circ}\text{C}$ and oxygen pressures >1.5 MPa) promote effective oxidation of organic carbon and graphitic precursors. Despite this, POX residues frequently contain jarosite and basic ferric sulfates. These phases can interfere with downstream cyanidation and often require additional neutralization or conditioning steps (Pewa, 2021; Lemos et al., 2025).

The main limitation is economic. High capital intensity and operating costs restrict POX to deposits with sufficient scale, grade, and operational stability to justify investment.

4.4. Biological oxidation (BIOX)

BIOX efficiently oxidizes sulfide minerals but has a limited impact on carbonaceous matter. This limits its effectiveness in preg-robbing ores. In systems dominated by reactive carbon, BIOX rarely improves gold recovery (Asamoah, 2021; Mendoza et al., 2024).

Its application is more relevant in mixed refractory ores. In these cases, sulfide oxidation enhances gold liberation, while carbonaceous matter must be controlled through chemical passivation or alternative leaching strategies. Hybrid BIOX–chemical approaches have been proposed, but industrial adoption remains limited (Xu et al., 2020; Cindy et al., 2021).



4.5. Blanking agents and chemical passivation

Chemical passivation is a key element in preg-robbing flowsheets and has no direct equivalent in sulfide-refractory processing. Blanking agents, such as kerosene, diesel, heavy oils, and polymeric surfactants, coat carbonaceous surfaces and block adsorption sites, reducing affinity for gold complexes (Pieterse, 2020; Owusu et al., 2021).

Additional approaches include alkaline conditioning with CaO and the use of oxidizing reagents, such as hypochlorite, permanganate, and peroxide-based systems. These treatments partially deactivate surface functional groups involved in gold adsorption (Garcia Rosales et al., 2024).

Their performance is highly sensitive to dosage, contact time, and pulp chemistry. Under-dosing leads to incomplete passivation, while overuse increases reagent consumption and promotes side reactions that can reduce overall recovery.

4.6. Emerging hybrid strategies

Recent studies show that no single pretreatment technology is universally effective for preg-robbing ores. Hybrid strategies address this limitation by combining complementary mechanisms. These approaches reduce the weaknesses of individual methods. Examples include POX followed by thiosulfate leaching to avoid cyanide-related losses, microwave-assisted oxidation to disrupt carbon structure, and alkaline preconditioning prior to glycine leaching to reduce adsorption (Javanshir et al., 2025; Lin et al., 2025).

This shift reflects a move from fixed unit operations to mineralogy-driven process sequences. Pretreatment is no longer treated as an isolated step but as part of an integrated flowsheet. The trend toward ore-specific design is evident in recent studies (Azizbek, 2025).

Pretreatment modifies the mineralogical and chemical environment but does not ensure high recovery. Residual carbon reactivity often persists. Therefore, the selection of a compatible leaching system becomes critical. It must account for both the modified ore and remaining adsorption effects. Section 5 examines these interactions in detail (Nwagboso, 2022).

Pretreatment selection is constrained by both metallurgical and economic factors. Technologies differ in their ability to suppress adsorption, as well as in CAPEX, OPEX, and operational robustness. No approach is universally applicable.

Table 3 compares the main pretreatment routes, highlighting their mechanisms, impact on preg-robbing, and practical limitations. The comparison emphasizes the trade-off between metallurgical performance and process complexity.

Table 3. Comparative evaluation of pretreatment technologies applied to preg-robbing refractory gold ores, Adapted from Ng et al. (2022), Owusu et al. (2021), Dyson et al. (2022), Amankwah and Ofori-Sarpong (2020), Dong et al. (2025), Javanshir et al. (2025), and Lin et al. (2025).

Pretreatment technology	Impact on preg-robbing	Mechanism of action	CAPEX level	OPEX level	Main limitations
Ultrafine grinding (UFG)	Often increases	Activates carbon surfaces by size reduction	Low–moderate	High	Enhances adsorption if not followed by passivation
Roasting (500–700 °C)	High elimination	Thermal oxidation of carbon to CO ₂	Moderate–high	High	Off-gas treatment, As volatilization, sintering risk
Chloridizing roasting	High elimination	Enhanced carbon and sulfide oxidation	High	High	Corrosion, reagent handling, gas treatment
Pressure oxidation (POX)	Very high	Complete oxidation of sulfides and carbon	Very high	High	High CAPEX, sulfate residues, complex operation
BIOX (sulfide-focused)	Limited	Oxidizes sulfides, not carbon	Moderate	Moderate	Ineffective for carbon-dominated ores
BIOX + chemical passivation	Moderate	Liberation + surface deactivation	Moderate	Moderate–high	Process complexity, reagent sensitivity
Chemical blanking agents	Conditional	Physical coating of carbon surfaces	Low	Moderate	Dosage-sensitive, reversible effects



Chemical oxidation (ClO ⁻ , MnO ₄ ⁻)	Moderate	Surface functional group deactivation	Low–moderate	Moderate	Competing reactions, control required
Microwave-assisted oxidation	Emerging	Carbon disordering and partial oxidation	Moderate	Moderate	Limited industrial scale-up
POX + thiosulfate	High	Carbon elimination + cyanide-free leaching	Very high	Moderate–high	Process integration complexity
Alkaline preconditioning + glycine	Conditional	Reduced adsorption under alkaline media	Low–moderate	Low–moderate	Sensitive to mineralogy and solution chemistry

Table 3 shows that pretreatment technologies differ not only in effectiveness but also in the mechanism by which preg-robbing is controlled. Oxidative routes, particularly roasting and pressure oxidation, are the only approaches that consistently eliminate preg-robbing. They achieve this by destroying reactive carbonaceous matter, rather than merely suppressing its activity. As a result, they provide the highest metallurgical reliability.

However, this effectiveness comes at a cost. These technologies are associated with high CAPEX, elevated energy demand, and significant environmental constraints, including off-gas treatment and residue management. Their application is therefore restricted to operations where scale and ore value justify the investment.

In contrast, lower-intensity approaches, such as chemical passivation and alkaline conditioning, act by modifying surface interactions rather than removing carbon. These methods have lower capital requirements but provide only partial, often unstable control. Their performance is highly sensitive to operating conditions, reagent dosage, and ore variability, which limits their robustness at an industrial scale.

Ultrafine grinding illustrates a critical limitation. Although it enhances gold liberation, it simultaneously increases the surface area of carbonaceous matter, often intensifying preg-robbing. This trade-off demonstrates that liberation and adsorption cannot be treated independently in carbonaceous systems.

BIOX-based routes occupy an intermediate position. While effective for sulfide oxidation, they have limited impact on carbonaceous matter. Their application is therefore restricted to ores where preg-robbing is not the dominant mechanism or where additional passivation strategies can be implemented.

Hybrid approaches provide the most balanced solution. By combining carbon elimination, surface modification, and alternative leaching systems, they reduce the limitations of individual technologies. However, this integration increases process complexity and requires careful control of interactions between unit operations.

Overall, Table 3 highlights a fundamental distinction between carbon elimination and carbon suppression strategies. Technologies that eliminate reactive carbon provide the most reliable performance but are capital- and energy-intensive. In contrast, suppression-based approaches are more flexible but less robust. This trade-off defines the practical limits of pretreatment selection in preg-robbing ores.

5. LEACHING SYSTEMS

Leaching performance in preg-robbing ores is not determined solely by gold liberation. It depends on the interaction between solution chemistry, carbonaceous matter, and the recovery route. Residual adsorption often persists even after pretreatment and can dominate process response (Ng, Wang, & Chen, 2022).

Under these conditions, lixiviant selection becomes critical. Its effectiveness is defined by its interaction with reactive carbon and its compatibility with downstream recovery. This section examines cyanide and alternative leaching systems, focusing on their sensitivity or resistance to preg-robbing behavior (Youlton, 2020; Manzila, 2022).

5.1. Cyanidation

Cyanidation remains the dominant method for gold extraction due to its maturity and compatibility with carbon-based recovery. In preg-robbing ores, however, its performance is fundamentally limited. The gold cyanide complex, Au(CN)₂⁻, exhibits strong affinity for reactive carbonaceous surfaces. Adsorption increases with higher redox potential and dissolved oxygen, conditions that also favor gold dissolution. This creates an inherent conflict in carbon-rich systems.



Operational strategies attempt to manage this effect. High carbon-in-leach (CIL) loadings are used to promote competitive adsorption. Blanking agents reduce surface activity by coating carbonaceous matter. Pre-oxidation lowers carbon reactivity. Control of dissolved oxygen and Eh aims to limit adsorption kinetics. Carbon scavenging stages may also be introduced upstream of leaching (Owusu et al., 2021).

These measures provide partial control but do not eliminate the underlying mechanism. In ores with high Preg-Robbing Index (PRI), recoveries remain limited, particularly when adsorption is rapid and irreversible (Ocampo-López et al., 2024).

Cyanidation performance is therefore highly sensitive to operating conditions. Variables that enhance dissolution often intensify adsorption. This trade-off constrains process optimization and defines a narrow operating window.

Table 4 summarizes the main cyanidation parameters affected by preg-robbing, linking process variables to their mechanisms and operational consequences.

Table 4. Sensitivity of cyanidation parameters to preg-robbing behavior. Adapted from Ng, Wang, and Chen (2022), Owusu et al. (2021), Niu et al. (2023), and Ocampo-López et al. (2024).

Cyanidation parameter	Effect on preg-robbing	Underlying mechanism	Operational implication
Carbon-in-leach (CIL) loading	mitigates (conditional)	Competitive adsorption between AC and natural carbon	Requires high carbon inventory and frequent regeneration
Dissolved oxygen (DO)	intensifies	Enhances Au(CN) ₂ ⁻ formation and adsorption kinetics	Tight DO control needed to balance leaching and losses
Redox potential (Eh)	intensifies at high Eh	Promotes rapid complex formation and surface interaction	Eh optimization critical in carbonaceous ores
Cyanide concentration	dual effect	Increases dissolution but does not suppress adsorption	Excess CN increases cost without recovery gains
Pulp pH	indirect	Influences surface charge and cyanide stability	Narrow operating window required
Activated carbon activity	mitigates	Higher affinity than natural carbon	Fouling and organic adsorption reduce effectiveness
Blanking agents	mitigates (temporary)	Physical blocking of carbon surface sites	Dosage-sensitive; effect may be reversible
Pre-oxidation	mitigates	Reduces surface reactivity of carbon	May introduce new reactive phases
Slurry residence time	intensifies	Longer contact enables adsorption equilibrium	Shorter residence times preferred
Carbon scavenging stage	mitigates	Removes gold-loaded natural carbon	Adds circuit complexity and co

Table 4 shows that cyanidation control in preg-robbing systems is intrinsically limited. No operating parameter suppresses adsorption without also affecting dissolution. Most variables act in opposing directions, forcing trade-offs.

Higher dissolved oxygen and redox potential accelerate gold dissolution but also increase adsorption kinetics. Increasing cyanide concentration improves solubilization but does not reduce affinity for carbonaceous matter. This leads to higher reagent consumption without proportional gains in recovery. Residence time further constrains performance, as longer contact promotes adsorption equilibrium.

Mitigation strategies provide only partial control. Increased carbon loading, blanking agents, and pre-oxidation reduce adsorption but remain sensitive to operating conditions and ore variability. Carbon-scavenging stages can limit losses but also add process complexity.

These requirements increase OPEX and reduce operational robustness. Cyanidation, therefore, operates within a narrow window in preg-robbing systems. At high preg-robbing intensity, adsorption dominates over dissolution, and conventional optimization becomes ineffective.

As a result, cyanidation is best suited to ores with moderate preg-robbing or to systems where pretreatment has significantly reduced carbon reactivity

5.2. Thiosulfate leaching

Thiosulfate leaching is the most developed alternative for preg-robbing ores. The gold–thiosulfate complex, $\text{Au}(\text{S}_2\text{O}_3)_2^{3-}$, exhibits lower affinity for reactive carbonaceous matter than $\text{Au}(\text{CN})_2^-$ (Vashist et al., 2022; Lin et al., 2025). This behavior explains its successful application in carbonaceous systems, particularly in Carlin-type ores.

Despite this advantage, thiosulfate systems present operational challenges. Thiosulfate is prone to decomposition and catalytic degradation, which increases reagent consumption. Process performance is highly sensitive to temperature, solution chemistry, and catalytic species. As a result, these systems require tighter control than conventional cyanidation (Vashist, 2020; Soleymani et al., 2021).

Lixiviant selection in preg-robbing ores is therefore not defined by dissolution efficiency alone. It depends on the interaction between gold complexes and carbonaceous matter. Different complexation systems exhibit distinct adsorption affinities, which directly influence gold losses during leaching.

Figure 4 compares the relative adsorption affinity of gold complexes in cyanide, thiosulfate, and halide systems, providing a conceptual basis for evaluating their susceptibility to preg-robbing.

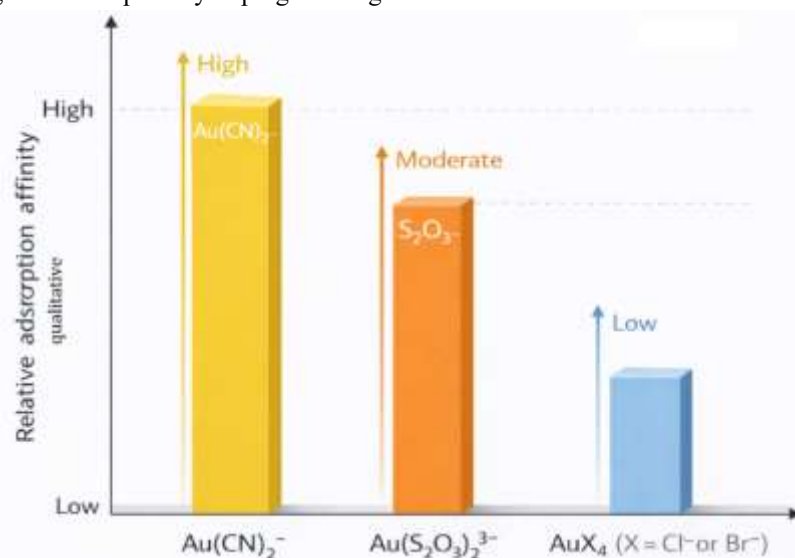


Figure 4. Comparison of the adsorption affinity of the gold–lixiviant complex on reactive carbon. Adapted from Vashist et al. (2022), Chaka and Rupprecht (2024), and Niu et al. (2025).

Figure 4 shows that adsorption affinity varies significantly with complex chemistry. The cyanide complex, $\text{Au}(\text{CN})_2^-$, exhibits the highest affinity for carbonaceous surfaces, which explains its vulnerability to preg-robbing. This strong interaction is consistent with the high adsorption capacity observed in carbon-rich ores.

Thiosulfate complexes, such as $\text{Au}(\text{S}_2\text{O}_3)_2^{3-}$, show moderate affinity. This reduces, but does not eliminate, adsorption losses. Their performance depends on operating conditions and the nature of the carbonaceous matter.

Halide complexes, represented by AuX_4^- (X = Cl⁻ or Br⁻), exhibit the lowest adsorption affinity. This behavior suggests a lower sensitivity to preg-robbing. However, their application is constrained by solution chemistry, reagent stability, and downstream recovery challenges.

The comparison highlights that lixiviant selection must consider not only dissolution kinetics but also adsorption behavior. Systems with lower affinity for carbonaceous matter can improve robustness in preg-robbing ores, but only when integrated into a compatible flowsheet.

5.3. Halide leaching systems

Chloride- and bromide-based systems operate under strongly oxidizing conditions and form highly soluble gold complexes, such as AuCl_4^- and AuBr_4^- . These complexes exhibit low affinity for carbonaceous matter, thereby reducing adsorption losses and making halide leaching suitable for ores with severe preg-robbing (Ljubetic & Liu, 2022; Rinne et al., 2022).

Operational constraints offset this advantage. Halide systems require corrosion-resistant materials, careful handling of chlorine species, and strict regulatory compliance. These factors limit large-scale adoption.

As a result, halide leaching is typically restricted to niche applications or hybrid flowsheets. Its use is justified when the severity of preg-robbing outweighs the added complexity and cost (Karppinen et al., 2024).

5.4. Glycine-based leaching

Alkaline glycine leaching is a low-toxicity and selective alternative for gold extraction. Under alkaline conditions, gold-glycinate complexes exhibit low affinity for carbonaceous matter, which reduces preg-robbing (Altinkaya et al., 2020). When combined with oxidants such as hydrogen peroxide or electrochemical systems, glycine can sustain stable dissolution and enable recovery routes that do not rely on activated carbon.

Despite these advantages, the technology remains at an early stage. Gold dissolution rates are generally lower than in cyanidation, and process performance is sensitive to oxidant control and mineralogical variability (Altinkaya, 2021).

Glycine systems are therefore best suited to specific cases. Their use is justified where environmental constraints or carbon reactivity limit cyanide performance.

5.5. Downstream recovery considerations

Downstream recovery in preg-robbing systems is dictated by the lixiviant. In cyanidation, recovery relies on CIL or CIP circuits. These require high carbon inventories and strict process control to limit competitive adsorption. Where carbon activity cannot be managed, Merrill–Crowe may offer a more stable alternative (Owusu et al., 2023).

Thiosulfate systems favor resin-based recovery. Resin-in-pulp (RIP) and resin-in-leach (RIL) reduce organic fouling and avoid competition with natural carbon (Vashist et al., 2022). Halide systems are typically coupled with electrowinning or solvent extraction, both of which bypass carbon adsorption. Glycine systems follow similar routes, using resin adsorption or electrowinning with specialized electrodes (Msumange et al., 2023).

Leaching performance, therefore, depends on the compatibility between lixiviant chemistry and recovery method. Each system generates distinct gold complexes that require specific recovery strategies. Process performance is governed by the interplay among complex stability, adsorption behavior, and recovery efficiency.

Figure 5 summarizes these relationships, emphasizing that lixiviant selection and downstream recovery must be treated as a single, integrated decision in preg-robbing ores.

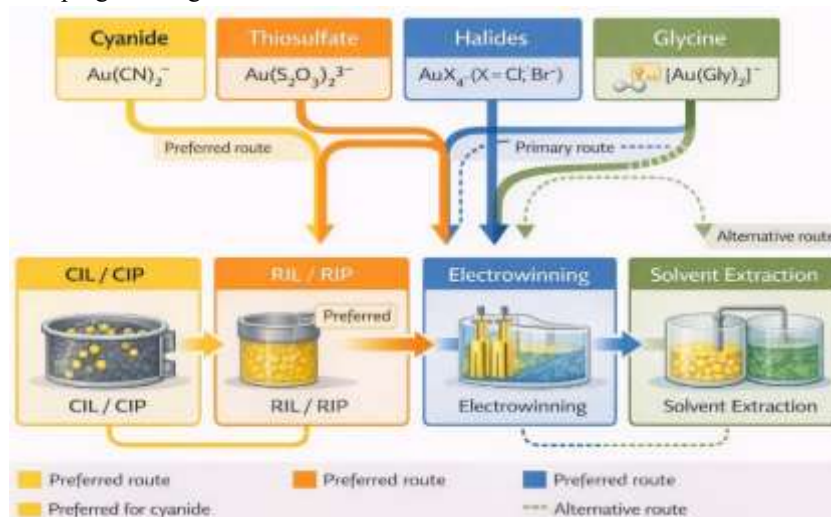


Figure 5. Linkage between lixiviant choice and downstream gold recovery options in preg-robbing systems. Adapted from Owusu et al. (2023) and Vashist et al. (2022).

Figure 5 shows that the chemistry of the gold complex controls the recovery strategy. Cyanide systems, based on $\text{Au}(\text{CN})_2^-$, are compatible with CIL/CIP due to the strong affinity of activated carbon. This same affinity also drives preg-robbing in carbonaceous ores.



Thiosulfate systems form $Au(S_2O_3)_2^{3-}$ and are not suited to carbon adsorption. Resin-based recovery (RIL/RIP) is therefore preferred, as it avoids competition with natural carbon. This distinction is essential for maintaining recovery efficiency.

Halide systems generate AuX_4^- ($X = Cl^-$ or Br^-) and are typically coupled with electrowinning or solvent extraction. These routes bypass carbon adsorption and reduce sensitivity to preg-robbing, but increase process complexity.

Glycine systems produce $Au(Gly)_2^-$ complexes, which are also only partially compatible with carbon-based recovery. Solvent extraction and electrowinning are therefore favored.

These relationships show that lixiviant selection cannot be separated from the recovery strategy. Systems that reduce adsorption losses often require alternative recovery routes. Robust process design must integrate both stages.

Lixiviant selection isn't enough; process performance also depends on water chemistry, reagent stability, redox conditions, and residual carbon interactions, which are discussed next.

6. OPERATIONAL AND ENVIRONMENTAL CONSTRAINTS

Operational robustness and environmental performance are critical in the treatment of preg-robbing ores. Even with sound mineralogical diagnosis and appropriate pretreatment, poor control of water chemistry, redox conditions, or reagent stability can reintroduce gold losses and reduce circuit reliability (Ng, Wang, & Chen, 2022).

These factors define the practical limits of process performance. This section examines the operational and environmental constraints that govern industrial feasibility

6.1. Water chemistry

Water chemistry directly controls preg-robbing behavior. Divalent cations, such as Ca^{2+} and Mg^{2+} , affect surface charge, complex stability, and reagent consumption. High hardness can reduce gold dissolution kinetics while altering adsorption on carbonaceous matter (Pereira & Barbosa, 2017; Valdivieso-Bermeo et al., 2020).

Natural organic matter and fine clays introduce additional constraints. Organic species compete with gold complexes for adsorption sites and can foul activated carbon and resins. Suspended clays increase reagent demand and limit mass transfer, particularly in high-carbon ores (Romero et al., 2024).

These interactions affect both the intensity of preg-robbing and leaching performance. Dissolved species and suspended phases modify speciation, adsorption, and transport. Their impact is often underestimated during process design.

Table 5 summarizes the key water chemistry parameters that influence preg-robbing and leaching, linking each variable to its operational implications.

Table 5. Influence of water chemistry parameters on preg-robbing behavior and leaching performance. Adapted from Valdivieso-Bermeo et al. (2020), Romero et al. (2024), Niu et al. (2023), and Rinne et al. (2022).

Water chemistry parameter	Effect on preg-robbing	Impact on leaching performance	Operational implication
Ca^{2+} concentration	Indirect increase	Reduced complex stability; scale formation	Lime management critical
Mg^{2+} concentration	Indirect increase	Inhibits leaching kinetics at high levels	Limits reagent efficiency
Bicarbonate / alkalinity	Conditional	Buffers pH; may destabilize complexes	Narrows operating window
Natural organic matter (NOM)	Increases	Fouls carbon and resins; competes for sites	Pretreatment or water treatment required
Suspended clays/fines	Increases	Adsorbs reagents; reduces mass transfer	Requires clarification or thickening
Ionic strength	Variable	Alters adsorption kinetics and speciation	Affects reproducibility
Sulfate ions	Indirect	Competes in POX residues; impacts CN efficiency	Conditioning step needed
Chloride ions	May reduce	Stabilizes halide complexes; corrosion risk	Material selection critical
Dissolved silica	Indirect	Scaling and surface fouling	Impacts downstream recovery

Table 5 shows that water chemistry adds significant constraints to preg-robbing control. Many parameters act indirectly by modifying surface interactions and solution speciation. Their combined impact is often substantial.

Divalent cations, such as Ca^{2+} and Mg^{2+} , reduce leaching efficiency and promote scaling. Natural organic matter and suspended fines increase adsorption losses by fouling carbon surfaces and competing for active sites. These effects limit both kinetics and recovery.

Alkalinity and ionic strength influence speciation and adsorption, often narrowing the operating window. Sulfate and chloride introduce system-specific effects. Sulfate can reduce cyanide efficiency in POX residues, while chloride stabilizes halide complexes but increases the risk of corrosion.

Water chemistry is therefore a primary control variable. It affects process stability and reproducibility and cannot be treated as secondary. Effective operation requires active management through conditioning, clarification, and water treatment.

These constraints are more severe in recycled-water circuits, where ionic strength and organic load accumulate over time. Reliable operation in preg-robbing systems requires integrated control of mineralogy, reagent chemistry, and water quality, rather than isolated optimization of leaching conditions.

6.2. Process control sensitivity

Preg-robbing ores are exceptionally sensitive to process control. Small fluctuations in redox potential (Eh) or dissolved oxygen (DO) can significantly alter adsorption kinetics and gold losses. Conditions favorable for gold dissolution may simultaneously accelerate adsorption on reactive carbon surfaces (Niu et al., 2023).

Mineralogical variability amplifies this sensitivity. Variations in carbon type, surface functionality, and sulfide association result in an unstable metallurgical response under fixed operating conditions (Nwaila et al., 2025). As a result, pre-robbing systems demand tighter control loops, higher sampling frequencies, and rapid-response strategies compared to conventional ores.

The interaction between redox conditions and oxygen availability plays a central role in preg-robbing behavior during cyanidation. These variables control both gold dissolution and the kinetics of adsorption onto carbonaceous matter. In carbon-rich systems, operating conditions that enhance leaching may simultaneously intensify gold losses.

Figure 6 presents a conceptual representation of the combined effect of redox potential (Eh) and dissolved oxygen (DO) on adsorption intensity in cyanide systems.

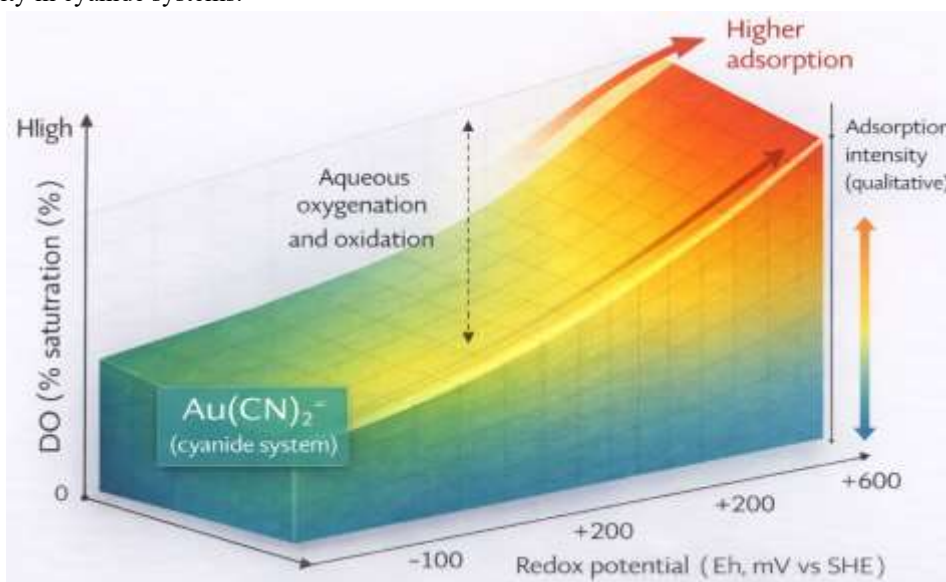


Figure 6. Conceptual sensitivity of preg-robbing behavior to redox potential and dissolved oxygen. Adapted from Niu et al. (2023), Nwaila et al. (2025), and Rinne et al. (2022).

Figure 6 shows that adsorption intensity increases with both redox potential and dissolved oxygen. These conditions promote rapid formation of $\text{Au}(\text{CN})_2^-$ and enhance its interaction with reactive carbonaceous surfaces. As a result, improved leaching kinetics are often accompanied by higher preg-robbing losses.

This relationship defines a critical operational trade-off. Conditions that maximize gold dissolution also accelerate adsorption. In high-carbon ores, process performance is therefore limited by adsorption kinetics rather than by dissolution.

The figure highlights that control of Eh and DO must be optimized within a constrained window. Excessive oxidation increases adsorption losses, while insufficient oxidation limits gold recovery. Stable operation requires balancing these competing effects.

This trend is system-dependent. The magnitude of adsorption is influenced by carbon structure, surface functionality, and solution chemistry. As a result, the surface shown should be interpreted as a qualitative envelope rather than a universal response.

Overall, Figure 6 reinforces that preg-robbing is not solely a mineralogical issue. It is also governed by operating conditions. Effective process control requires integrating thermodynamic drivers with adsorption behavior.

6.3. Reagent stability

Thiosulfate systems degrade rapidly at high redox potentials or in the presence of excess copper, increasing reagent consumption and reducing selectivity (Vashist et al., 2022). Glycine systems are also sensitive; high oxidation potential and temperature can degrade ligands or destabilize gold complexes if not carefully managed (Altinkaya et al., 2020).

Halide systems present distinct constraints. Chloride and bromide can be volatilized under strongly oxidizing or high-temperature conditions. These systems require closed-loop operation and corrosion-resistant materials (Rinne et al., 2022).

As a result, non-cyanide systems demand continuous monitoring of solution chemistry to maintain stability and performance.

6.4. Gas and residue management

Roasting produces gaseous emissions such as CO₂, SO₂, and arsenic species, necessitating gas-cleaning systems (Amankwah & Ofori-Sarpong, 2020). Pressure oxidation reduces emissions but produces acidic sulfate residues that require neutralization (Lemos et al., 2025).

Residual carbon in tailings isn't inert; partially deactivated carbon may regain adsorption capacity as conditions change, impacting long-term stability and metal mobility (Schindler et al., 2025).

Environmental performance is a primary constraint in the selection of pretreatment technologies for preg-robbing ores. Each route generates distinct gaseous, liquid, and solid outputs that require dedicated management strategies. These outputs directly affect process feasibility, regulatory compliance, and operating costs.

Thermal, oxidative, and halide-based systems vary in environmental impact. Roasting mainly emits gases, pressure oxidation produces acidic sulfate residues, and halide systems burden the liquid phase with halide-rich brines.

Figure 7 summarizes the main pretreatment routes and their associated outputs, linking each process to its corresponding environmental management requirements.

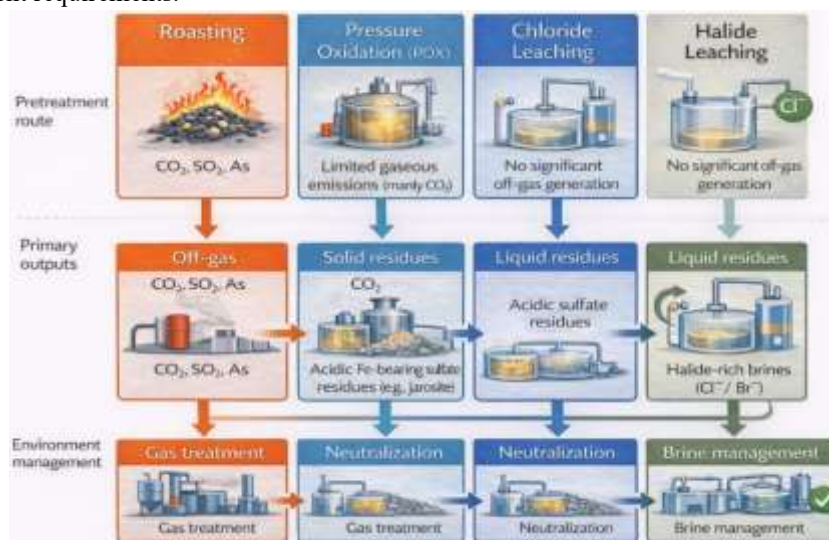


Figure 7. Linkage between pretreatment route, gas generation, residue characteristics, and environmental controls.

Adapted from Lemos et al. (2025), Rinne et al. (2022), and Surimbayev et al. (2024).



Figure 7 shows that environmental constraints are strongly process-dependent. Roasting generates significant off-gas streams containing CO₂, SO₂, and volatile species such as arsenic, requiring robust gas treatment systems. In contrast, pressure oxidation produces limited gaseous emissions but generates acidic, Fe-bearing sulfate residues that typically require neutralization and stabilization.

Halide-based systems present a different profile. Gas emissions are minimal, but process streams are dominated by halide-rich brines (Cl⁻ / Br⁻), which require controlled handling, recirculation, or immobilization. These systems transfer the environmental burden from the gas phase to the liquid phase.

This comparison highlights a fundamental trade-off. Technologies that minimize gaseous emissions often increase the complexity of managing liquid or solid residues. As a result, environmental performance cannot be assessed in isolation for a single output stream.

Pretreatment selection must therefore consider the full balance between gas, liquid, and solid outputs. The optimal route depends on site-specific constraints, including regulatory limits, water availability, infrastructure, and waste management capacity.

Overall, Figure 7 reinforces that environmental control is an integral component of flowsheet design. Process selection must be driven not only by metallurgical performance, but also by the ability to manage the associated environmental liabilities in a stable and economically viable manner.

6.5. Environmental liabilities and footprint

Environmental liabilities vary significantly with the processing route. Roasting generates the highest greenhouse and acid gas emissions, requiring extensive gas treatment. Pressure oxidation is energy-intensive but provides better containment of emissions. Thiosulfate and glycine systems reduce toxicity risks but produce complex effluents that demand advanced water management (Surimbayev et al., 2024).

Carbonaceous matter is a critical factor in long-term environmental performance. Its interaction with metals and organic species affects geochemical stability, adsorption–desorption behavior, and potential metal release under changing redox conditions (Junussov et al., 2021).

Operational and environmental constraints further limit the applicability of pretreatment technologies for preg-robbing ores. These constraints are coupled with mineralogy and process chemistry. They directly influence adsorption behavior, reagent stability, and residue management.

Gas emissions, liquid effluents, and solid residues differ markedly across pretreatment routes. Roasting is constrained by off-gas treatment requirements. Pressure oxidation generates acidic sulfate residues that require neutralization and stabilization. Halide systems shift the burden to liquid-phase management, including brine handling, corrosion control, and closed-loop operation.

These differences translate into distinct CAPEX, OPEX, and regulatory burdens. Technology selection cannot be based solely on metallurgical performance.

Table 6 compares the main operational and environmental constraints associated with pretreatment technologies for preg-robbing ores, highlighting their implications for process selection and industrial implementation.

Table 6. Comparative environmental footprint of leaching and pretreatment technologies for preg-robbing ores. Adapted from Amankwah and Ofori-Sarpong (2020), Lemos et al. (2025), Surimbayev et al. (2024), and Altinkaya et al. (2020).

Technology	Main environmental load	Gaseous emissions	Liquid effluents	Solid residues	Overall environmental risk
Cyanidation (CIL/CIP)	Toxic reagents; adsorption losses	Low	CN-bearing effluents	Carbon-loaded tailings	Moderate
Ultrafine grinding (UFG)	High energy demand	Low	Low	Fine reactive tailings	Moderate
Roasting	Carbon oxidation	High CO ₂ , SO ₂ , As	Low	Oxidized calcine	High
Pressure oxidation (POX)	Energy and acid generation	Low	Acidic sulfate liquors	Jarosite-rich residues	Moderate–high



BIOX	Biological oxidation by-products	Very low	Moderate (acidic)	Bio-oxidized solids	Low–moderate
Thiosulfate leaching	Reagent instability	Very low	Thiosulfate-rich effluents	Low-toxicity residues	Low–moderate
Halide leaching	Corrosive environment	Possible halogen losses	Halide brines	Minimal solids	Moderate
Glycine leaching	Organic reagents	Very low	Glycine-containing liquors	Benign tailings	Low
Hybrid routes (POX + non-cyanide)	Combined impacts	Low–moderate	Complex mixed streams	Stabilized residues	Moderate

Table 6 shows that environmental and operational constraints are process-dependent and often define the practical limits of each technology. Roasting effectively removes reactive carbon but is constrained by complex gas treatment requirements and strict emission controls. Pressure oxidation reduces gaseous emissions but shifts the burden to solid residue management, particularly acidic sulfate phases.

Halide-based systems minimize off-gas generation but introduce challenges in liquid-phase management. Halide-rich brines require controlled recirculation, corrosion-resistant materials, and secure containment. These requirements increase process complexity and capital intensity.

Environmental constraints are not secondary variables. They directly affect process stability, regulatory compliance, and long-term liability. In many cases, they outweigh differences in metallurgical performance.

Pretreatment selection must therefore balance carbon removal efficiency with environmental manageability. Technologies that are metallurgically effective may become impractical under site-specific constraints.

Operational complexity and environmental liabilities translate directly into cost and risk. These factors determine whether a technically viable flowsheet can be implemented at an industrial scale. The next section examines the economic implications and flow sheet selection, integrating metallurgical performance with CAPEX, OPEX, and risk tolerance.

7. ECONOMIC ASSESSMENT

Economic viability ultimately determines the selection of processing routes for preg-robbing ores. Technologies that are metallurgically effective may not be implementable when capital intensity, operating cost, regulatory compliance, and long-term liabilities are considered together (Ahtiainen, 2020).

These factors define the boundary between technical feasibility and industrial application. This section evaluates CAPEX, OPEX, energy demand, environmental liabilities, and regulatory constraints within an integrated framework.

7.1. Capital expenditure (CAPEX)

Capital requirements vary by more than an order of magnitude across available pretreatment and leaching routes. Pressure oxidation and roasting are consistently the most capital-intensive options due to autoclaves, gas-handling systems, materials of construction, and ancillary infrastructure (Dyson et al., 2022; Lemos et al., 2025).

By contrast, cyanidation circuits that incorporate blanking agents or carbon management strategies require relatively low upfront investment. However, this apparent advantage is often offset by limited metallurgical performance in high-PRI ores and by the need for oversized carbon circuits and auxiliary conditioning steps (Owusu et al., 2021; Gutierrez, 2021).

Hybrid flowsheets occupy an intermediate position. POX followed by non-cyanide leaching or alkaline glycine circuits requires higher initial investment than conventional CIL but significantly lower CAPEX than standalone roasting–cyanidation routes (Ahtiainen et al., 2021; Mabwe, 2024).

Capital intensity is a primary constraint in the selection of processing routes for preg-robbing ores. Differences in equipment requirements, materials of construction, and process integration lead to wide variability in CAPEX across technologies. These differences are not only quantitative but also structural, reflecting distinct levels of technological maturity and operational complexity.



High-temperature and high-pressure systems require specialized infrastructure, while alternative lixivants and hybrid routes introduce additional integration challenges. In contrast, conventional cyanidation circuits offer lower capital barriers but limited flexibility in controlling preg-robbing.

Table 7 compares the relative CAPEX intensity of pretreatment and leaching routes, identifying the main cost drivers and associated risk profiles.

Table 7. Relative CAPEX intensity of pretreatment and leaching routes for preg-robbing ores. Adapted from: Ahtiainen, (2020)

Processing route	Main CAPEX drivers	Relative CAPEX level	CAPEX risk profile
Conventional CIL with blanking agents	Carbon inventory, conditioning tanks	Low	Low technical risk, limited metallurgical upside
CIL with carbon scavenging stage	Additional solid-liquid separation	Low-moderate	Moderate complexity, incremental gains
Ultrafine grinding + CIL	High-power mills, classification	Moderate	Energy-driven CAPEX escalation
BIOX + CIL	Bioreactors, aeration, residence time	Moderate	Long commissioning and scale-up risk
Roasting + cyanidation	Roaster, off-gas treatment, materials	High	High permitting and emission-control risk
Chloridizing roasting	Corrosion-resistant equipment	Very high	Severe materials and compliance risk
Pressure oxidation (POX) + CIL	Autoclaves, oxygen systems	Very high	High capital lock-in, proven robustness
POX + non-cyanide leaching	Autoclave + alternative recovery	Very high	Reduced environmental risk, high upfront cost
Halide leaching circuits	Corrosion-resistant reactors	High	Specialized materials and containment
Glycine-based leaching	Extended leach tanks, control systems	Low-moderate	Low toxicity, emerging technology risk

Table 7 shows that CAPEX increases with process intensity and complexity. Low-capital routes, such as conventional CIL with blanking agents, offer operational simplicity but limited effectiveness in high preg-robbing systems. Incremental modifications, including carbon scavenging and ultrafine grinding, improve performance but increase cost and energy demand.

Biological and thermal pretreatment routes occupy an intermediate position. BIOX systems require long residence times and complex reactor design. Roasting incurs significant capital costs for off-gas treatment and emissions control.

High-intensity technologies, such as pressure oxidation and chloridizing roasting, exhibit the highest CAPEX. These routes provide robust metallurgical performance but require specialized equipment, corrosion-resistant materials, and long implementation timelines. Their application is therefore limited to operations with sufficient scale and economic margin.

Alternative lixiviant systems, including halide and glycine-based routes, show moderate to high CAPEX. Their cost depends on reactor design, material selection, and process integration. Although they may reduce environmental liabilities, they introduce uncertainties related to scale-up and operational stability.

CAPEX is not only a cost metric but also a proxy for technical risk and operational commitment. High-capital systems offer greater robustness but reduce flexibility. Low-capital options are more adaptable but less effective under severe preg-robbing conditions.

Intermediate solutions, such as BIOX or ultrafine grinding combined with conventional leaching, provide partial mitigation at moderate cost. However, they do not eliminate the influence of carbon reactivity on recovery. These trade-offs show that CAPEX must be evaluated alongside mineralogical diagnosis and long-term operational risk, rather than as an isolated economic parameter.

7.2. Operating expenditure (OPEX)

Operating costs are primarily driven by reagent consumption, maintenance, and water management. Non-cyanide lixiviants, such as thiosulfate and glycine, generally increase OPEX. This is due to reagent instability, the use of catalytic metals, and the need for tighter process control (Vashist et al., 2022; Altinkaya, 2021).

Chemical passivation introduces an additional layer of cost. Blanking agents, surfactants, and polymeric inhibitors require continuous dosing and strict control. Their consumption scales with carbon surface area rather than gold grade, which penalizes low-grade ores (Figuroa et al., 2020; Grigoreva & Boduen, 2023).

Cyanidation retains a cost advantage at moderate preg-robbing intensity. In high-PRI systems, this advantage is reduced. Increased carbon inventories, regeneration losses, and the need for scavenging stages raise operating costs and process risk (Ocampo-López et al., 2024).

7.3. Energy consumption

Energy demand is a key differentiator among processing routes for preg-robbing ores. Ultrafine grinding, roasting, and pressure oxidation are the most energy-intensive operations (Shi et al., 2025). Their impact on OPEX is significant, particularly in regions with high electricity costs or carbon pricing.

Non-cyanide leaching systems operate at lower energy intensity than cyanide leaching systems. This advantage is partly offset by auxiliary requirements, including electrochemical oxidation, temperature control, and intensive process monitoring (Altinkaya et al., 2020). Energy efficiency must therefore be evaluated at the circuit level rather than at the unit-operation scale.

Energy demand also contributes directly to the environmental footprint. Differences across processing routes reflect variations in process intensity, operating conditions, and equipment design.

Figure 8 compares the relative energy demand of major processing routes, highlighting the increase associated with high-temperature and high-pressure systems.

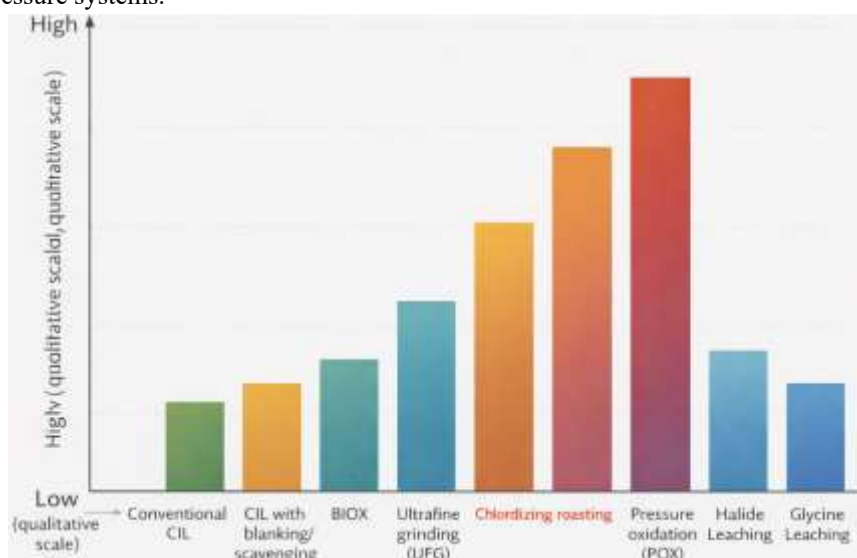


Figure 8. Relative energy intensity of pretreatment and leaching technologies for preg-robbing ores. Adapted from Ahtiainen (2020), Dyson et al. (2022), Shi et al. (2025), and Altinkaya et al. (2020).

Figure 8 shows that energy demand increases with process intensity. Conventional cyanidation operates at relatively low energy levels. Incremental modifications, including carbon management and ultrafine grinding, introduce moderate increases.

Thermal and pressure-based technologies dominate the upper range. Roasting and pressure oxidation exhibit the highest energy demand due to elevated temperatures, oxygen supply, and auxiliary systems. These requirements contribute significantly to both OPEX and carbon footprint.

Alternative lixiviant systems operate at a lower energy level. Halide and glycine leaching operate under milder conditions. However, their overall cost is influenced more by reagent consumption and process control than by energy demand alone.



Energy demand, therefore, acts as a key discriminator between technologies. High-energy routes offer robust metallurgical performance but increase operating cost and environmental impact. Lower-energy systems are more flexible but may require additional measures to control preg-robbing behavior.

Non-cyanide leaching systems, including glycine and halide routes, show lower intrinsic energy demand during leaching. Auxiliary requirements, such as oxidant generation and process control, may partially offset this advantage. These contrasts highlight the need to evaluate energy consumption at the flowsheet level rather than at the unit-operation scale.

7.4. Environmental liabilities and regulatory constraints

Environmental liabilities introduce significant economic risk in preg-robbing processing routes. Ores containing carbonaceous matter, arsenic, or volatile elements require intensive control measures during roasting or oxidation. Gas treatment, residue stabilization, and long-term monitoring increase both CAPEX and closure costs (Amankwah & Ofori-Sarpong, 2020).

Carbonaceous tailings pose challenges as residual reactive carbon alters geochemistry, affects metal mobility, and complicates tailings storage design (Schindler et al., 2025). These traits lead to stricter permits and higher financial guarantees in some regions.

Regulatory frameworks increasingly favor lower-toxicity lixivants and reduced emissions. Cyanide remains permitted under controlled conditions, but its social acceptance is declining. Glycine and thiosulfate systems benefit from a more favorable regulatory perception, although this advantage may be offset by complex effluent management requirements (Surimbayev et al., 2024).

Regulatory and environmental constraints, therefore, act as primary cost drivers. They extend beyond emissions and effluent quality to include permitting, chemical handling restrictions, and long-term liability associated with residues. These factors translate into direct and indirect costs, including compliance infrastructure, monitoring, and post-closure management.

Processing routes have different regulations. Cyanide systems face strict rules for transport, storage, and detoxification. Emission permits and residue stability limit thermal and oxidative routes. Halide and alternative lixiviant systems involve controls over corrosive reagents, brine management, and chemical persistence.

In many cases, regulatory burden becomes a decisive factor in process selection. Table 8 summarizes the main regulatory constraints, environmental cost drivers, and long-term liabilities associated with major processing routes for preg-robbing ores.

Table 8. Regulatory and environmental cost drivers associated with preg-robbing processing routes. Adapted from Amankwah and Ofori-Sarpong (2020), Lemos et al. (2025), Schindler et al. (2025), and Surimbayev et al. (2024)

Processing route	Main regulatory constraint	Environmental cost driver	Long-term liability
Conventional cyanidation (CIL/CIP)	Cyanide handling and transport	Detoxification of effluents; carbon management	Moderate (water and carbon residues)
Cyanidation + blanking agents	Organic additives regulation	Organic fouling; reagent disposal	Moderate
Ultrafine grinding-based flowsheets	Energy intensity	Indirect CO ₂ footprint	Low–moderate
BIOX-based routes	Biological effluent control	Acidic liquors; sulfate generation	Low
Roasting	Air emission permits	CO ₂ , SO ₂ , As volatilization	High (air and solid residues)
Chloridizing roasting	Halogen emission limits	Corrosion products; halide release	Very high
Pressure oxidation (POX)	Autoclave safety regulations	Acidic sulfate residues	Moderate–high
POX + non-cyanide leaching	Multi-regulatory frameworks	Mixed liquid effluents	Moderate
Thiosulfate leaching	Reagent stability oversight	Thiosulfate degradation products	Low–moderate



Halide leaching	Chlorine and bromine control	Halide brines; corrosion	High
Glycine-based leaching	Minimal chemical restriction	Organic-rich effluents	Low
Hybrid low-toxicity routes	Integrated compliance	Combined residue streams	Moderate

Table 8 shows that regulatory constraints and environmental cost drivers are strongly route-specific. Cyanidation systems are governed by chemical handling and detoxification requirements. Although technically mature, they carry persistent liabilities related to water quality and carbon residues.

Thermal routes, particularly roasting and chloridizing roasting, exhibit the highest regulatory burden. Air emission permits, combined with CO₂, SO₂, and arsenic volatilization, impose significant capital and operating costs. These routes also carry substantial long-term liabilities associated with atmospheric emissions and solid residues.

Pressure oxidation shifts the regulatory focus toward residue management and operational safety. Autoclave systems require strict safety controls, while acidic sulfate residues must be neutralized and stabilized prior to disposal.

Halide-based systems have a different regulatory profile, with limited gas emissions but challenges in handling chlorine, bromine, and halide-rich brines related to containment, corrosion, and liquid management. These issues raise capital costs and environmental risks.

Low-toxicity alternatives like glycine and thiosulfate reduce regulatory pressure but bring uncertainties over reagent stability and effluent composition. Their long-term liabilities are lower but depend on site-specific water management.

Regulatory burden is therefore not a secondary constraint. It directly influences CAPEX, OPEX, and long-term liability, and can override purely metallurgical considerations.

This comparison shows that selecting processes for preg-robbing ores requires considering regulatory compliance, environmental costs, and technical performance. Technologies with good metallurgical results may be impractical when factoring in regulatory and environmental liabilities.

The next section presents a decision-oriented synthesis, integrating mineralogy, pretreatment, leaching, environmental risk, and economics into practical selection criteria.

8. DECISION MATRIX FOR FLOWSHEET SELECTION

Choosing flowsheets for preg-robbing ores involves multiple criteria, not just a single best technology. Factors such as mineralogy, adsorption kinetics, and operability influence robustness and the risk of failure (Ng, Wang, & Chen, 2022; Surimbayev et al., 2024). Case studies show high-PRI systems often underperform in cyanidation, even with mitigation (Dyson et al., 2022; Valdivieso-Bermeo et al., 2020).

The objective of this section is to translate these findings into a decision-oriented framework. The proposed matrix links key ore attributes to defensible processing routes. It follows the logic adopted in recent geometallurgical and process-selection approaches for complex gold systems (Nwaila et al., 2020; Maganga et al., 2023).

8.1. Decision criteria

Primary route selection criteria include: (i) preg-robbing severity and adsorption kinetics; (ii) reactive carbon nature and distribution; (iii) sulfides and arsenic co-occurrence; (iv) environmental/regulatory exposure; (v) infrastructure readiness; and (vi) energy/water constraints (Ng, Yang, Su, Zhong, & Chen, 2022; Youlton, Kinnaird, & Youlton, 2021).

These criteria are strongly interdependent. Changes in one parameter often propagate through the entire flowsheet.

For example, roasting can effectively suppress carbon reactivity, but it significantly increases permitting complexity and off-gas management requirements (Amankwah & Ofori-Sarpong, 2020; Espinoza-Martínez et al., 2025).

8.2. Weighted evaluation framework

To compare processing routes, the decision matrix assigns weights to five dimensions: metallurgical performance, CAPEX, OPEX, environmental impact, and operational robustness. Weighting is essential, as high-PRI ores are often constrained by robustness rather than theoretical recovery (Owusu et al., 2021; Owusu et al., 2023).



Non-cyanide systems show a trade-off: they reduce carbon losses but have constraints with reagent stability and recovery (Javanshir et al., 2025; Karppinen et al., 2024).

Selecting an appropriate route requires evaluating multiple criteria. Mineralogical attributes, adsorption kinetics, and carbon reactivity define ore behavior, while environmental constraints, infrastructure, and resource intensity determine practical feasibility.

These factors are strongly coupled. Improvements in metallurgical performance often introduce additional operational or regulatory burdens. Route selection must therefore balance recovery efficiency with implementation risk and long-term sustainability.

A systematic framework is needed to convert ore characteristics into justifiable processing strategies. Table 9 outlines key decision criteria and their impact on route choice, aiding flowsheet screening and optimization.

Table 9. Decision matrix for flowsheet selection in preg-robbing refractory gold ores. Adapted from Ahtiainen (2020), Ng, Wang, and Chen (2022), Dyson et al. (2022), Altinkaya et al. (2020), and Surimbayev et al. (2024).

Processing route	Metallurgical performance	CAPEX	OPEX	Environmental impact	Operational robustness	Overall suitability
Conventional CIL	Low–moderate	Low	Low	Moderate	Low	Not recommended
CIL + blanking agents	Moderate	Low	Moderate	Moderate	Low–moderate	Conditional
UFG + CIL	Moderate	Moderate	High	Moderate	Low	Conditional
BIOX + CIL	Moderate	Moderate	Moderate	Low–moderate	Moderate	Conditional
Roasting + cyanidation	High	High	High	High	High	Conditional
POX + cyanidation	Very high	Very high	High	Moderate	Very high	Recommended
POX + thiosulfate	Very high	Very high	Moderate–high	Low–moderate	Very high	Recommended
Thiosulfate (no POX)	High	Moderate	High	Low–moderate	Moderate	Conditional
Halide leaching	High	High	Moderate	Moderate–high	Moderate	Niche
Glycine-based leaching	Moderate	Low–moderate	Moderate	Low	Moderate	Emerging

Table 9 shows that route selection is governed by a combination of mineralogical, operational, and environmental constraints. No single parameter defines the optimal flowsheet. Instead, decisions emerge from the interaction between adsorption severity, carbon characteristics, and system-level constraints.

High preg-robbing severity and reactive carbon favor alternative lixivants or hybrid flowsheets. However, these options often require greater infrastructure, tighter process control, and higher capital investment. Conversely, conventional cyanidation remains viable under low-severity conditions but rapidly loses effectiveness as adsorption increases.

The presence of sulfides and arsenic introduces additional complexity. These components often necessitate pretreatment, which can improve metallurgical performance but significantly increase environmental burden and regulatory exposure.

Infrastructure readiness and resource availability further constrain feasible options. Energy-intensive routes, such as roasting or pressure oxidation, may be technically effective but impractical in regions with limited utilities or strict environmental regulations.

Overall, Table 9 highlights that robust flowsheet selection requires an integrated, multi-criteria approach. Decisions based solely on laboratory performance are insufficient for preg-robbing ores. Instead, successful implementation depends on aligning mineralogy, process chemistry, and external constraints within a coherent operational framework.

8.3. Decision classes

Processing routes are classified as recommended, conditionally viable, niche, or not recommended, reflecting the variability in carbonaceous ores and mineralogical heterogeneity that influences adsorption and gold recovery (Gökdemir et al., 2025; Nwaila et al., 2025).

Processing route selection for preg-robbing ores depends on adsorption severity and project complexity. As preg-robbing intensity rises, traditional leaching become less effective, needing alternative chemistries and integrated flowsheets.

Different lixiviant systems occupy specific positions in this decision space, reflecting trade-offs among metallurgical performance, complexity, reagent management, and regulatory considerations. The choice of technology should consider system robustness and feasibility, not just gold recovery.

Figure 9 shows a decision map linking preg-robbing severity to project complexity, highlighting the shift from cyanidation to alternative lixiviants and hybrid flowsheets as system demands grow.

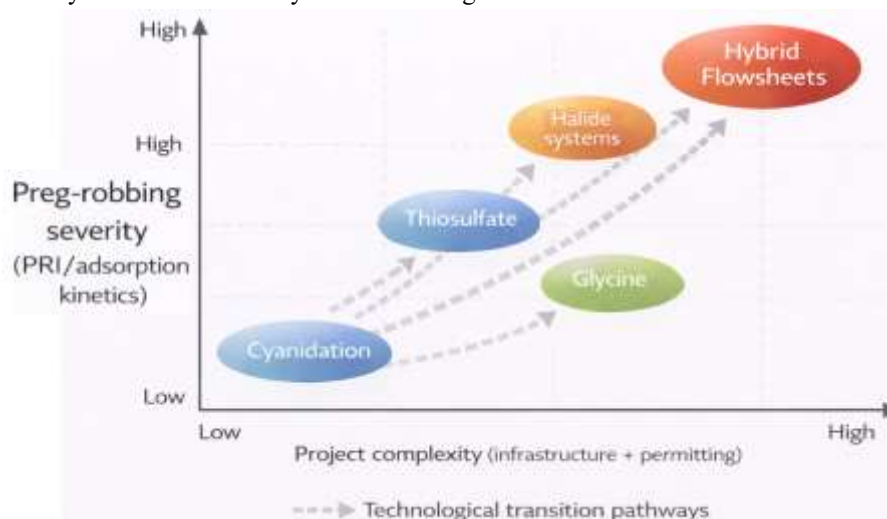


Figure 9. Decision space for processing routes as a function of preg-robbing severity and operational complexity. Adapted from Ng, Wang, and Chen (2022) and Surimbayev et al. (2024)

Figure 9 shows that increasing preg-robbing severity drives processing routes toward higher levels of project complexity. Cyanidation remains suitable for low-severity systems but becomes ineffective as adsorption losses increase.

Thiosulfate occupies an intermediate position, offering reduced sensitivity to preg-robbing at the expense of greater chemical and operational complexity. Glycine-based systems extend this trend, providing further reduction in adsorption losses while requiring tighter control of reaction conditions and reagent stability.

Halide-based systems operate at high levels of both severity tolerance and project complexity. Their low affinity for carbonaceous matter makes them suitable for strongly preg-robbing ores, but their implementation is constrained by corrosion, reagent management, and regulatory considerations.

Hybrid flowsheets represent the upper boundary of the decision space. These systems combine pretreatment, alternative lixiviants, and advanced recovery strategies to achieve robust performance under severe preg-robbing conditions. Their application is typically justified only when simpler routes fail to deliver acceptable recovery.

Overall, the figure demonstrates that preg-robbing control is not achieved through a single technology. Instead, increasing severity requires progressively integrated and complex solutions, reinforcing the need for a system-level approach to flowsheet design.

This decision matrix provides a structured synthesis of the review. The next section consolidates conclusions and research gaps and explicitly flags where the evidence base is strongest and where it remains dominated by laboratory-scale studies (Page et al., 2021; Schindler et al., 2025).

9. FUTURE TRENDS AND RESEARCH GAPS

Ore quality continues to decline, while mineralogical complexity increases. Despite progress in pretreatment, leaching chemistry, and operational control, several scientific and technological gaps still limit the development of robust and scalable solutions (Ng, Wang, & Chen, 2022; Surimbayev et al., 2024).

Future progress in controlling preg-robbing ores relies on coordinated advances across various domains. Limitations are not due to missing technologies but to a lack of integration among mineralogical characterization, process engineering, environmental management, and digital control.

Each domain addresses a distinct aspect of the problem. Mineralogical tools define carbon reactivity, process engineering determines treatment pathways, environmental strategies govern long-term liabilities, and digitalization enables adaptive operation under variable ore conditions.

A structured roadmap is therefore required to align short-term improvements with long-term technological development. Figure 10 presents a forward-looking framework that organizes key research directions across time horizons and technical domains.

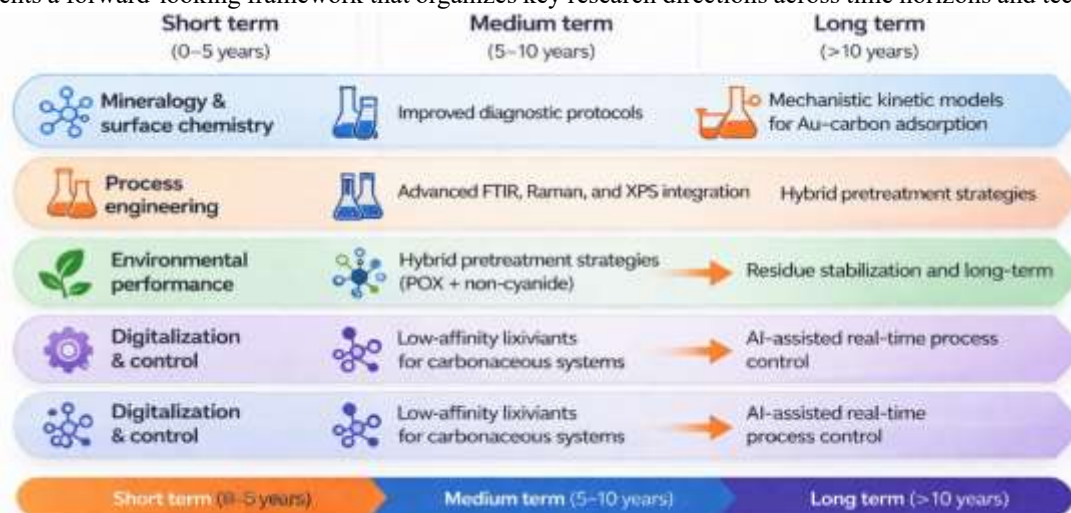


Figure 10. Research and technology roadmap for managing preg-robbing ores. Adapted from Ng, Wang, and Chen (2022), Maganga et al. (2023), Nwaila et al. (2025), Kondos and Choi (2025), and Schindler et al. (2025).

Figure 10 shows that progress in preg-robbing control is expected to follow a staged and integrated trajectory. Short-term efforts focus on improving diagnostic capability, particularly by integrating advanced spectroscopic techniques and more robust leaching protocols. These developments aim to better resolve carbon reactivity and adsorption behavior.

Medium-term advances are driven by process integration. Hybrid pretreatment strategies and improved control of solution chemistry are expected to enhance flexibility and reduce sensitivity to ore variability. At this stage, linking mineralogical understanding with process response becomes critical.

Long-term developments emphasize system-level optimization. Nanoscale characterization, residue stabilization, and AI-assisted process control are key components of future flowsheets. These approaches aim to reduce uncertainty, improve reproducibility, and enable real-time adaptation to changing operating conditions.

The roadmap also highlights the increasing importance of environmental performance. Long-term stability of carbonaceous residues and geochemical behavior under evolving conditions are central to regulatory compliance and closure planning.

Overall, Figure 10 reinforces that no single technology can resolve preg-robbing. Sustainable progress will depend on integrating characterization, processing, environmental management, and digital control into coherent, adaptive flowsheets.



9.1. Advanced characterization of carbonaceous reactivity

A major limitation in current practice is the incomplete understanding of carbon reactivity at the nanoscale. Conventional bulk characterization does not reliably distinguish between inert graphite and highly reactive disordered carbon. As a result, adsorption behavior is often misinterpreted (Junussov et al., 2021; Schindler et al., 2025; Xue et al., 2025).

Progress depends on advanced spectroscopic and imaging techniques capable of resolving surface functional groups, structural defects, and adsorption sites at relevant length scales. These methods provide the level of detail required to link carbon structure with reactivity.

Integrating nanoscale characterization with automated mineralogy and geometallurgical models remains a key research frontier.

9.2. Kinetic modeling of gold adsorption and preg-robbing dynamics

Industrial decisions are still largely based on empirical indices, such as the PRI. These metrics provide limited predictive power under variable redox conditions, temperatures, and solution chemistries. They do not capture the dynamic nature of adsorption and desorption processes (Ghasemi et al., 2022; Niu et al., 2023).

There is a clear need for mechanistic and kinetic models that describe the time-dependent interaction of gold complexes with carbonaceous matter. Such models are essential for reliable process simulation, scale-up, and dynamic control of leaching circuits treating variable ore blends (Lee, 2022; Lazar, 2025).

9.3. Development of low-affinity alternative lixiviants

Alternative lixiviants have reduced, but not eliminated, preg-robbing. Thiosulfate and glycine systems still face limitations related to stability, reagent consumption, and downstream recovery (Altinkaya, 2021; Vashist et al., 2022).

Future research should focus on ligands with intrinsically low affinity for carbonaceous surfaces, while maintaining adequate leaching kinetics and compatibility with industrial recovery technologies (Wei et al., 2025; Javanshir et al., 2025).

Electrochemical and bio-assisted lixiviation methods also warrant further investigation.

9.4. Hybrid pretreatment systems with reduced emissions

Single-technology solutions rarely address all dimensions of preg-robbing. Hybrid pretreatment systems that combine thermal, chemical, electrochemical, or biological steps offer more balanced approaches to metallurgical performance and environmental impact (Shi et al., 2025; Zhao et al., 2025).

However, their industrial maturity remains limited. Reliable scale-up data are still scarce.

Future research should prioritize energy efficiency, emissions reduction, and integration with non-cyanide leaching systems.

9.5. Environmental stabilization of residues and circular strategies

Carbonaceous residues are not chemically inert. Their long-term behavior controls metal mobility, tailings stability, and closure liabilities (Wei et al., n.d.; Schindler et al., 2025).

Future work must address stabilization, reuse, and valorization of these residues. This requires integrating preg-robbing processing routes with circular-economy principles and sustainable mining frameworks (Maganga et al., 2023).

9.6. Digitalization and AI-assisted process control

Ore variability remains a primary driver of failure in preg-robbing systems. Conventional control strategies are often insufficient to manage rapid changes in adsorption behavior. Digital twins, advanced sensors, and AI-assisted optimization provide new tools for real-time adaptation. These approaches enable dynamic adjustment of redox conditions, reagent dosing, and residence time (Pereira, 2025; Nwaila et al., 2025; Kondos & Choi, 2025).

Integrating geometallurgical models with digital process control represents a critical opportunity to improve robustness and reduce operating risk. This integration allows process response to be aligned with mineralogical variability rather than fixed operating setpoints.

Despite recent advances, significant gaps remain in the understanding and control of preg-robbing behavior. These limitations are not confined to individual techniques. They reflect a lack of integration between mineralogical characterization, adsorption kinetics, and process design.



Uncertainty persists across multiple scales. Nanoscale carbon reactivity is still poorly resolved, and adsorption models remain weakly constrained by experimental data. Alternative lixiviants and hybrid pretreatment strategies show potential but lack consistent industrial validation.

These gaps limit predictive capability and constrain flowsheet optimization. As a result, process selection often relies on empirical adjustments rather than mechanistic understanding.

Preg-robbing ores will continue to challenge conventional gold metallurgy. However, advances in characterization, modeling, hybrid processing, and digitalization provide credible pathways to improved recovery, reduced environmental impact, and greater operational stability. Progress will depend on integrating complementary solutions within robust, mineralogy-driven flowsheets rather than on identifying a single breakthrough technology.

Table 10 summarizes the key research gaps, their current maturity, expected impact on preg-robbing control, and the associated technical challenges.

Table 10. Key research gaps and expected impact on preg-robbing control. Adapted from Altinkaya (2021), Vashist et al. (2022), Maganga et al. (2023), and Kondos and Choi (2025).

Research gap	Current maturity	Expected impact	Key challenge
Nanoscale carbon reactivity characterization	Low–moderate	High	Method integration and cost
Kinetic adsorption modeling	Low	High	Data scarcity and validation
Low-affinity lixiviants	Moderate	Moderate–high	Stability and recovery
Hybrid low-emission pretreatments	Moderate	High	Scale-up and energy efficiency
Residue stabilization strategies	Low	Moderate	Long-term behavior
AI-assisted process control	Emerging	Very high	Data quality and integration

Table 10 shows that the most impactful research gaps are associated with fundamental understanding rather than incremental optimization. Nanoscale characterization of carbon reactivity and kinetic adsorption modeling exhibit high potential but remain constrained by limited data and methodological challenges.

Emerging approaches, including low-affinity lixiviants and hybrid low-emission pretreatments, offer promising pathways to reduce preg-robbing. However, their effectiveness depends on improved control of stability, selectivity, and process integration.

Residue stabilization remains underdeveloped. Long-term behavior of carbonaceous tailings, particularly under changing redox conditions, is not well understood. This gap has direct implications for environmental risk and regulatory compliance.

AI-assisted process control represents a high-impact frontier. Its application could enable real-time adaptation to ore variability and dynamic adsorption behavior. However, its effectiveness is limited by data quality, sensor reliability, and integration with existing control systems.

Overall, the identified gaps highlight a shift in research priorities. Future progress depends on linking mineralogical detail, adsorption kinetics, and process control within a unified framework. Without this integration, advances in individual areas are unlikely to translate into robust industrial solutions for preg-robbing ores.

10. CONCLUSIONS

Preg-robbing remains one of the most complex and persistent forms of gold refractoriness. It is driven by the strong affinity between carbonaceous matter and dissolved gold complexes. This review shows that the problem cannot be addressed through generic flowsheets or isolated unit operations. Effective treatment requires a mineralogy-driven approach, in which the origin and surface reactivity of carbonaceous matter guide process selection.

Mineralogical diagnosis is the critical starting point. It defines whether preg-robbing behavior is reversible, establishes the limits of conventional cyanidation, and determines the need for pretreatment, passivation, or alternative lixiviants. Flowsheets that neglect this step consistently show unstable performance under variable ore conditions.

No single pretreatment or lixiviant provides a universal solution. Cyanidation remains viable only within narrow mineralogical windows and under strict control. More consistent outcomes are achieved through integrated flowsheets that combine oxidative pretreatment, chemical passivation, alternative leaching systems, and recovery methods adapted to the modified ore.



Hybrid processing routes offer the most defensible solutions for high-severity systems. They address carbon reactivity while maintaining control over adsorption, reagent stability, and downstream recovery. However, these benefits are offset by higher capital intensity, increased process complexity, and greater regulatory exposure.

Preg-robbing is therefore a systems-level challenge. Industrially viable solutions require simultaneous optimization of metallurgical performance, economic constraints, operational robustness, and environmental management. Future progress will depend less on isolated technologies and more on integrating characterization, process design, and control into coherent, adaptable flowsheets.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author Contributions

Conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, and writing—review and editing: A.C.P. All authors have read and agreed to the published version of the manuscript.

Data Availability

The datasets generated in the current study are available from the corresponding author upon reasonable request.

Ethical Approval

This article does not contain any studies involving human participants or animals conducted by any of the authors.

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