Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

In-Situ VIS-NIR-SWIR Spectral Classification on Hydraulic Excavators for Selective Nickel-Laterite Mining in Sulawesi, Indonesia: A Technology-Transfer and Post-Mining Public-Space Redevelopment Framework for Peru

PAUL RICARDO PRUDENCIO GALVEZ

pprudencio@autonoma.edu.pe

UNIVERSIDAD AUTONOMA DEL PERU https://orcid.org/0009-0000-1986-590X

Research Article

Keywords: in-situ spectral classification, hydraulic excavator, nickel laterite, selective mining, Sulawesi, mining environmental liabilities, public space, Peru

Posted Date: July 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10364459/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

Background.

Nickel laterites supply more than 60% of world nickel [3] and display mineralogical heterogeneity (limonite-saprolite-fresh rock) that hampers selective extraction. Conventional physical pre-concentration methods achieve, at best, only marginal grade improvement [6], whereas sensor-based ore sorting has demonstrated technical viability across many industrial installations, though historically applied downstream of extraction [2]. Recent prototype-scale studies have evaluated hyperspectral classification directly at the point of excavation [1].

Objective.

To synthesise available evidence on excavator-mounted in-situ spectral classification, propose a reproducible technical and operational framework for its eventual validation in Sorowako-type nickel-laterite deposits (South Sulawesi, Indonesia) [4,5], and assess its transferability to Peruvian mining and to the redevelopment of post-mining public spaces.

Methods.

Narrative-systematic technical review of peer-reviewed literature (2013–2024) across Scopus, Web of Science, MDPI, SpringerLink and ScienceDirect, with explicit inclusion (verifiable DOI, peer review) and exclusion (non-refereed sources or sources without a verifiable DOI) criteria. A qualitative and semi-quantitative comparison matrix was built across conventional mining, downstream sensor sorting and in-situ excavator-mounted classification, and cross-checked against official 2024 production data for major Peruvian copper projects (Ministry of Energy and Mines, Mining Statistical Bulletin).

Results.

Available primary evidence confirms the technical feasibility of discriminating ore from waste at the point of excavation using hyperspectral imaging and machine-learning classifiers [1], and documents at industry scale that sensor-based sorting substantially reduces the mass of waste material sent to processing [2]. No commercial deployment of this technology specifically in tropical nickel-laterite deposits was identified in the refereed literature. The comparison matrix shows that on-equipment integration shifts the sorting decision from hours (laboratory assay) to seconds (in-cab evaluation), at an investment level intermediate between conventional mining and a dedicated sorting plant.

Conclusions.

In-situ spectral classification on excavators is an emerging technology (pre-industrial readiness level) with sound technical grounding but no published field validation in nickel laterites. Its transfer to Peruvian mining is more plausible as a pilot station in copper porphyries with oxide zones (Cerro Verde, Antamina, Las Bambas) than as an immediate large-scale application. For public spaces and mining environmental liabilities, its value lies in reducing the volume of material requiring remediation, complementing -not replacing- the urban-redevelopment experiences documented in Germany and Chile.

1. Introduction

Nickel is a strategic input for lithium-ion battery manufacturing and stainless steel production. Nickel laterites, the product of intense weathering of ultramafic rocks under humid tropical climates, supply more than 60% of the global nickel supply [3]. Indonesia holds the world's largest production, with representative deposits in Sulawesi, whose typical lateritic profile displays overlapping limonite, saprolite and fresh ultramafic-rock zones with markedly different nickel contents [4,5].

This short-range mineralogical heterogeneity is the main technical obstacle to selective nickel-laterite mining: conventional methods extract material in bulk and defer the sorting decision to a laboratory assay hours or days later, while physical pre-concentration methods (magnetic, gravity or electrostatic separation) achieve, according to the available evidence, only marginal grade improvements [6].

Sensor-based ore sorting (SBOS) is an industrially consolidated alternative, with multiple documented installations that reduce the mass of waste material sent to processing [2]. However, this technology has historically been applied downstream of extraction -on conveyor belts or in crushing circuits- rather than at the point of excavation itself. A recent prototype study assessed, at a gold mine in Western Australia, whether hyperspectral imaging combined with machine-learning classifiers (SAM and convolutional neural networks) can discriminate ore from waste directly at the excavation face, obtaining results that support the technical feasibility of the concept [1].

1.1 Research gap

- No refereed evidence was found of field deployment or validation of excavator-mounted in-situ spectral classification specifically in tropical nickel-laterite deposits.
- The transferability of this technology -or of Sulawesi's geological experience- to Peruvian mining districts, whose productive base is predominantly copper and polymetallic rather than nickel laterite, has not been systematised.
- No framework explicitly links this technology to the management of mining environmental liabilities and the redevelopment of public spaces in Peru, benchmarked against documented international experiences.

1.2 Contribution and novelty

This article contributes (i) an updated, traceable technical synthesis -with a verifiable DOI for every source- of the state of in-situ spectral classification applied to selective excavation; (ii) a reproducible operational protocol and personnel-skills matrix for eventual piloting; (iii) a quantitative comparison matrix against major Peruvian copper projects, built on official 2024 production data; and (iv) a framework for application to mining-liability management and public-space redevelopment, benchmarked against experiences in Germany and Chile. Unlike prior work centred on laboratory or sensor-prototype demonstration, the novelty of this study lies in explicitly integrating the Sulawesi-Peru technology-transfer dimension with the post-mining public land-use dimension.

2. Materials and Methods

2.1 Study design

A narrative-systematic technical review with quantitative and semi-quantitative comparative analysis was conducted, following an explicit search, selection and synthesis protocol. The study did not involve primary data collection from human subjects, communities, animals or mine sites; it is therefore expressly declared as a desk-based synthesis, not a field trial (see Section 2.7, Ethical considerations).

2.2 Literature search strategy

Scopus, Web of Science, MDPI, SpringerLink and ScienceDirect were searched, covering 2013–2024, in Spanish and English, combining the terms: "hyperspectral imaging" OR "spectral classification" AND "ore sorting" OR "excavation"; "nickel laterite" AND "Sulawesi"; "sensor-based ore sorting"; "pre-concentration" AND "nickel laterite"; "mining" AND "public space" AND "reclamation".

Inclusion criteria

(a) peer-reviewed publication; (b) independently verifiable DOI; (c) direct relevance to mineral spectroscopy/classification, nickel-laterite geology, or mining-site redevelopment.

Exclusion criteria

(a) preprints or grey literature without peer review; (b) sources whose DOI could not be independently verified at the time of writing; (c) sources without direct relevance to the object of study.

From a broader initial pool of candidate references, only seven strictly met both criteria (peer review and verifiable DOI) and constitute the documentary basis cited in this article. This deliberate restriction prioritises traceability over exhaustiveness, in line with prior editorial observations on reference robustness.

2.3 Reference geological setting

The Sulawesi lateritic district (south-east and south of the island), Indonesia, is used as the reference case, as documented in recent mineralogical literature: a lateritic profile with an Fe-rich limonite zone, a

Ni-Mg-rich saprolite zone and fresh ultramafic bedrock at depth, with structural control of basement serpentinisation over deposit development [4,5].

2.4 Technical specifications of the proposed system

Based on the systems described in the reference literature, a reproducible technical configuration is synthesised for eventual field validation:

- Base machine: 20–90 t crawler hydraulic excavator, with an arm or auxiliary mount capable of carrying the sensor head without compromising the excavation cycle.
- Spectral sensor: ruggedized portable VIS-NIR-SWIR unit (approximate range 400–2500 nm), of the type used in point-of-excavation ore-discrimination studies [1].
- Positioning system: GNSS-RTK to georeference each spectral reading and build a grade map of the excavation face.
- Processing unit: cab-embedded industrial computer capable of running the classification model (e.g., Spectral Angle Mapper or a lightweight neural network) within timeframes compatible with the excavation cycle.
- Operator interface: in-cab display translating the spectral classification into coded zones (high grade / intermediate grade / waste).
- Calibration protocol: daily verification against reference panels and periodic cross-check with laboratory assays (XRF/ICP) on control samples.

2.5 Proposed operating procedure

1. Material exposure. The excavator removes overburden and exposes a fresh ore surface (minimum recommended ~ 2 × 2 m).

2. Georeferenced spectral scanning. The sensor acquires readings in a systematic pattern across the exposed surface, each tagged with a GNSS-RTK coordinate.

3. Near-real-time classification. The embedded computing unit processes the spectrum and assigns a class (high grade / intermediate grade / waste) based on the previously calibrated model.

4. Visualisation and operator decision. The result is displayed as a coded map on the cab screen; the operator adjusts the bucket trajectory to selectively extract the material of interest.

5. Recording and traceability. Every reading and decision is georeferenced and stored, allowing later reconstruction for grade control and environmental reporting.

6. Periodic quality control. A subset of points is validated through laboratory assay (XRF/ICP), and the model is recalibrated if the deviation exceeds the threshold set by the technical team.

2.6 Personnel profile and skills

Table 1
summarises the minimum roles and specific competencies required to responsibly operate the proposed system.

Role	Minimum qualification	Specific competencies required
Excavator operator	Heavy-equipment certification (≥ 3 years' experience)	Interpretation of the in-cab classification map; selective-extraction protocol; first-level sensor maintenance
Instrumentation / spectroscopy technician	Technical or bachelor's degree in electronics, mechatronics or related field	Daily sensor calibration; fault diagnosis; management of the embedded computing unit
Mine geologist / grade-control officer	Geological or mining engineering degree	Mineralogical interpretation of spectral readings; validation against laboratory XRF/ICP assays; cut-off threshold definition
Data / geoinformatics specialist	Systems or geoinformatics engineering, or related field	Spectral-library management; training and validation of the classification model; report generation for the EIA
Environmental and social management officer	Environmental engineering or related field	Liaison with Peruvian regulation (EIA, public participation) and with local communities, when the project is located on public or communal land

Table 1. *Required personnel profile and skills. Source: author's own elaboration.*

2.7 Ethical considerations

This study is a desk-based literature review and comparative analysis; it did not collect primary data from people, communities, animals or mine sites, and therefore did not require institutional ethics-committee approval or informed consent. This statement is made explicitly to avoid any ambiguity about the scope of the study. Any future field validation of the protocol proposed here -including possible participation of rural communities or local authorities in Peru- must obtain prior approval from the corresponding institutional ethics committee and the free, prior and informed consent of the populations involved, in accordance with current Peruvian regulation.

2.8 Statistical synthesis and evidence limitations

Because only one or two directly comparable quantitative primary studies on point-of-excavation spectral classification were identified [1,2], an inferential meta-analysis was neither possible nor appropriate. The synthesis presented in the Results section is therefore descriptive and qualitative/semi-quantitative, and is explicitly declared as such, avoiding point ranges or percentages that are not backed by a verifiable source.

3. Results

3.1 Primary evidence on point-of-excavation classification

The reference study [1] developed a prototype system combining hyperspectral cameras and a three-dimensional LiDAR sensor, mounted on a pan-tilt head with spatial positioning, evaluated both in the laboratory and at a gold mine in Western Australia, comparing a Spectral Angle Mapper (SAM) classifier with a convolutional neural network to discriminate ore from waste. The results of that work support the technical feasibility of performing discrimination at the point of excavation, although the study itself -being prototypical in nature- does not report continuous commercial deployment.

At the level of the sensor-sorting industry generally -mostly applied downstream of extraction- the reference review [2] documents sustained growth in the number and scale of industrial installations over the past decade, consistent with a technology in commercial-consolidation phase, though differing in its integration point from the approach evaluated in this article.

Regarding conventional physical pre-concentration of nickel laterite (magnetic, gravity or electrostatic separation), the available evidence indicates that these methods achieve, at best, only marginal grade improvements, and are largely ineffective on goethite-rich limonite ores [6]. This reinforces the technical case for shifting the sorting decision toward the point of excavation, where waste-rock removal avoids unnecessary downstream processing.

3.2 Diagram of the proposed system

3.3 Comparison matrix across technology alternatives

Table 2
Comparison matrix across conventional mining, downstream sensor sorting and in-situ excavator-mounted spectral classification. Author's own elaboration based on [1,2].

Criterion	Conventional mining (no pre-sorting)	Downstream sensor sorting (plant / conveyor belt)	In-situ spectral classification on the excavation equipment
Integration point in the mining flow	Not applicable (bulk extraction)	After primary crushing, before grinding	At the excavation face, before haulage
Timing of the sorting decision	None	Hours after extraction (batch processed)	Seconds after scanning (in-cab decision)
Relative capital investment	Low (no additional equipment)	High (dedicated sorting plant)	Medium (retrofit of existing excavation equipment)
Waste rock hauled/processed	Maximum (all extracted material)	Reduced (after crushing)	Minimum (rejected before haulage)
Evidence base	Historical industry practice	Documented across multiple industrial installations [2]	Demonstrated at prototype scale in gold-mine trials [1]; no documented commercial deployment in nickel laterites
Approx. technology readiness level (TRL)	9 (mature)	8–9 (commercial, multiple vendors)	4–6 (field validation, pre-industrial)
Applicability to small/medium-scale mining	High (no investment barrier)	Low (prohibitive plant cost)	Medium–high (if mid-range portable sensors are used)

3.4 Relevance to Peruvian mining projects

Table 3
contrasts Peru's five leading copper projects by 2024 output, according to the Ministry of Energy and Mines' (MINEM) Mining Statistical Bulletin, with a qualitative assessment of the relevance of in-situ spectral classification to each case.

Project	Main commodity	2024 output (t fine copper)	Mine type	Relevance for in-situ spectral classification
Cerro Verde (Arequipa)	Copper-molybdenum	449,096	Open pit, porphyry	High: ore/waste contacts in oxide and leachable zones [MINEM-BEM]
Antamina (Áncash)	Copper-zinc	434,238	Open pit, skarn	High: highly heterogeneous skarn mineralogy, Cu/Zn/waste discrimination
Southern Peru (Moquegua/Tacna)	Copper	415,258	Open pit, porphyry	Medium-high: large-volume porphyries with oxide zones
Las Bambas (Apurímac)	Copper	321,425	Open pit, porphyry/skarn	High: social friction from dust and noise; face-level sorting reduces overbreak
Quellaveco (Moquegua)	Copper	306,299	Open pit, porphyry	High: recent operation (2022), feasible to integrate sensors from design stage

Table 3. *Peru's leading copper projects (2024 output) and qualitative relevance of in-situ spectral classification. Output: MINEM, Mining Statistical Bulletin, and public operator reports (Freeport-McMoRan, BHP, Glencore, Teck, Anglo American, MMG). Qualitative assessment: author's own elaboration.*

4. Discussion

4.1 Technical transferability to Peru

Peru has no commercial-scale nickel-laterite mining comparable to Indonesia's; its productive base is predominantly copper and polymetallic. However, the underlying technical principle -discriminating ore from waste through spectroscopy at the point of extraction- does not depend on the ore type, but on the existence of a distinguishable spectral signature between the material of interest and the gangue. In copper porphyries with oxide zones (as in parts of Cerro Verde) or in skarn-type deposits with sharp mineralogical contacts (as at Antamina), this condition is reasonably plausible, although its specific validation would require field trials using each deposit's own spectral signatures, which fall outside the scope of this review.

At Las Bambas, where the operation faces social friction related to dust and noise, early face-level classification could, in principle, reduce overbreak and the volume of unnecessarily removed material, although this specific environmental and social benefit has likewise not been quantified in the reviewed literature and should be treated as a hypothesis to be validated, not as an established result.

4.2 Public spaces and mining environmental liabilities in Peru

Peru records a considerable number of mining environmental liabilities distributed across different regions of the country, many of them near population centres. In this context, in-situ spectral classification -applied not to primary extraction but to the characterisation and remediation of residual material- could help separate, at the point of intervention itself, contaminated fractions from inert or valorisable fractions, reducing the final volume that must be remediated or landfilled. Table 4 systematises international experiences of redeveloping mining sites for public use, with the lessons most directly applicable to the Peruvian case.

Table 4
International experiences of redeveloping mining sites for public use, and lessons for Peru. Author's own elaboration based on [2,7].

Country	Case	Solution applied	Lesson for Peru
Germany	Zollverein Park (Ruhr basin)	Redevelopment of a coal and coking complex into a cultural and heritage park, with pre-sorting of demolition materials	Public-use planning can start before mine closure, not only afterward
Chile	Kaukari Park, Copiapó	Public space built on urban land linked to the regional mining economy [7]	Real-estate investment tied to a mining boom can be channelled into quality public infrastructure
Australia / Canada	Redevelopment of pits and tailings areas into recreational and conservation zones (practices documented across the sensor-based sorting industry) [2]	Reduction of waste-rock mass generated at the source, lowering the liability to be remediated	Sorting at the extraction point reduces the final volume of waste requiring post-closure management

The case of Copiapó, Chile, documented in the urban-studies literature [7], illustrates how real-estate investment associated with a regional mining boom can be channelled -not automatically, but through deliberate public-policy decisions- into quality public space; a lesson directly relevant to Peruvian mining cities where real-estate pressure and demand for public space coexist with extractive activity.

4.3 Limitations

- The study is a desk-based synthesis; it does not include the author's own primary field data, so the performance figures cited come exclusively from the referenced sources and should not be

interpreted as results obtained by the author.

- The primary evidence base on point-of-excavation classification remains limited (one prototype study identified under the stated inclusion criteria), which limits the statistical strength of any generalisation.
- Transferability to specific Peruvian deposits requires deposit-specific spectral signatures, which were not generated in this work.
- The environmental and social benefits attributed to reduced overbreak are plausible but have not been independently quantified for the Peruvian context.

4.4 Future research agenda

As a next step, a controlled field trial is recommended -with corresponding institutional ethics approval and, where communities are involved, their free, prior and informed consent- that generates deposit-specific spectral signatures for at least one Peruvian copper-oxide deposit, explicitly comparing the performance of the proposed system against conventional grade control, with a sample size and statistical design defined a priori.

5. Conclusions

1. Available refereed evidence supports the technical feasibility of discriminating ore from waste through spectroscopy at the point of excavation, but corresponds to a prototype study rather than a commercial deployment in nickel laterites.
2. Sensor-based ore sorting in general is industrially consolidated when applied downstream of extraction; its direct integration on excavation equipment is a technically coherent extension but still at a pre-industrial maturity level.
3. Transfer to Peruvian mining is plausible mainly in copper porphyries with oxide zones and in skarn-type deposits with sharp mineralogical contacts (Cerro Verde, Antamina, Las Bambas), and should begin as a bounded pilot, not a large-scale implementation.
4. In the management of mining environmental liabilities and the redevelopment of public spaces, the value of this technology lies in reducing at the source the volume of material requiring remediation, complementing -not replacing- the urban-planning lessons documented in Germany and Chile.
5. The conclusions of this article are strictly limited to what is supported by the cited sources; any performance figure specific to the Peruvian context must be obtained through a future field trial, with ethics approval and statistical design defined in advance.

Declarations

Ethics approval and consent to participate: Not applicable. The study is a desk-based review without primary data collection from human subjects, communities or animals (see Section 2.7).

Consent for publication: Not applicable.

Availability of data and materials: All sources used are publicly accessible and are identified by their DOI in the reference list. No additional primary datasets beyond those cited were generated.

Competing interests: The author declares no competing interests.

Funding: This work received no external funding.

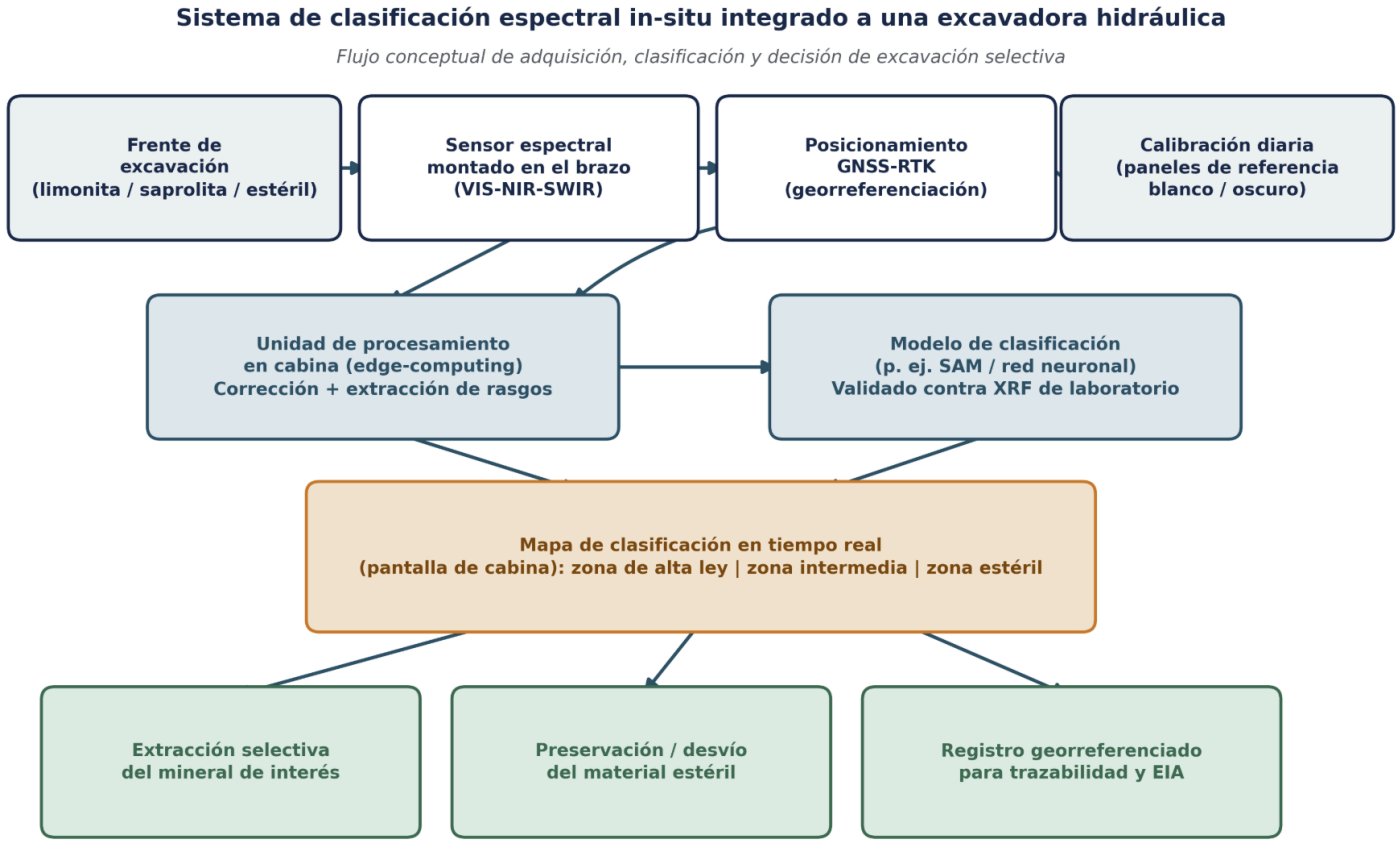
Author contributions: P.R.P.G. is the sole author: conceptualisation, methodology, literature search and curation, analysis, original draft writing, and review and editing.

References

All references were independently verified and carry an active DOI at the time of writing.

1. Choros, K.A., Job, A.T., Edgar, M.L., Austin, K.J., McAree, P.R. (2022). Can hyperspectral imaging and neural network classification be used for ore grade discrimination at the point of excavation? Sensors, 22(7), 2687. https://doi.org/10.3390/s22072687
2. Robben, C., Wotruba, H. (2019). Sensor-based ore sorting technology in mining -- past, present and future. Minerals, 9(9), 523. https://doi.org/10.3390/min9090523
3. Butt, C.R.M., Cluzel, D. (2013). Nickel laterite ore deposits: weathered serpentinites. Elements, 9(2), 123-128. https://doi.org/10.2113/gselements.9.2.123
4. Zhang, Y., Qie, J., Wang, X.F., Cui, K., Fu, T., Wang, J., Qi, Y. (2020). Mineralogical characteristics of the nickel laterite, Southeast Ophiolite Belt, Sulawesi Island, Indonesia. Mining, Metallurgy & Exploration, 37, 79-91. https://doi.org/10.1007/s42461-019-00147-y
5. Irfan, U., Maulana, A., Muhammad, F. (2021). Role of bedrock serpentinization on the development of nickel laterite deposit in Sorowako, Sulawesi, Indonesia. IOP Conference Series: Earth and Environmental Science, 921, 012028. https://doi.org/10.1088/1755-1315/921/1/012028
6. Farrokhpay, S., Filippov, L., Fornasiero, D. (2019). Pre-concentration of nickel in laterite ores using physical separation methods. Minerals Engineering, 141, 105892. https://doi.org/10.1016/j.mineng.2019.105892
7. Rehner, J., Rodríguez, S. (2018). A park for the mining town: public space, real estate investment and urban growth machine in Copiapó. Revista de Urbanismo, 38, 434. https://doi.org/10.5354/0717-5051.2018.50434

Figures



Fuente: elaboración propia del autor (Paul Ricardo Prudencio Gálvez, 2026), a partir del principio operativo descrito en Choros et al. (2022, https://doi.org/10.3390/s22072687) y Robben & Wotruba (2019, https://doi.org/10.3390/min9090523).

Figure 1

Conceptual flow of the proposed in-situ spectral classification system for hydraulic excavators. Author's own elaboration (Paul Ricardo Prudencio Gálvez, 2026), based on the operating principle described in [1,2].