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RESEARCH PAPER

Heap-borehole bio-leaching of precious and non-ferrous metals under continental climate conditions: a perforated-tube thermal activation approach

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ABSTRACT

A novel heap-borehole bio-leaching method with integrated thermal activation was developed and evaluated for the recovery of copper, nickel, and gold from low-grade ores under continental winter conditions. The method employs a dual perforated-tube system installed in boreholes drilled to a depth of 10 m within the ore heap. An outer acid-resistant HDPE tube (diameter 100 mm) and a coaxial inner tube (diameter 50 mm) with graduated perforation sizes (0.5, 1.5, and 2.5 mm for every 3 m segment) distribute oxidising bacterial solutions directly into the ore mass, while a heating cable maintains the internal temperature at 15–20 °C during winter periods with ambient temperatures of −20 to −30 °C. Bench-scale trials were conducted for 120 days under unheated outdoor conditions to simulate sub-zero winter environments. Comparative experiments included a baseline acid-only treatment, an analogue biooxidation prototype, a perforated-tube variant, and the full proposed method combining all factors. The proposed method achieved copper extraction of 86.46 %, nickel extraction of 54.03 %, and gold extraction of 84.29 % — representing improvements of approximately 30–35 percentage points over the prototype for copper and gold, and approximately 28 percentage points for nickel. The results demonstrate that integrated borehole delivery, microbial oxidation, and controlled thermal activation overcome the principal limitations of conventional heap leaching in cold climates, enabling year-round operation and economically viable recovery of precious and non-ferrous metals.

Keywords: heap leaching; borehole perforated tubes; bioleaching; thermal activation; copper recovery; nickel recovery; gold recovery

INTRODUCTION

Heap leaching (HL) is one of the most widely applied low-cost hydrometallurgical techniques for the recovery of copper, gold, nickel, and other valuable metals from low-grade or complex ores [1, 2]. The principal advantages of the method — relatively low capital expenditure, simplicity of scale-up, the ability to process large ore volumes with no tailings storage requirements, and the possibility of solution recirculation — have established it as an attractive option in modern extractive metallurgy [3].

Despite these advantages, conventional heap leaching faces several well-documented challenges. Recovery losses are significant for mixed ores of complex mineralogy containing primary sulphides, refractory gold occluding in sulphide matrices, and native precious metals associated with silicate gangue [4]. Incomplete penetration of leach solutions into the ore interior, channelling, and poor aeration restrict contact between the lixiviant and valuable minerals, resulting in low overall extraction efficiencies [5].

Among the most critical constraints on heap leaching operations in continental or subarctic climates — including large regions of Kazakhstan, Russia, Canada, and Mongolia — is seasonal temperature limitations. Standard drip-irrigation heap leaching systems are severely impaired at ambient temperatures below 0 °C. Surface-applied solutions freeze, bacterial cultures are inactivated, and evaporation of solutions in summer paradoxically adds to operational costs [6]. The bacterium Acidithiobacillus ferrooxidans, the principal bioleaching microorganism for sulphide ores, exhibits optimal metabolic activity at temperatures of 20–40 °C and essentially ceases oxidative activity below 10 °C [7, 8]. Alternative acidophilic cultures — including certain Ferroplasma, Burkholderia sp., and Bacillus subtilis strains — may tolerate lower temperatures but still require controlled minimum conditions for meaningful performance [9, 10].

Nickel resources, concentrated in sulphide and laterite deposits, represent a growing focus of heap leaching research. Laterite ores account for approximately 60 % of global nickel reserves, while sulphide ores (40 % of reserves) are of particular interest due to the co-occurrence of cobalt, copper, gold, and platinum-group metals [1]. Acid heap leaching of oxidised nickel laterites typically requires higher sulphuric acid concentrations than copper leaching, often exceeding 50 $g \cdot L^{-1}$ under cold winter conditions [11, 12]. Bio-assisted leaching of nickel using acidophilic bacterial consortia has been reported at extraction levels of approximately 35 % over 140-day column tests, highlighting the potential for improvement [13]. Laterite ores with elevated iron content may additionally yield iron phosphate as a valuable by-product from leach tailings [14]. For gold-bearing refractory sulphide ores, biooxidation pretreatment followed by cyanidation is the established processing route, but performance is strongly temperature-dependent [15, 16].

Existing patents describe perforated-tube borehole systems to improve solution distribution in heap leaching operations [17]. A further development of this approach, incorporating combined air and solution delivery through a connector-type flow-distribution device at an air-to-solution volume ratio of 3:1, has been proposed and patented to intensify the biooxidation process [18]. However, these systems do not in themselves address the thermal activation requirement for continuous winter-season operation, which is the principal limitation identified in the present work.

The objective of the present study was to develop and evaluate a heap-borehole bio-leaching method incorporating: (i) a dual coaxial perforated-tube system for subsurface solution delivery; (ii) in-situ thermal activation via a heating cable to maintain bioleaching-compatible temperatures in winter; and (iii) combined biological oxidation and acid/cyanide leaching. Comparative bench-scale trials over 120 days, covering copper, nickel, and gold ore types, were conducted to quantify the metallurgical benefits of the proposed approach relative to a baseline and established prototype configurations.

MATERIAL AND METHODS

Ore Characterisation

Three ore types were selected for the comparative leaching trials: a copper ore with a copper grade of 0.517 % Cu, a nickel ore with a nickel grade of 1.34 % Ni, and a gold-bearing ore with a gold content of 1.4 $g \cdot t^{-1}$ Au. Ore preparation followed standard heap-leaching practices (crushing and size classification). The detailed mineralogical characterisation of the ores was outside the scope of the present study.

Experimental Configuration

Bench-scale tests were performed over 120 days (November to March) in unheated open-air facilities, with ambient temperatures ranging from −20 °C to +2–3 °C.

Tests simulated heap leaching on a limited ore volume. Four experimental variants were evaluated in parallel for each ore type:
Variant 1 — Baseline: Standard heap leaching with acidic solution (copper and nickel) or sodium cyanide solution (gold) applied through a conventional surface drip-irrigation system. No additional oxidation or thermal treatment.
Variant 2 — Analogue/Prototype (biooxidation + acid or cyanide): Ore pre-treated by surface application of an adapted A. ferrooxidans bacterial culture during a preceding warm-season period, followed by standard surface drip-irrigation leaching at winter conditions.
Variant 3 — Perforated tubes + acid or cyanide (without bio or thermal): Leach solution delivered through the proposed perforated-tube borehole system without heating or biological pre-oxidation.
Variant 4 — Proposed method (perforated tubes + thermal activation + biooxidation + acid or cyanide): Full combination of in-situ bacterial oxidation delivered through the borehole system with thermal heating cable maintaining 15–20 °C (for copper and gold) or up to 30 °C (for nickel), plus surface drip irrigation of the leach solution.
All test variants were operated at a total surface irrigation density of 10 $L \cdot m^{-2} \cdot h^{-1}$ (equivalent volume). In Variant 4, approximately half of the leach solution volume was injected through the inner perforated tube, with the remainder applied via the drip surface system.

Perforated-Tube Assembly

The perforated-tube system consisted of two coaxially mounted acid-resistant high-density polyethylene (HDPE, PE-100) plastic tubes installed vertically in a borehole drilled to 10 m depth at 120 mm borehole diameter. HDPE was selected for its chemical resistance to dilute sulphuric acid and its retention of ductility and impact strength at sub-zero temperatures (down to −30 °C), ensuring mechanical integrity under both the cold ambient conditions and the 15–30 °C heated internal environment maintained during the trials. The outer tube had an outer diameter of 100 mm with 2.5 mm perforations uniformly distributed. The inner tube (50 mm outer diameter) featured graduated perforation sizes of 0.5, 1.5, and 2.5 mm for every 3 m section from bottom to top, ensuring progressive solution distribution along the borehole depth. The annular space between the tubes was filled with an inert moisture-permeable filler (quartz sand or mineral wool). A heating cable was wound around the inner tube to achieve a total heated length of 20 m (including the helical wrap); nominal power consumption was 150 W per borehole. Temperature was monitored via sensors installed in the central segment. Flow control at the borehole head was managed by a valve-barometer-flow-meter assembly. For a treated surface area of 1,000 m², 40 borehole units were deployed, each covering approximately 25 m² of heap surface.
Fig. 1 presents the assembly schematic for the perforated-tube segments; **Fig. 2** shows the assembled tube configuration in cross-section.

Solution Preparation and Leaching Conditions

Copper ore was leached with a 2 % (v/v) sulphuric acid solution. Nickel ore was leached with a 10 % (v/v) sulphuric acid solution, reflecting the higher acid demand of lateritic nickel ores. Gold ore was leached by cyanidation with a 1 $g \cdot L^{-1}$ sodium cyanide solution after establishment of alkaline conditions (pH raised from 2.0 to 10.5 by alkali wash following biooxidation). For Variants 2 and 4, the bacterial culture applied to copper and gold ores was an A. ferrooxidans strain adapted to the respective ore type. For Variant 4, the oxidising bacterial solution was injected into the borehole under controlled temperature; for Variant 2, the bacterial application was conducted during the preceding warm season via surface irrigation. Solution temperatures in the non-heated variants (1–3) measured 5–6 °C at the inlet and 2–3 °C in the productive solution. Heating in Variant 4 maintained the ore mass temperature at 18–20 °C around the borehole for copper and gold, and at up to 30 °C for nickel.

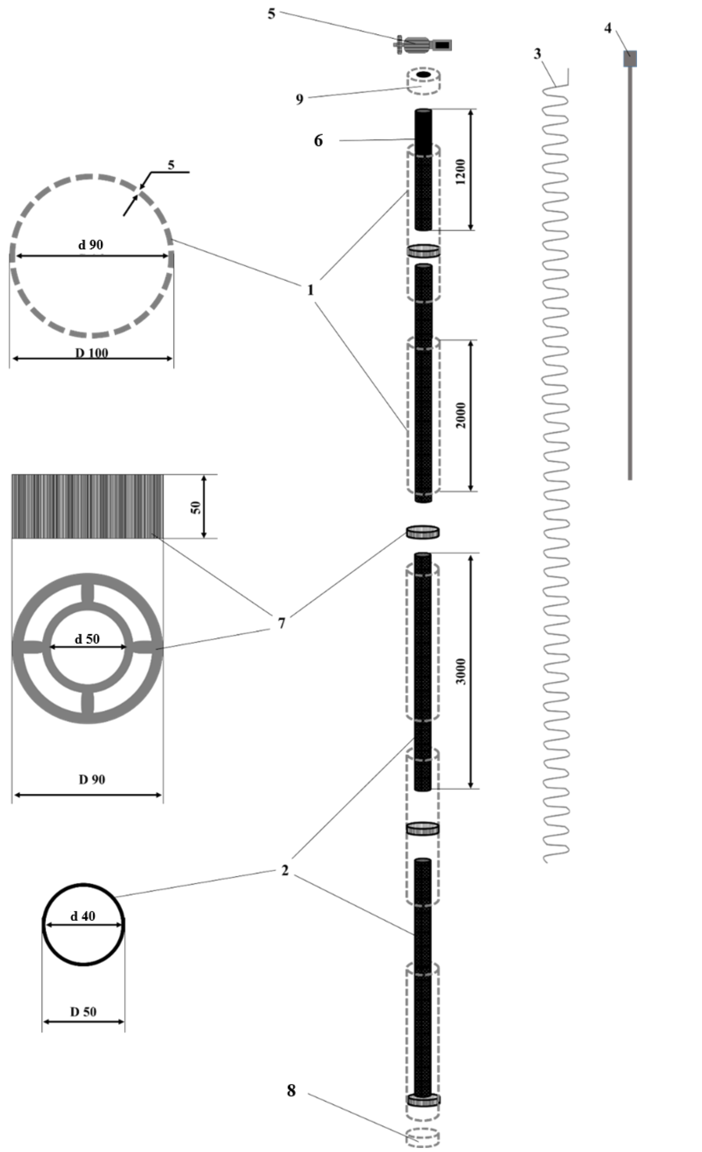

Fig. 1 Assembly schematic of perforated-tube segments for a 10 m borehole. 1 – outer perforated tube segments (D=100 mm); 2 – inner perforated tube segments (D=50 mm); 3 – heating cable wrapped around inner tube; 4 – temperature sensor; 5 – flow-control assembly; 6 – upper segment of inner tube; 7 – centralising coupling flanges; 8 – bottom plug of outer tube (non-perforated above heap surface); 9 – top plug of outer tube.

Analytical Methods

Metal extraction recovery (%) was calculated from the concentrations of copper, nickel, and gold in the collected productive solutions and the initial metal contents in the ore charge, at 10-day intervals throughout the 120-day trial period. Solution analyses were performed by standard analytical methods appropriate for each metal; full instrumental details were outside the scope of the present report.

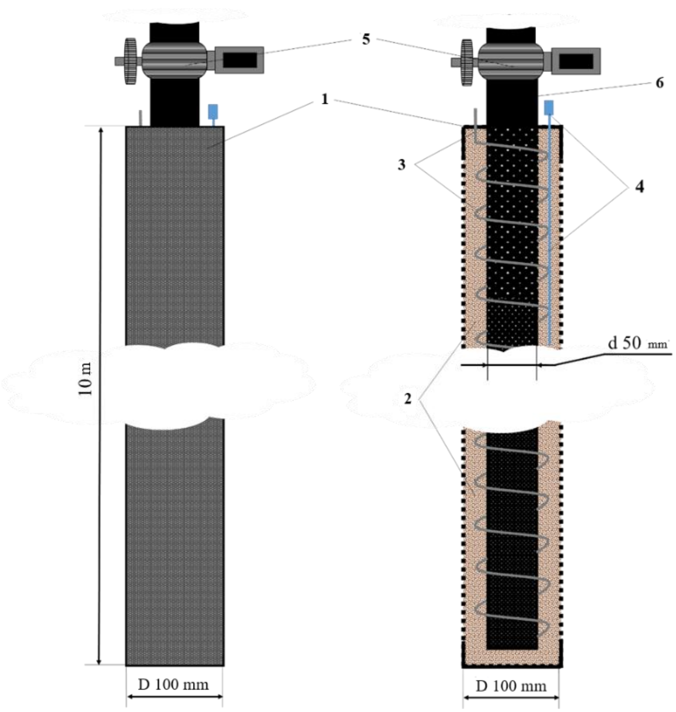

Fig. 2 Cross-sectional diagram of assembled perforated-tube unit installed in the heap borehole. 1 – outer perforated tube (D=100 mm); 2 – inner perforated tube segments (D=50 mm); 3 – heating cable wrapped around inner tube; 4 – temperature sensor; 5 – flow-control assembly; 6 – upper segment of inner tube;

RESULTS

Copper Extraction

Table 1 Cumulative copper extraction (%) for all four variants over the 120-day trial period.

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Duration, days	Baseline (H_2SO_4 only)	Analogue/Prototype (bio-oxidation + H_2SO_4)	Perforated tubes + H_2SO_4	Proposed method (tubes + thermo + bio + H_2SO_4)
10	2.13	4.30	3.43	8.99
20	5.27	11.51	7.54	15.09
30	8.12	20.12	9.86	19.54
40	11.12	26.60	13.54	32.50
50	17.41	32.21	18.38	40.81
60	21.28	38.10	23.21	54.74
70	26.89	42.65	28.53	61.80
80	32.30	47.20	34.82	72.53
90	39.56	50.97	43.52	81.24
100	44.10	53.58	45.65	85.88
110	46.23	55.90	48.36	86.07
120	46.81	57.83	49.61	86.46

The baseline variant (H_2SO_4 only) achieved a final copper extraction of 46.81 % after 120 days, consistent with the behaviour expected from standard sulphuric acid leaching of primary copper ore under sub-zero conditions, where reaction kinetics are markedly slow. The analogue/prototype variant (pre-season biooxidation + H_2SO_4) reached 57.83 %, confirming the benefit of prior sulphide oxidation. Perforated-tube delivery without bio-oxidation or heating (Variant 3) yielded 49.61 %, modestly above the baseline, attributable to improved solution distribution. The proposed method (Variant 4) achieved 81.24 % extraction by day 90, ultimately reaching 86.46 % by day 120.

Nickel Extraction

Table 2 presents cumulative nickel extraction (%) for all four variants over 120 days.
Nickel extraction under baseline conditions remained extremely low throughout the trial, reaching only 12.74 % after 120 days, confirming the poor performance of standard drip-irrigation heap leaching at sub-zero temperatures for nickel ores. Analogue/prototype biooxidation approximately doubled this to 25.67 %.

Table 2 Cumulative nickel extraction (%) for baseline, analogue/prototype, perforated-tube, and proposed method variants over 120 days
Perforated-tube delivery without thermal activation (Variant 3) reached 31.72 %. The proposed method achieved 35.07 % by day 90 and 54.03 % by day 120.

Duration, days	Baseline (H_2SO_4 only)	Analogue/Prototype (bio-oxidation + H_2SO_4)	Perforated tubes + H_2SO_4	Proposed method (tubes + thermo + bio + H_2SO_4)
10	0.45	0.91	1.72	2.03
20	1.34	4.05	3.10	6.01
30	2.09	7.01	7.63	9.14
40	4.89	10.40	11.18	13.66
50	8.21	12.46	13.51	17.13
60	9.03	14.85	15.88	21.31
70	10.17	16.83	18.49	26.12
80	11.32	18.73	20.49	30.67
90	12.09	20.86	23.84	35.07
100	12.61	22.46	25.30	41.49
110	12.72	24.81	30.19	47.31
120	12.74	25.67	31.72	54.03

Gold Extraction

Table 3 presents cumulative gold extraction (%) for all four variants over 120 days. Cyanidation was initiated after alkaline pre-wash (pH adjusted from 2.0 to 10.5) for variants involving prior biooxidation.

Simple cyanidation without activation factors (Variant 1) recovered 39.64 % of gold after 120 days. Biooxidation pre-treatment or perforated-tube delivery individually raised extraction to 73.57–74.82 %. The proposed method (Variant 4), combining borehole delivery, thermal maintenance at approximately 20 °C, and in-situ biooxidation, achieved gold extraction of 84.29 % over the same period.

Table 3 Cumulative gold extraction (%) for baseline, analogue/prototype, perforated-tube, and proposed method variants over 120 days

Duration, days	Baseline (CN⁻ only)	Analogue/Prototype (bio-oxidation + pH adjustment + CN⁻)	Perforated tubes + CN⁻	Proposed method (tubes + thermo + bio + pH 2.0→10.5 + CN⁻)
10	2.68	4.82	5.75	8.75
20	7.50	8.04	8.21	14.64
30	15.71	16.79	17.50	19.64
40	20.71	23.04	24.64	27.14
50	25.71	31.25	32.14	35.71
60	27.86	35.36	36.25	43.57
70	28.75	40.36	45.54	51.96
80	31.96	55.54	56.25	60.71
90	33.57	63.57	64.64	68.57
100	37.86	65.36	68.57	72.32
110	38.39	72.86	73.57	78.04
120	39.64	73.57	74.82	84.29

Heap-Borehole Layout

Figure 3 illustrates the layout of the proposed heap-borehole leaching system for a 1,000 m² treated surface area, showing the winter (drip irrigation) and summer (wobbler/sprinkler) configurations.

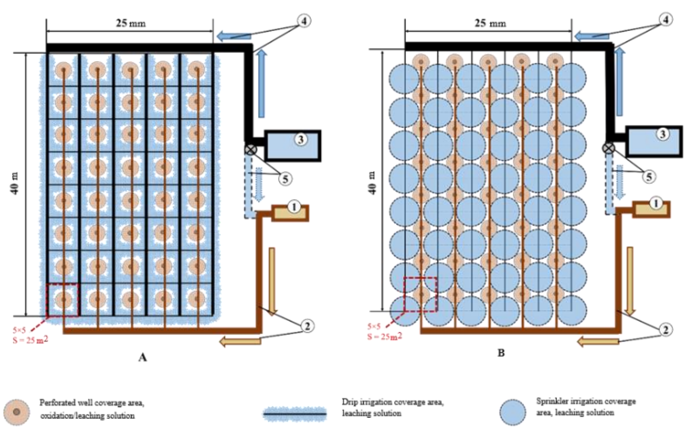

Fig. 3 Layout schematic of the heap-borehole bio-leaching system for a 1,000 m² heap surface. (A) Winter configuration with drip irrigation; (B) Summer configuration with wobbler sprinklers. 1 – bio-solution storage tank; 2 – pipelines supplying bio-oxidising solution to borehole systems; 3 – leach solution storage tank; 4 – pipelines supplying leach solution to surface irrigation; 5 – connection node linking leach solution pipeline to borehole system.

DISCUSSION

The experimental results clearly demonstrate that the combination of in-situ borehole solution delivery, thermal activation, and biological oxidation is substantially more effective for winter heap leaching than any single factor applied in isolation. This finding is consistent with fundamental process chemistry: bacterial oxidative dissolution of sulphide minerals is strongly temperature-dependent, and the heating cable system maintained conditions conducive to A. ferrooxidans activity (15–20 °C) throughout the trial, despite ambient temperatures falling to −20 °C.

For copper, the proposed method delivered a final extraction of 86.46 %, representing a gain of approximately 30–35 percentage points over the analogue/prototype and nearly double the baseline extraction. The kinetic advantage is equally significant: extraction exceeding 80 % was achieved by day 90, whereas the analogue/prototype required the full 120 days to reach 57.83 %. The accelerated kinetics are attributable to the dual effect of thermal activation enhancing bacterial metabolic rates, and the perforated-tube system improving reagent penetration into the ore mass interior — a well-known limitation of surface drip systems for deep heaps [5, 19]. The critical importance of biooxidation in liberating copper from sulphide matrices has been widely documented [3, 20], and the present results corroborate this for a sub-zero operational context.

Nickel extraction results are more modest in absolute terms (54.03 % at 120 days for the proposed method), which is consistent with the inherently more chemically resistant nature of laterite and sulphide nickel ores and the higher acid demand required for complete dissolution [11, 13]. The baseline extraction of 12.74 % under winter conditions confirms the near-impossibility of economically viable nickel heap leaching without process intensification in cold climates. The incremental improvements from each additional factor (biooxidation alone: +12.93 %; perforated tube alone: +18.98 %; full proposed method: +41.29 % over baseline) quantitatively demonstrate the additive nature of the three process enhancements. The elevated target temperature of 30 °C employed for the nickel variant is justified by the higher activation energy of nickel sulphide and laterite dissolution reactions relative to copper minerals. Acidophilic organisms tolerant of nickel laterite environments — including Burkholderia sp. [9] and Bacillus subtilis [10], as well as Aspergillus and Penicillium for organic acid leaching [16] — may offer further improvements over A. ferrooxidans for nickel-specific applications.

Gold recovery of 84.29 % by the proposed method is particularly noteworthy given that the ore grade was only 1.4 g·t⁻¹, a level at which conventional cyanidation alone (39.64 %) would typically be considered borderline economically viable for heap operations. The essential role of the biooxidation pre-step in liberating gold from sulphide hosts — reflected in the jump from 39.64 % (Variant 1) to 73.57 % (Variant 2) — is well established in the refractory gold literature [15]. Mineralogical characterisation of comparable Kazakhstani refractory gold-bearing ores has confirmed that gold at grades of 1.55–1.6 g·t⁻¹ is predominantly associated with pyrite and requires oxidative pretreatment to achieve acceptable cyanidation recoveries [21]. The additional improvement achieved by the proposed method (+10.7 percentage points over Variant 2 and Variant 3) is attributable to the improved distribution and thermal stability of the bacterial population within the ore mass, avoiding lethal ultraviolet irradiation in summer and freezing in winter.

From a thermal energy perspective, the heating cable system consumes approximately 150 W per borehole at 20 m effective length. In winter operation at −20 to −30 °C, monthly energy consumption per borehole is estimated at 55–60 kWh. For a 1,000 m² heap requiring 40 boreholes, total heating energy amounts to approximately 2,200–2,400 kWh·month⁻¹, equivalent to the continuous power demand of roughly 3 kW. This is a manageable operational cost that is economically offset by the substantially higher metal recovery: for low-grade copper ores (0.2–0.5 % Cu), the incremental revenue from the proposed method relative to the prototype covers the operating costs by a factor of approximately 1.4; for gold ores (1.0–2.0 g·t⁻¹ Au), by a factor of 1.5–1.6; and for oxidised nickel ores, by a factor of not less than 2.0 at prevailing metal prices.

The modular perforated-tube design additionally provides operational flexibility: tubes may be demounted after the oxidation phase and redeployed to adjacent heap sections, while the borehole pipeline infrastructure supports subsequent leach solution distribution — reducing capital investment in repeated applications. The use of amino acid-based or other biochemical additives in the leach solution may offer a further avenue for improving copper extraction from sub-standard ores in future iterations of the method [22]. Optimisation of process parameters, including borehole spacing and solution distribution, is supported by specialised hydrometallurgical modelling tools that enable automated calculation of metal extraction efficiency across the full process flowsheet [23]. The technology is also applicable, in principle, to in situ leaching of uranium and rare earth elements [19], though experimental validation of these applications remains to be studied.

A limitation of the present study is the bench-scale nature of the experiments: heat losses, hydraulic head distribution, and microbial community dynamics may differ at industrial heap scales. Quantitative mineralogical characterisation of the ore types was not reported, preventing attribution of specific extraction improvements to individual mineral phases. Future work should include column and pilot-scale trials, detailed ore mineralogy, and systematic optimisation of borehole spacing, heating cable power density, and bacterial inoculation protocols for each ore type.

CONCLUSION

A heap-borehole bio-leaching method with integrated thermal activation was developed and experimentally validated under sub-zero winter conditions during a 120-day trial. The key findings are as follows:

(1) The proposed method, combining subsurface solution delivery via a dual coaxial perforated-tube system, A. ferrooxidans-mediated biooxidation, and in-situ thermal maintenance at 15–20 °C (copper, gold) or up to 30 °C (nickel) via a heating cable, achieved copper extraction of 86.46 %, nickel extraction of 54.03 %, and gold extraction of 84.29 % over 120 days under winter conditions.

(2) These values represent improvements of approximately 30–35, 28, and 10 percentage points, respectively, over the analogue/prototype employing conventional surface biooxidation without thermal borehole activation, and are nearly double baseline acid-only or cyanide-only extraction values for copper and gold.

(3) Thermal activation via the heating cable system is confirmed as a critical enabling factor for year-round bio-heap leaching in continental climates, sustaining bacterial metabolic activity in the ore mass interior at ambient temperatures down to −30 °C.

(4) The operational economics of the proposed method are favourable: incremental revenue from improved metal recovery covers implementation costs by factors of 1.4, 1.5–1.6, and ≥2.0 for copper, gold, and nickel ores respectively.

Future research should address pilot-scale validation, ore mineralogical characterisation, and optimisation of system parameters (borehole spacing, cable power density, inoculum concentration) for specific ore types and climate zones.

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