
- Course code: MNE 304
- Course title: Mineral Processing Technology
- Course credit load: 3

# Series 1: Foundations of Ores and Minerals

**Series outline**

- **1.1 Ores, Minerals, and Rocks**
  - 1.1.1 Definition and classification of ores
  - 1.1.2 Mineral types and rock-forming processes
  - 1.1.3 Economic significance of ores and minerals

- **1.2 Structures and Textures of Minerals**
    - 1.2.1 Crystallographic structures
    - 1.2.2 Textural features and genesis
    - 1.2.3 Implications for mineral treatment
- **1.3 Ore Analysis Techniques**
    - 1.3.1 Qualitative assaying methods
    - 1.3.2 Quantitative chemical analysis
    - 1.3.3 Mineralogical analysis techniques
- **1.4 Significance in Mineral Processing**
    - 1.4.1 Relationship between mineral properties and processing methods
    - 1.4.2 Case examples of mineral genesis influencing treatment
    - 1.4.3 Practical applications in laboratory and industry

**Introduction**

Minerals are the foundation of the materials we use every day, from the metals in our mobile phones to the cement in our buildings. Before these resources can be processed and transformed into useful products, it is essential to understand their natural occurrence, structures, and properties. This Series sets the stage for the entire course by introducing you to the basic concepts of ores, minerals, and rocks, and by showing how their characteristics influence the methods used in mineral processing.

The aim of this Series is to equip you with the knowledge and skills needed to define, classify, and analyse ores and minerals, and to explain how their structures and textures determine their treatment in mineral processing.

We shall commence this Series by exploring the definitions and classifications of ores, minerals, and rocks, and their economic significance. Next, we will examine the structures and textures of minerals, considering their crystallographic and textural features and their implications for mineral genesis and treatment. Following that, we will study ore analysis techniques, including qualitative and quantitative assaying and mineralogical analysis. Finally, we will wrap up by discussing the significance of these foundations in mineral processing, linking mineral properties to practical applications in laboratory and industry.

**Series Learning Outcomes**

Upon completing this Series, you should be able to:

- **SLO 1.1** define ores, minerals, and rocks, and classify them according to their properties and economic significance,
- **SLO 1.2** explain the crystallographic structures and textural features of minerals and analyse their role in mineral genesis and treatment,
- **SLO 1.3** demonstrate qualitative and quantitative ore analysis techniques, including chemical and mineralogical methods,
- **SLO 1.4** evaluate the significance of mineral properties in determining appropriate processing methods and practical applications.

## 1.1 Ores, Minerals, and Rocks

### 1.1.1 Definition and classification of ores

An **ore** is a naturally occurring material that contains valuable minerals which can be extracted profitably. The classification of ores is based on factors such as mineral content, grade, and economic viability. For example, iron ore is classified according to its iron content, while bauxite is classified by its aluminium oxide concentration.

Fill in the blank: An ore is a naturally occurring material that contains ______ minerals which can be extracted profitably.

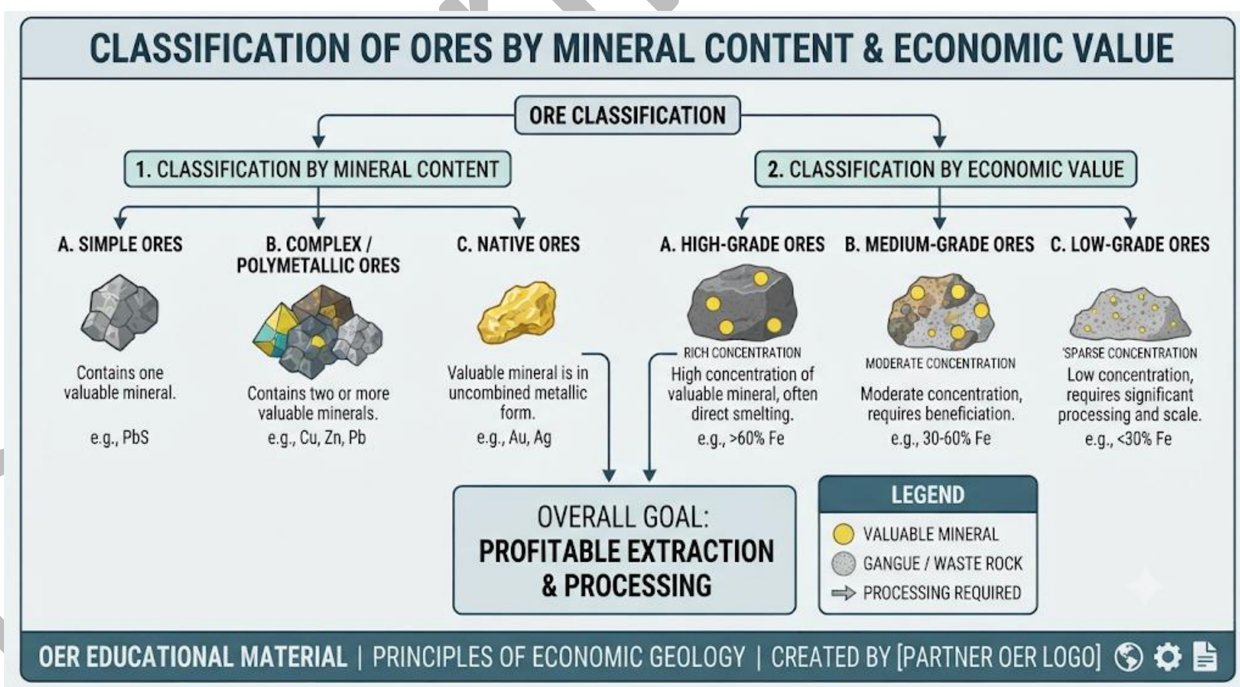
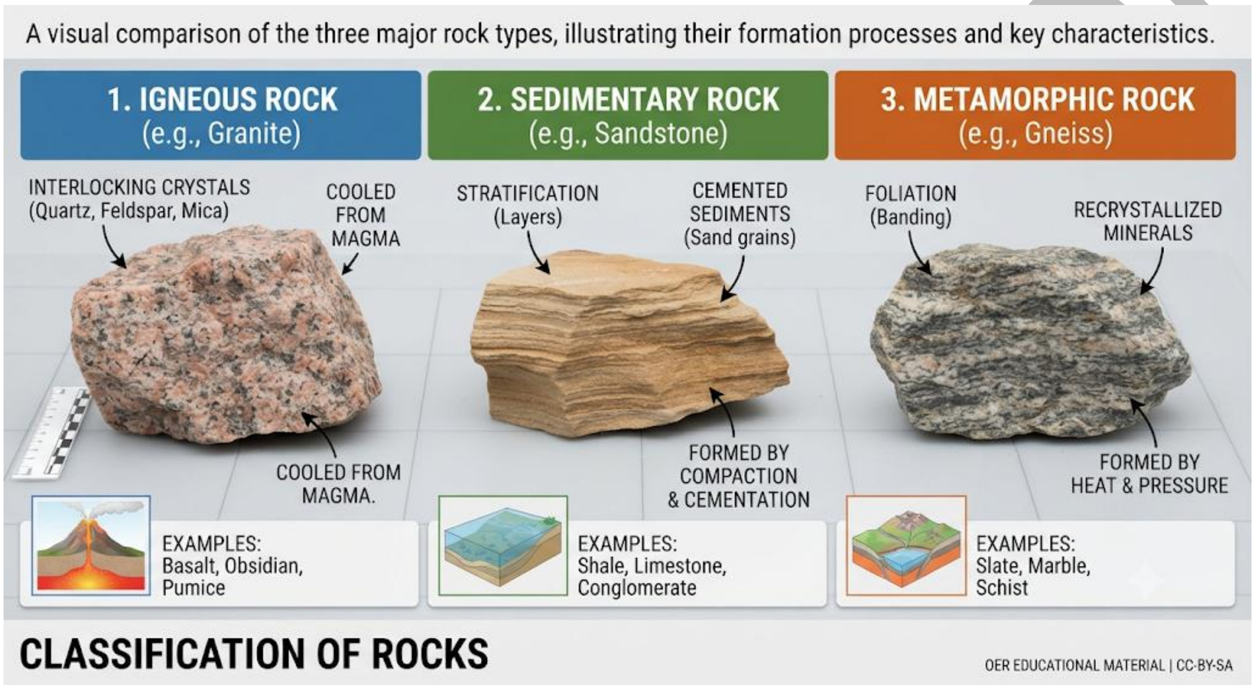



Diagram showing different types of ores and their classifications *Figure 1.1: Classification of ores*

### 1.1.2 Mineral types and rock-forming processes

A **mineral** is a naturally occurring inorganic substance with a definite chemical composition and crystalline structure. Minerals combine to form **rocks**, which are broadly classified into igneous, sedimentary, and metamorphic types. Igneous rocks form from cooled magma, sedimentary rocks form from compacted sediments, and metamorphic rocks form when existing rocks are altered by heat and pressure.

Fill in the blank: Rocks are broadly classified into ______, sedimentary, and metamorphic types.



Photographs of igneous, sedimentary, and metamorphic rocks *Plate 1.1: Examples of rock types*

### 1.1.3 Economic significance of ores and minerals

The **economic significance** of ores and minerals lies in their role as raw materials for industries. For instance, copper ores are vital for electrical wiring, while limestone is essential in cement production. The profitability of mining depends on factors such as ore grade, extraction costs, and market demand.

Fill in the blank: The profitability of mining depends on ore grade, extraction costs, and ______ demand.

**ECONOMIC SIGNIFICANCE OF MINERALS: A GLOBAL PERSPECTIVE**

| | MINERAL ORE / GROUP | PRIMARY MINERALS | INDUSTRIAL USES | KEY INDUSTRIES |
|---|---|---|---|---|
| METALLIC MET.1 MINERALS | IRON ORE | Hematite ($Fe_2O_3$), Magnetite ($Fe_3O_4$) | Steel production, automotive bodies, construction beams, machinery. | Construction, Automotive, Manufacturing, Infrastructure |
| | COPPER | Chalcopyrite ($CuFeS_2$), Native Copper (Cu) | Electrical wiring, plumbing pipes, motors, electronics, renewable energy components | Electronics, Construction, Power Generation, Telecommunications |
| | ALUMINUM | Bauxite (Aluminium Ore) | Aircraft construction, beverage cans, window frames, electrical transmission | Aerospace, Packaging, Construction, Transportation |
| | PRECIOUS METALS | Gold (Au), Silver (Ag), Platinum (Pt) | Jewelry, currency reserves, electronics contacts, catalytic converters, dentistry. | Finance, Jewelry, Electronics, Automotive, Healthcare |
| INDUSTRIAL MINERALS | CONSTRUCTION MATERIALS | Limestone ($CaCO_3$), Gypsum ($CaSO_4 \cdot 2H_2O$) | Cement manufacturing, concrete aggregate, drywall/plaster, road base. | Construction, Infrastructure, Building Materials |
| | FERTILIZER MINERALS | Potash (Potassium minerals), Phosphate Rock (Apatite) | Agricultural fertilizers (N-P-K), animal feed supplements, industrial chemicals. | Agriculture, Chemical Manufacturing |
| | CERAMICS & GLASS | Silica Sand ($SiO_2$), Feldspar, Kaolin Clay | Glass containers, flat glass, ceramic tiles, sanitary ware, fiberglass. | Glass Manufacturing, Ceramics, Construction |
| ENERGY MINERALS | COAL | Anthracite, Bituminous, Lignite | Electricity generation, steel production (coking coal), industrial heating. | Power Generation, Metallurgy, Manufacturing |
| | URANIUM | Uraninite ($UO_2$) | Nuclear power generation, medical isotopes, research reactors. | Energy, Healthcare, Research |



OER EDUCATIONAL MATERIAL | ECONOMIC GEOLOGY MODULE | CREATED BY [PARTNER OER LOGO]

Box 1.1: Selected examples of economically significant minerals

**Pilot questions 1.1**

1. Define ore and explain how it is classified.
2. Distinguish between minerals and rocks.
3. Identify the three main types of rocks and describe how each is formed.
4. State two examples of economically significant minerals and their uses.
5. Explain one factor that influences the profitability of mining.

## 1.2 Structures and Textures of Minerals

### 1.2.1 Crystallographic structures

A **crystallographic structure** refers to the orderly arrangement of atoms within a mineral. This arrangement determines the mineral's physical properties such as hardness, cleavage, and optical behaviour. For example, diamond and graphite are both composed of carbon, yet their different atomic arrangements result in vastly different properties.

Fill in the blank: Diamond and graphite are both composed of ______, yet their atomic arrangements make them very different.

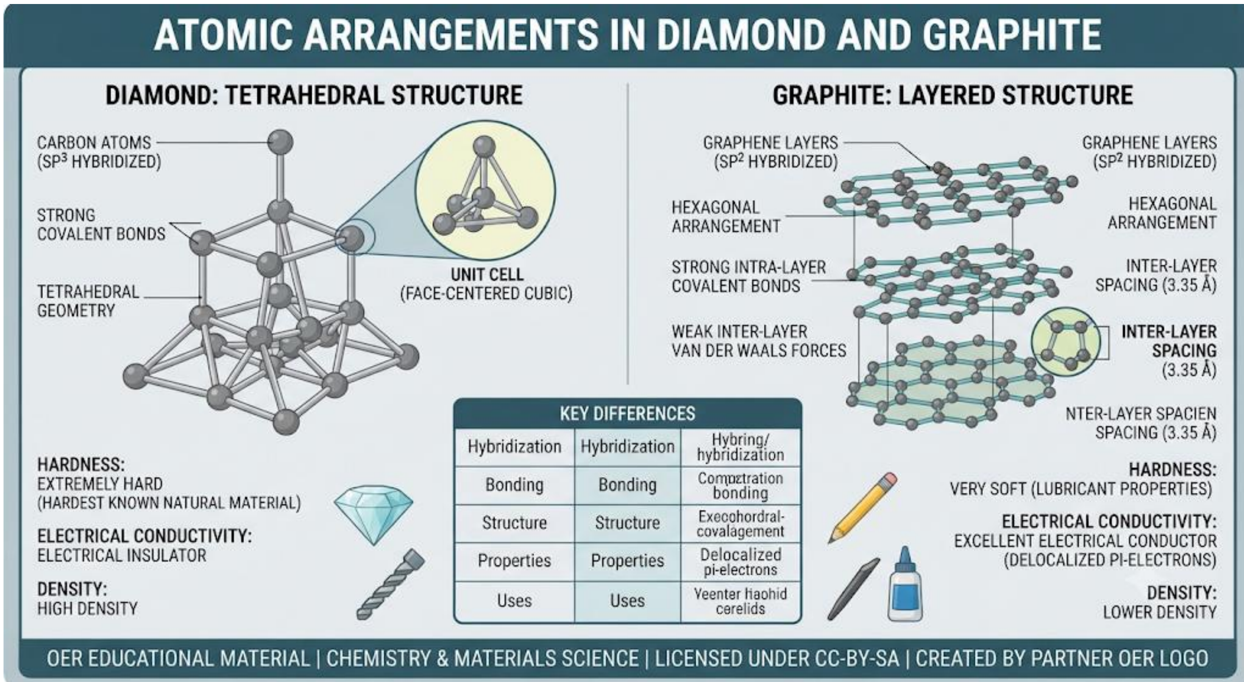
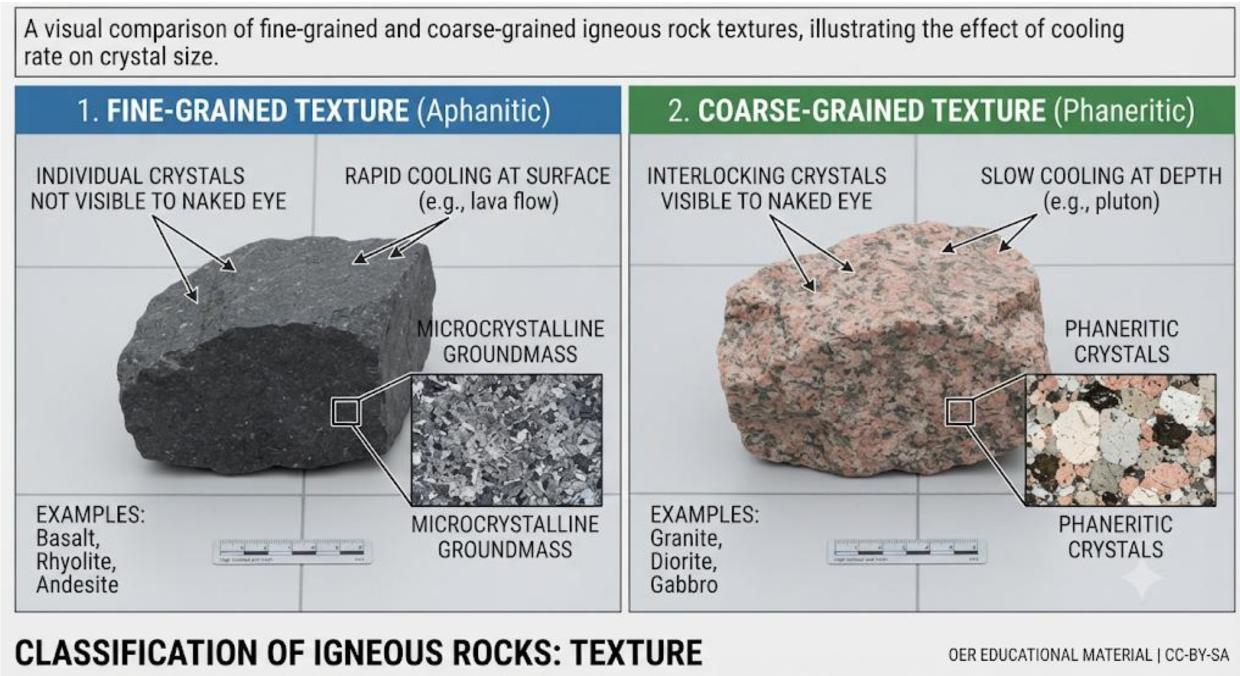



Diagram comparing atomic structures of diamond and graphite *Figure 1.2: Crystallographic structures of diamond and graphite*

### 1.2.2 Textural features and genesis

**Texture** in minerals refers to the size, shape, and arrangement of mineral grains within a rock. Textural features provide clues about the **genesis**, or origin, of the mineral deposit. For instance, fine-grained textures often indicate rapid cooling of magma, while coarse-grained textures suggest slower cooling. Textures also influence how easily minerals can be liberated during processing.

Fill in the blank: Fine-grained textures often indicate ______ cooling of magma.

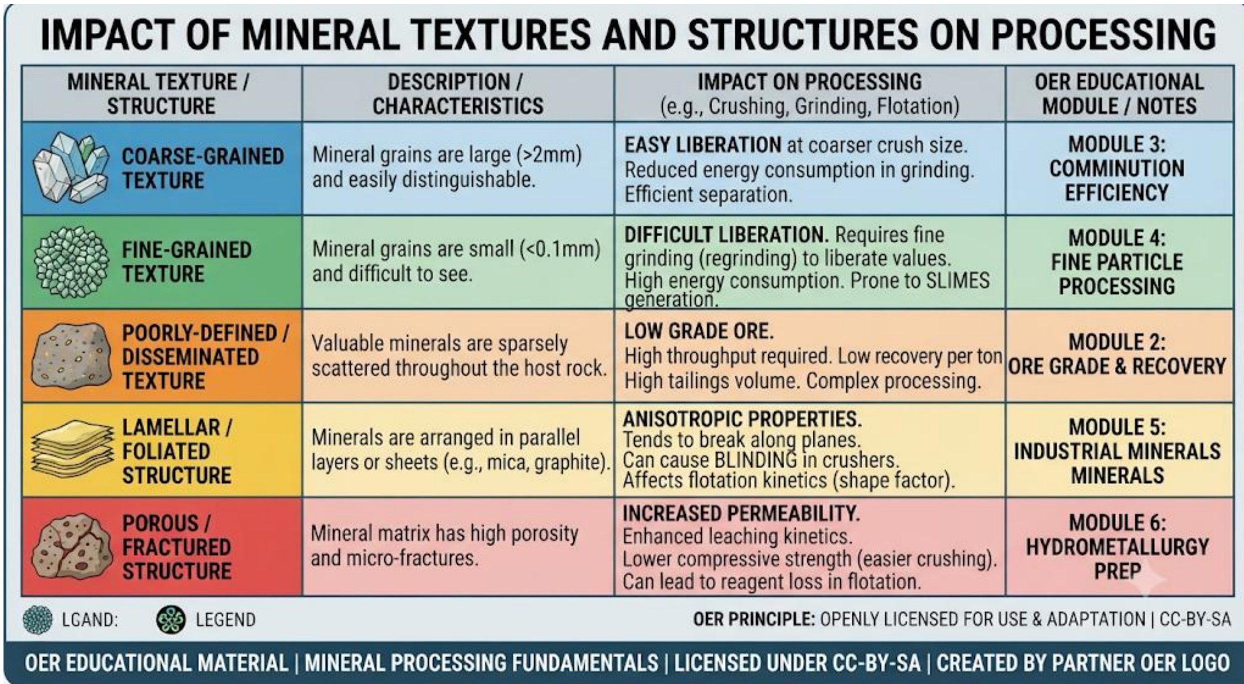


Photographs of fine-grained and coarse-grained rock textures *Plate 1.2: Examples of mineral textures*

### 1.2.3 Implications for mineral treatment

The **implications** of mineral structures and textures for treatment are significant. Minerals with complex structures may require more intensive comminution, while certain textures can enhance or hinder separation processes. For example, minerals with interlocking grains are harder to liberate, whereas those with distinct boundaries are easier to separate. Understanding these features allows engineers to design more efficient processing flowsheets.

Fill in the blank: Minerals with interlocking grains are harder to ______ during processing.



**IMPACT OF MINERAL TEXTURES AND STRUCTURES ON PROCESSING**

| MINERAL TEXTURE / STRUCTURE | DESCRIPTION / CHARACTERISTICS | IMPACT ON PROCESSING (e.g., Crushing, Grinding, Flotation) | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|
| COARSE-GRAINED TEXTURE | Mineral grains are large (>2mm) and easily distinguishable. | **EASY LIBERATION** at coarser crush size. Reduced energy consumption in grinding. Efficient separation. | MODULE 3: COMMINUTION EFFICIENCY |
| FINE-GRAINED TEXTURE | Mineral grains are small (<0.1mm) and difficult to see. | **DIFFICULT LIBERATION.** Requires fine grinding (regrinding) to liberate values. High energy consumption. Prone to SLIMES generation. | MODULE 4: FINE PARTICLE PROCESSING |
| POORLY-DEFINED / DISSEMINATED TEXTURE | Valuable minerals are sparsely scattered throughout the host rock. | **LOW GRADE ORE.** High throughput required. Low recovery per ton High tailings volume. Complex processing. | MODULE 2: ORE GRADE & RECOVERY |
| LAMELLAR / FOLIATED STRUCTURE | Minerals are arranged in parallel layers or sheets (e.g., mica, graphite). | **ANISOTROPIC PROPERTIES.** Tends to break along planes. Can cause BLINDING in crushers. Affects flotation kinetics (shape factor). | MODULE 5: INDUSTRIAL MINERALS MINERALS |
| POROUS / FRACTURED STRUCTURE | Mineral matrix has high porosity and micro-fractures. | **INCREASED PERMEABILITY.** Enhanced leaching kinetics. Lower compressive strength (easier crushing). Can lead to reagent loss in flotation. | MODULE 6: HYDROMETALLURGY PREP |

LGAND: LEGEND

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Box 1.2: Influence of mineral structures and textures on processing methods

**Pilot questions 1.2**

1. Define crystallographic structure and explain its importance in mineral properties.
2. Distinguish between fine-grained and coarse-grained textures.
3. Explain how textural features provide clues about mineral genesis.
4. Describe one implication of mineral texture for processing.
5. Give an example of how atomic arrangement affects mineral properties.

## 1.3 Ore Analysis Techniques

### 1.3.1 Qualitative assaying methods

**Qualitative assaying** refers to the identification of the types of minerals present in an ore without measuring their exact quantities. This involves techniques such as visual inspection, flame tests, and simple chemical reactions that reveal the presence of specific elements. For example, a flame test can show sodium by its bright yellow colour. These methods are often used as preliminary steps before more detailed quantitative analysis.

Fill in the blank: A flame test can reveal the presence of ______ by its bright yellow colour.

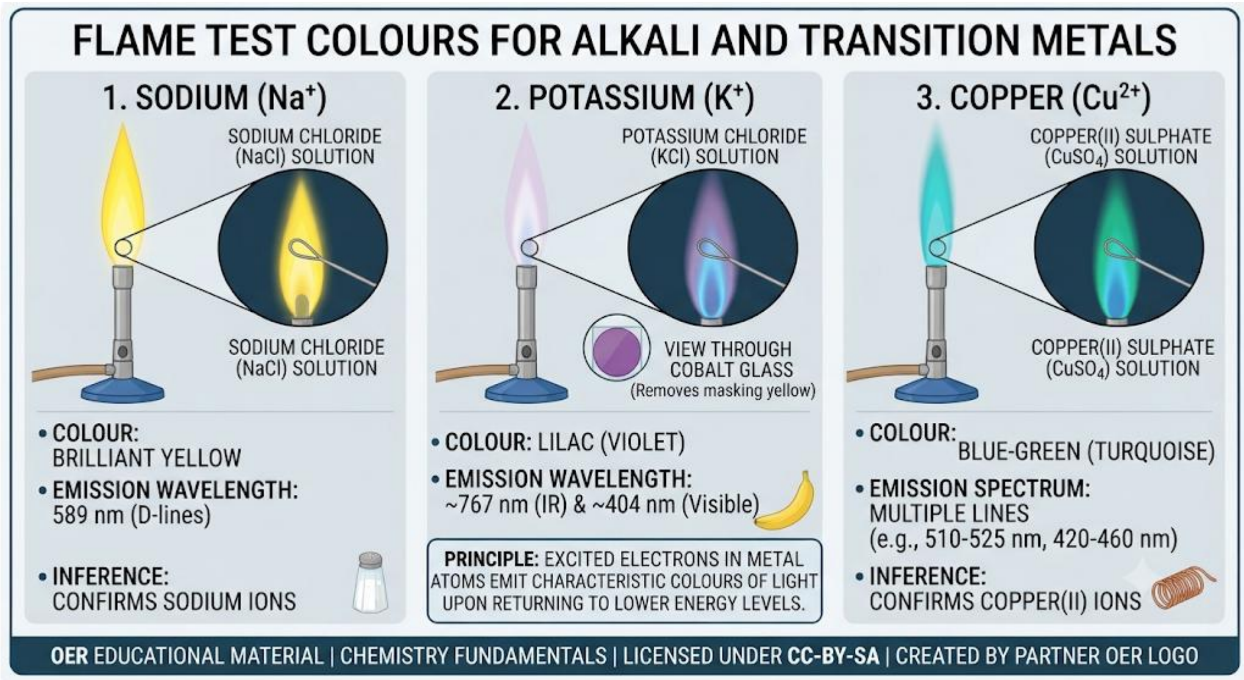


Diagram showing flame test colours for different elements *Figure 1.3: Flame test colours for selected elements*

#### 1.3.2 Quantitative chemical analysis

**Quantitative chemical analysis** measures the exact amount of a particular element or compound in an ore. Techniques include gravimetric analysis, titration, and instrumental methods such as atomic absorption spectroscopy. These methods provide precise data on ore grade, which is critical for determining economic viability. For instance, the aluminium oxide content in bauxite must be quantified before deciding on its suitability for processing.

Fill in the blank: Quantitative chemical analysis provides precise data on ore ______, which is critical for economic viability.

**COMPARISON OF QUANTITATIVE CHEMICAL ANALYSIS METHODS: PRINCIPLES & APPLICATIONS**

| ANALYTICAL METHOD | PRINCIPLE & INSTRUMENTATION (Illustrative) | COMMON USES & APPLICATIONS | KEY ADVANTAGES / LIMITATIONS | |
|---|---|---|---|---|
| 1. GRAVIMETRIC ANALYSIS (Precipitates) | MEASUREMENT OF MASS Analyte is selectively precipitated from solution, filtered, dried, and weighed. (e.g., $Ag^+ + Cl^- \rightarrow AgCl(s)$ precipitated) | • DETERMINATION OF CHLORIDE IN WATER • SULFATE IN SOIL • NICKEL IN ALLOYS Ideal for high-accuracy determination of major components. | HIGH ACCURACY & PRECI (if done correctly). No calibration standards needed (absolute method). Requires a standard reference. | TIME-CONSUMING & LABOR-INTENSIVE. Requires pure, filterable precipitate. Not suitable for trace analysis. Precipitalı. |
| 2. TITRATION (Volumetric Analysis) | MEASUREMENT OF VOLUME A titrant of known concentration reacts stoichiometrically with the analyte until an endpoint is reached (visual indicator or electrode). (e.g., Acid-Base, Redox, Complexometric). | • DETERMINATION OF ACETIC ACID IN VINEGAR • VITAMIN C (ASCORBIC ACID) IN JUICE • WATER HARDNESS ($Ca^{2+}/Mg^{2+}$) | RAPID & CONVENIENT. VERSATILE FOR VARIOUS ANALYTES. Lower capital cost. | REQUIRES A KNOWN STOICHIOMETRY. Subject to visual endpoint errors. Less sensitive for trace levels. |
| 3. ATOMIC ABSORPTION SPECTROSCOPY (AAS) (Hollow cathode lamp, Nebulizer, Monochromator, Detector) | MEASUREMENT OF LIGHT ABSORPTION Gaseous atoms of the analyte absorb characteristic wavelengths of light from a specific hollow cathode lamp in a flame or furnace. (e.g., Trace metal analysis). | • TRACE METALS IN DRINKING WATER (e.g., Pb, Cd, As) • CALCIUM IN BLOOD SERUM • COPPER IN ORE SAMPLES | HIGHLY SENSITIVE FOR TRACE METALS (ppm to ppb). SELECTIVE for specific elements. RAPID MULTI-ELEMENT ANALYSIS (sequential). | HIGH CAPITAL COST (Instrument). Requires dissolved samples. Interferences can occur (chemical, spectral). |

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Table 1.1: Common quantitative analysis methods and their applications

### 1.3.3 Mineralogical analysis techniques

**Mineralogical analysis** involves studying the mineral composition and structure of ores using specialised tools such as petrographic microscopes and X-ray diffraction. These techniques help identify mineral phases, textures, and associations, which are essential for designing effective processing methods. For example, identifying intergrowths of valuable and gangue minerals can guide the choice of separation technique.

Fill in the blank: Mineralogical analysis often uses a ______ microscope to study mineral composition and textures.

Photograph of a petrographic microscope in use *Plate 1.3: Petrographic microscope for mineralogical analysis*

**Pilot questions 1.3**

1. Define qualitative assaying and give one example of its application.
2. Explain the importance of quantitative chemical analysis in determining ore grade.
3. List two techniques used in quantitative chemical analysis.
4. Describe the role of mineralogical analysis in mineral processing.
5. Identify one instrument commonly used in mineralogical analysis.

## 1.4 Significance in Mineral Processing

### 1.4.1 Relationship between mineral properties and processing methods

The **relationship** between mineral properties and processing methods is central to mineral engineering. Properties such as hardness, density, magnetic susceptibility, and surface chemistry determine which separation techniques are most effective. For example, minerals with high density are suited to gravity separation, while those with magnetic properties can be processed using magnetic separators.

Fill in the blank: Minerals with high ______ are suited to gravity separation methods.

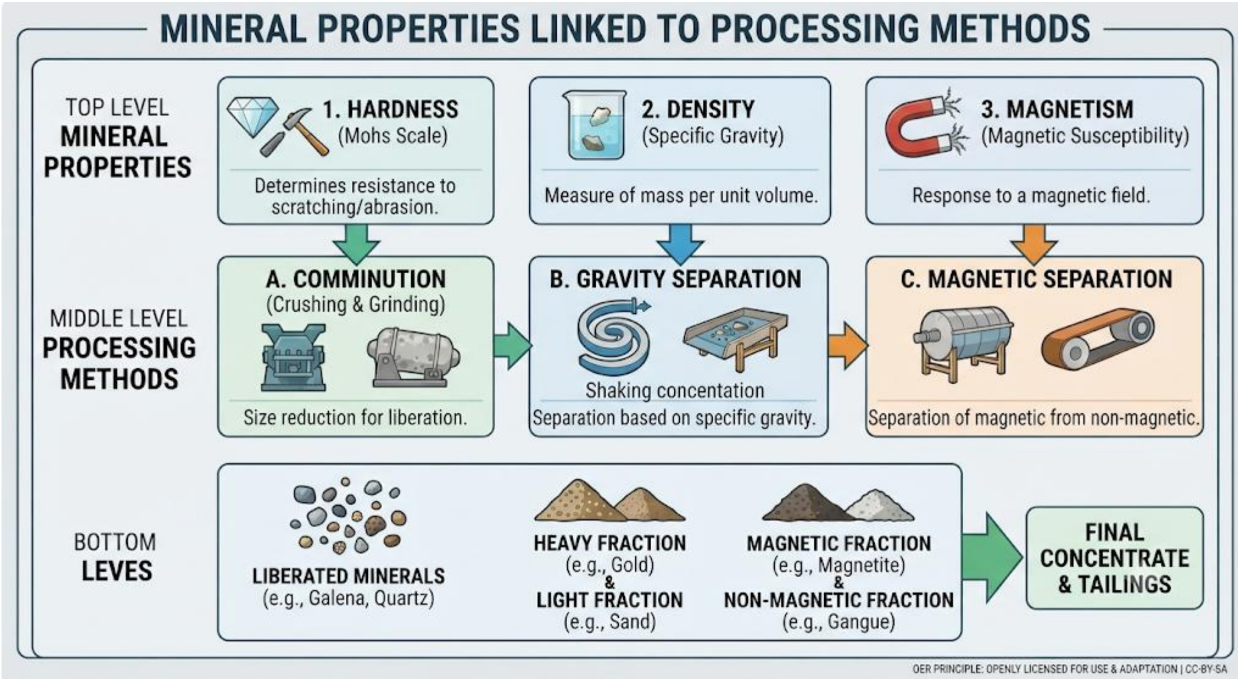
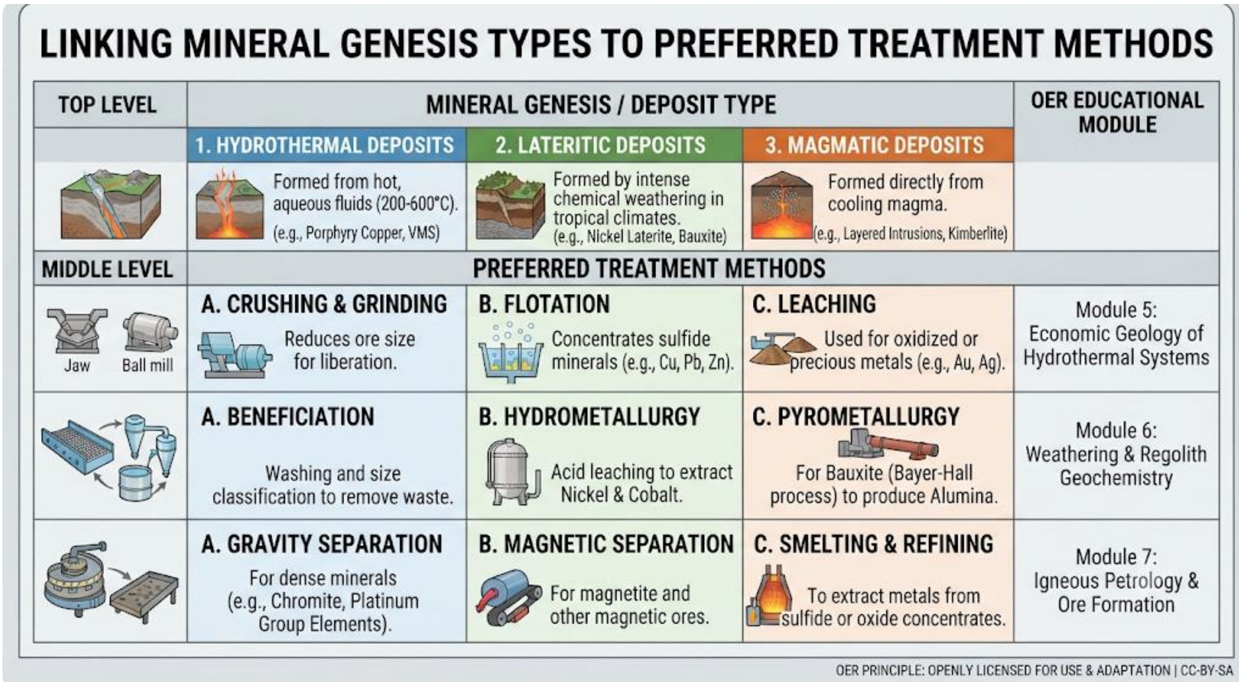


Diagram linking mineral properties to processing methods *Figure 1.4: Relationship between mineral properties and processing techniques*

### 1.4.2 Case examples of mineral genesis influencing treatment

**Mineral genesis** refers to the origin and formation of minerals. The genesis of a mineral deposit often influences its treatment. For instance, sulphide ores formed in hydrothermal environments may require flotation, while lateritic bauxite deposits are more suited to leaching. Recognising the genesis helps engineers anticipate challenges such as impurities or complex mineral associations.

Fill in the blank: Sulphide ores formed in hydrothermal environments are often treated using ______ methods.



LINKING MINERAL GENESIS TYPES TO PREFERRED TREATMENT METHODS

| TOP LEVEL | MINERAL GENESIS / DEPOSIT TYPE | | | OER EDUCATIONAL MODULE |
|---|---|---|---|---|
| | 1. HYDROTHERMAL DEPOSITS | 2. LATERITIC DEPOSITS | 3. MAGMATIC DEPOSITS | |
| | Formed from hot, aqueous fluids (200-600°C). (e.g., Porphyry Copper, VMS) | Formed by intense chemical weathering in tropical climates. (e.g., Nickel Laterite, Bauxite) | Formed directly from cooling magma. (e.g., Layered Intrusions, Kimberlite) | |
| MIDDLE LEVEL | PREFERRED TREATMENT METHODS | | | |
| Jaw, Ball mill | A. CRUSHING & GRINDING Reduces ore size for liberation. | B. FLOTATION Concentrates sulfide minerals (e.g., Cu, Pb, Zn). | C. LEACHING Used for oxidized or precious metals (e.g., Au, Ag). | Module 5: Economic Geology of Hydrothermal Systems |
| | A. BENEFICIATION Washing and size classification to remove waste. | B. HYDROMETALLURGY Acid leaching to extract Nickel & Cobalt. | C. PYROMETALLURGY For Bauxite (Bayer-Hall process) to produce Alumina. | Module 6: Weathering & Regolith Geochemistry |
| | A. GRAVITY SEPARATION For dense minerals (e.g., Chromite, Platinum Group Elements). | B. MAGNETIC SEPARATION For magnetite and other magnetic ores. | C. SMELTING & REFINING To extract metals from sulfide or oxide concentrates. | Module 7: Igneous Petrology & Ore Formation |

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Box 1.3: Examples of mineral genesis and corresponding treatment methods

### 1.4.3 Practical applications in laboratory and industry

The **practical applications** of mineral properties and genesis are evident in both laboratory experiments and industrial practice. In the laboratory, petrographic microscopes are used to identify mineral components, while bench-scale tests simulate separation processes. In industry, flowsheets are designed based on mineralogical data to maximise recovery and minimise losses. This integration of theory and practice ensures efficient and sustainable mineral processing.

Fill in the blank: In industry, flowsheets are designed based on ______ data to maximise recovery and minimise losses.

Photograph of a mineral processing laboratory setup *Plate 1.4: Laboratory applications in mineral processing*

**Pilot questions 1.4**

1. Explain how mineral properties influence the choice of processing methods.
2. Give one example of mineral genesis and its corresponding treatment method.
3. Describe the role of petrographic microscopes in laboratory practice.
4. State one way flowsheets are used in industry.
5. Why is understanding mineral genesis important for processing efficiency?

**Series Summary**

This Series has introduced you to the foundations of ores and minerals, which form the basis of mineral processing technology. We began by defining and classifying ores, minerals, and rocks, highlighting their economic significance. Then we examined the crystallographic structures and textural features of minerals, considering how these influence mineral genesis and treatment. Following that, we explored ore analysis techniques, including qualitative assaying, quantitative chemical analysis, and mineralogical methods. Finally, we discussed the significance of mineral properties and genesis in determining appropriate processing methods, linking theory to laboratory and industrial practice.

By completing this Series, you should now be able to define and classify ores, minerals, and rocks, explain their structures and textures, demonstrate ore analysis techniques, and evaluate the significance of mineral properties in mineral processing. These skills directly align with the Series Learning Outcomes and provide a strong foundation for the subsequent Series in this course.

**Glossary of Terms**

- **Crystallographic structure**: The orderly arrangement of atoms within a mineral that determines its physical properties.
- **Economic significance**: The importance of ores and minerals as raw materials for industries, influencing profitability and demand.
- **Genesis**: The origin and formation process of a mineral deposit, which affects its treatment in processing.
- **Mineral**: A naturally occurring inorganic substance with a definite chemical composition and crystalline structure.
- **Mineralogical analysis**: The study of mineral composition and structure using tools such as petrographic microscopes and X-ray diffraction.
- **Ore**: A naturally occurring material containing valuable minerals that can be extracted profitably.
- **Qualitative assaying**: Methods used to identify the types of minerals present in an ore without measuring their exact quantities.
- **Quantitative chemical analysis**: Techniques used to measure the exact amount of a particular element or compound in an ore.
- **Rock**: A naturally occurring solid composed of one or more minerals, classified as igneous, sedimentary, or metamorphic.
- **Texture**: The size, shape, and arrangement of mineral grains within a rock, providing clues about its genesis.

**Concept Check Questions [Series 1]**

**Objective questions**

1. Define ore. (Linked to SLO 1.1)
2. Which type of rock forms from cooled magma? (Linked to SLO 1.1)
3. What instrument is commonly used in mineralogical analysis? (Linked to SLO 1.3)

**Short-answer questions**

4. Explain how crystallographic structure influences mineral properties. (Linked to SLO 1.2)

5. State one difference between qualitative and quantitative ore analysis. (Linked to SLO 1.3)
6. Give one example of mineral genesis and its corresponding treatment method. (Linked to SLO 1.4)

**Long-answer questions**

7. Analyse how mineral textures influence liberation and separation processes in mineral processing. (Linked to SLO 1.2)
8. Evaluate the significance of mineral properties in designing industrial flowsheets. (Linked to SLO 1.4)

**Answers to Concept Check Questions [Series 1]**

**Objective questions**

1. An ore is a naturally occurring material containing valuable minerals that can be extracted profitably.
2. Igneous rock.
3. Petrographic microscope.

**Short-answer questions**

4. Crystallographic structure determines physical properties such as hardness, cleavage, and optical behaviour.
5. Qualitative analysis identifies mineral types, while quantitative analysis measures exact amounts.
6. Sulphide ores formed in hydrothermal environments are often treated using flotation.

**Long-answer questions**

7. **Basic response**: Fine-grained textures indicate rapid cooling and may hinder liberation, while coarse-grained textures facilitate separation. **Value-added response**: Outstanding learners may discuss how interlocking grains complicate comminution, requiring more energy, and how distinct boundaries improve efficiency in separation processes.
8. **Basic response**: Mineral properties such as density and magnetism guide the choice of separation methods in flowsheet design. **Value-added response**: Outstanding learners may evaluate how integrating mineralogical data with economic considerations ensures sustainable and cost-effective processing.

**Answers to Pilot Questions [Series 1]**

1. An ore is a naturally occurring material containing valuable minerals, classified by mineral content and economic value.

2. Minerals are inorganic substances with definite composition and structure, while rocks are aggregates of minerals.
3. Igneous, sedimentary, and metamorphic rocks.
4. Copper for electrical wiring, limestone for cement production.
5. Market demand.
6. Crystallographic structure is the atomic arrangement that influences mineral properties.
7. Fine-grained textures indicate rapid cooling, coarse-grained textures indicate slow cooling.
8. Textural features reveal genesis and influence liberation.
9. Interlocking grains hinder liberation.
10. Diamond and graphite differ due to atomic arrangement.
11. Qualitative assaying identifies mineral types, e.g., flame test.
12. Quantitative analysis determines ore grade.
13. Gravimetric analysis and titration.
14. Mineralogical analysis identifies mineral phases and textures.
15. Petrographic microscope.
16. Properties such as density and magnetism determine processing methods.
17. Hydrothermal sulphide ores treated by flotation.
18. Petrographic microscopes identify mineral components.
19. Flowsheets maximise recovery and minimise losses.
20. Genesis influences impurities and treatment efficiency.

**References and Attributions [Series 1]**

- Figure 1.1: Classification of ores. Suggested AI prompt: “Create a labelled diagram showing types of ores classified by mineral content and economic value.” Search string: “classification of ores diagram OER.”
- Plate 1.1: Examples of rock types. Suggested AI prompt: “Generate images of igneous, sedimentary, and metamorphic rocks side by side.” Search string: “igneous sedimentary metamorphic rock images OER.”
- Figure 1.2: Crystallographic structures of diamond and graphite. Suggested AI prompt: “Create a labelled diagram showing atomic arrangements in diamond and graphite.” Search string: “diamond graphite crystal structure diagram OER.”

- Plate 1.2: Examples of mineral textures. Suggested AI prompt: “Generate side-by-side images of fine-grained and coarse-grained rock textures.” Search string: “igneous rock textures fine coarse OER.”
- Box 1.2: Influence of mineral structures and textures on processing methods. Suggested AI prompt: “Create a table showing mineral structures/textures and their impact on processing.” Search string: “mineral textures processing impact table OER.”
- Figure 1.3: Flame test colours for selected elements. Suggested AI prompt: “Create a labelled diagram showing flame test colours for sodium, potassium, and copper.” Search string: “flame test colours diagram OER.”
- Table 1.1: Common quantitative analysis methods and their applications. Suggested AI prompt: “Create a table listing gravimetric analysis, titration, and atomic absorption spectroscopy with their uses.” Search string: “quantitative chemical analysis methods table OER.”
- Plate 1.3: Petrographic microscope for mineralogical analysis. Suggested AI prompt: “Generate an image of a petrographic microscope being used to study mineral samples.” Search string: “petrographic microscope mineral analysis OER.”
- Figure 1.4: Relationship between mineral properties and processing techniques. Suggested AI prompt: “Create a flow diagram showing mineral properties linked to processing methods.” Search string: “mineral properties processing methods diagram OER.”
- Box 1.3: Examples of mineral genesis and corresponding treatment methods. Suggested AI prompt: “Create a table showing mineral genesis types and their preferred treatment methods.” Search string: “mineral genesis treatment methods table OER.”
- Plate 1.4: Laboratory applications in mineral processing. Suggested AI prompt: “Generate an image of a mineral processing laboratory with microscopes and separation equipment.” Search string: “mineral processing laboratory equipment OER.”

# Series 2: Comminution and Particle Analysis

**Series outline**

- **2.1 Basic comminution theory**
  - 2.1.1 Principles of size reduction
  - 2.1.2 Energy requirements in comminution

- ## Introduction
- Mineral processing begins with breaking down large pieces of ore into smaller fragments so that valuable minerals can be liberated and separated. This process, known as **comminution**, is fundamental because it directly influences the efficiency of subsequent concentration and recovery methods. Alongside comminution, the accurate measurement and presentation of particle sizes is equally important, as it guides engineers in selecting appropriate equipment and designing effective flowsheets.
- The aim of this Series is to provide you with a clear understanding of comminution principles, equipment, and processes, as well as the techniques used for particle sizing and analysis. By mastering these concepts, you will be able to explain how ores are reduced, how particle sizes are measured, and how this information is applied in mineral processing.
- We shall commence this Series by examining the basic theories of comminution, focusing on size reduction, energy requirements, and particle liberation. Next, we will explore comminution equipment and processes, including crushing and grinding operations. Following that, we will study particle sizing by screening, considering its principles, applications, and limitations. We will then move on to particle sizing by classification, where hydraulic and mechanical classifiers, as well as cyclones, will be discussed. Finally, we will conclude with particle size analysis, looking at measurement methods, data presentation, and practical applications in mineral processing.

**Series Learning Outcomes**

Upon completing **Series 2: Comminution and Particle Analysis**, you should be able to:

- **SLO 2.1** explain the basic principles of comminution, including size reduction, energy requirements, and particle liberation,
- **SLO 2.2** describe the main types of comminution equipment and processes, and analyse factors affecting their efficiency,
- **SLO 2.3** demonstrate how particle sizing is carried out using screening methods, and evaluate their applications and limitations,
- **SLO 2.4** apply particle sizing techniques using classification methods, including hydraulic classifiers and cyclones,
- **SLO 2.5** present and interpret particle size data using appropriate analysis methods in mineral processing.

## 2.1 Basic Comminution Theory

### 2.1.1 Principles of size reduction

**Comminution** is the process of reducing the size of ore particles to liberate valuable minerals. The principle behind size reduction is to apply mechanical forces such as compression, impact, and attrition to break down large pieces of ore into smaller fragments. The choice of method depends on the hardness and structure of the ore. For example, brittle ores are more easily broken by impact, while tougher ores may require compression.

Fill in the blank: The process of reducing ore particle size to liberate valuable minerals is called ______.

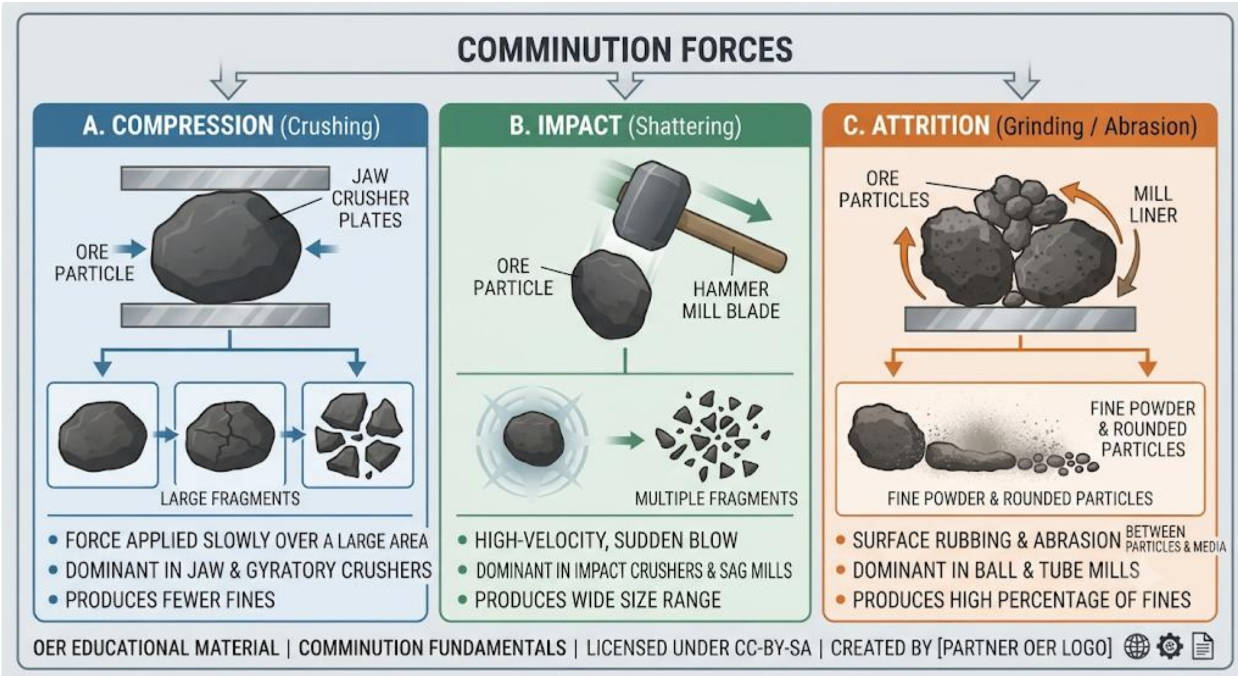

Diagram showing compression, impact, and attrition forces in comminution *Figure 2.1: Principles of size reduction in comminution*

### 2.1.2 Energy requirements in comminution

The **energy requirement** in comminution refers to the amount of energy needed to achieve a desired level of size reduction. Several theories, such as Kick's law, Rittinger's law, and Bond's law, attempt to quantify this relationship. Kick's law states that energy required is proportional to the size reduction ratio, while Rittinger's law relates energy to the new surface area created. Bond's law provides a practical estimate for industrial applications.

Fill in the blank: Rittinger's law relates energy requirement to the new ______ area created during comminution.

TOP LEVEL

**COMPARISON OF COMMINUTION ENERGY LAWS: KICK'S, RITTINGER'S, & BOND'S**

| ENERGY LAW | PROPOSED BY (Year) | KEY PRINCIPLE / HYPOTHESIS | MATHEMATICAL EXPRESSION | DOMAIN OF APPLICABILITY |
|---|---|---|---|---|
| 1. KICK'S LAW | Frederick Kick (1885) | ENERGY REQUIRED IS PROPORTIONAL TO THE REDUCTION RATIO. The energy per unit mass depends only on the ratio of initial size to final size, regardless of the actual sizes. (e.g., Energy = C * log(F/P)) | $E = K_k * \ln(R_r)$ or where $R_r = \frac{F}{P}$ | DOMINANT FOR COARSE CRUSHING (Large particles, >10mm) |
| 2. RITTINGER'S LAW | Peter von Rittinger (1867) | ENERGY REQUIRED IS PROPORTIONAL TO THE NEW SURFACE AREA CREATED. The work done in crushing is directly proportional to the increase in specific surface area. (e.g., Energy = C * (1/P - 1/F)) | $E = K_r * \left(\frac{1}{P} - \frac{1}{F}\right)$ | DOMINANT FOR FINE GRINDING (Small particles, <1mm) |
| 3. BOND'S LAW (Third Theory) | Fred C. Bond (1952) | ENERGY REQUIRED IS PROPORTIONAL TO THE LENGTH OF NEW CRACKS FORMED. A compromise between Kick's and Rittinger's, often called the "Work Index" method. It is the most widely used for mill design. (e.g., Energy = $W_i$ * $\left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right)$)) | $E = W_i \cdot \sqrt{\frac{100}{P}} \cdot \left(1 - \frac{1}{\sqrt{R_r}}\right)$ (simplified version) | DOMINANT FOR GENERAL CRUSHING & GRINDING (Intermediate to Fine particles, 10mm to 100µm) |

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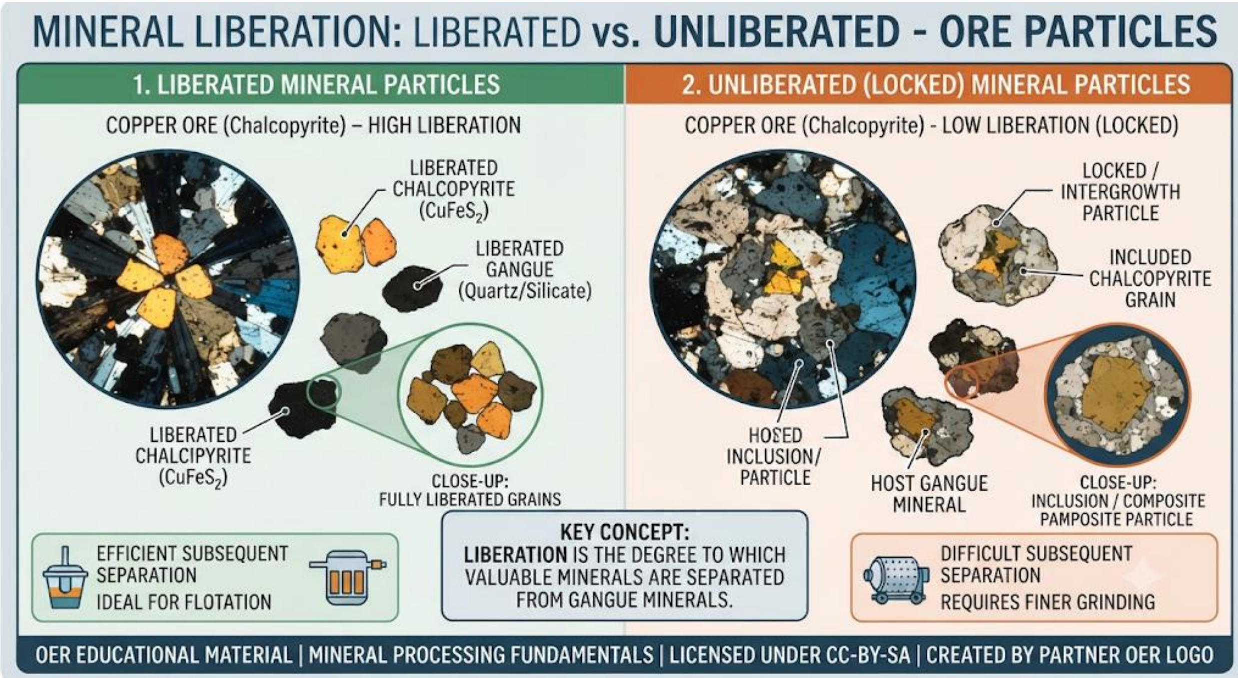
Table 2.1: Comparison of comminution energy laws

### 2.1.3 Liberation of mineral particles

**Liberation** refers to the process of freeing valuable minerals from the surrounding gangue material. Effective liberation is essential for successful separation in later stages of mineral processing. The degree of liberation depends on the texture of the ore and the extent of size reduction. For example, ores with interlocking grains may require finer grinding to achieve adequate liberation.

Fill in the blank: Effective liberation is essential for successful ______ in later stages of mineral processing.



Photograph of ore samples showing liberated and unliberated mineral particles *Plate 2.1: Examples of mineral liberation in ores*

**Pilot questions 2.1**

1. Define comminution and explain its purpose in mineral processing.
2. Distinguish between compression, impact, and attrition forces in comminution.
3. State the main principle of Kick's law.
4. Explain how Rittinger's law relates energy to surface area.
5. Why is mineral liberation important in processing?

**2.2 Comminution Equipment and Processes**

**2.2.1 Crushing equipment and operations**

**Crushing** is the first stage of comminution, where large ore fragments are reduced to smaller sizes using mechanical force. Common crushing equipment includes jaw crushers, gyratory crushers, and cone crushers. Jaw crushers use compression between two plates, gyratory crushers employ a gyrating spindle, and cone crushers provide finer reduction. The choice of equipment depends on ore hardness, feed size, and desired product size.

Fill in the blank: Jaw crushers reduce ore size by applying ______ between two plates.

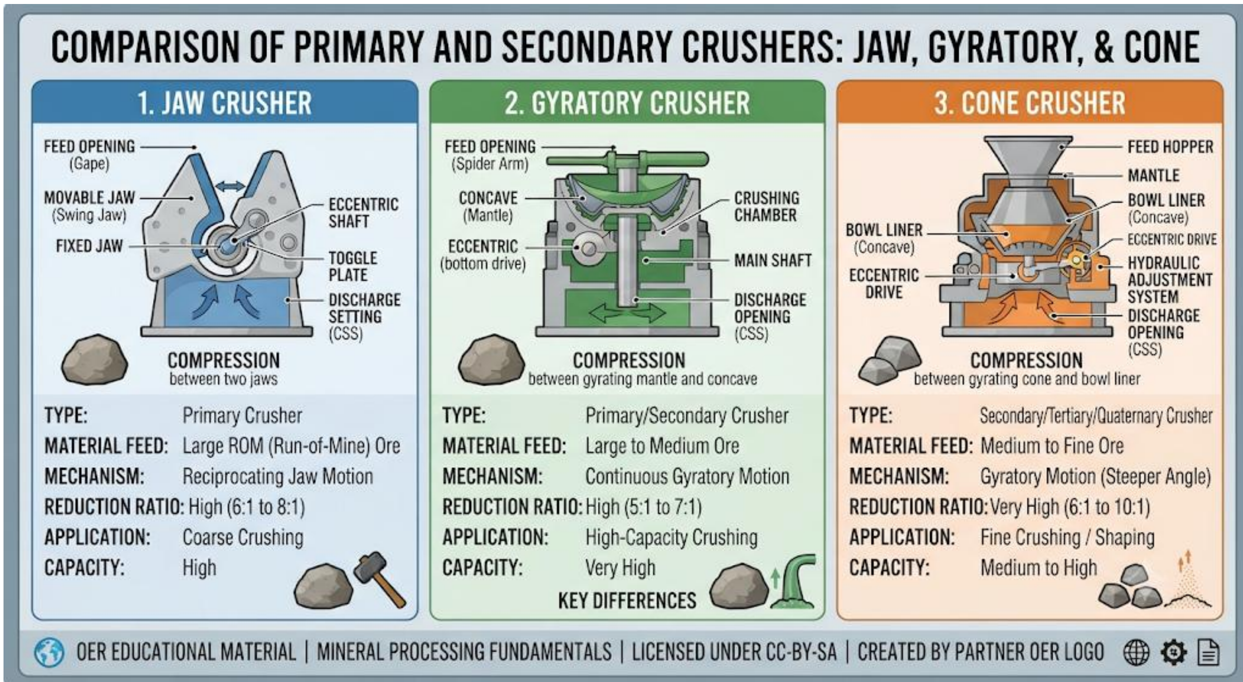


Diagram showing jaw, gyratory, and cone crushers *Figure 2.2: Types of crushing equipment*

### 2.2.2 Grinding mills and circuits

**Grinding** is the second stage of comminution, where crushed ore is further reduced to fine particles. Grinding mills include ball mills, rod mills, and semi-autogenous (SAG) mills. Ball mills use steel balls as grinding media, rod mills use steel rods, and SAG mills combine ore itself with grinding media. Grinding circuits may be open or closed, with classifiers used in closed circuits to control particle size.

Fill in the blank: Ball mills use steel ______ as grinding media to reduce ore size.

Photograph of a ball mill in operation *Plate 2.2: Ball mill used in mineral processing*

### 2.2.3 Factors affecting comminution efficiency

The **efficiency** of comminution depends on several factors, including ore hardness, moisture content, feed size, and equipment design. Harder ores require more energy, while excessive moisture can clog equipment. Proper feed size ensures effective reduction, and equipment design influences throughput and product quality. Engineers must balance these factors to achieve optimal performance and minimise energy consumption.

Fill in the blank: Excessive ______ content in ore can clog comminution equipment and reduce efficiency.

**FACTORS AFFECTING COMMINUTION EFFICIENCY: KEY ORE AND OPERATIONAL VARIABLES**

| TOP LEVEL | | | |
|---|---|---|---|
| COMMINUTION FACTOR | DESCRIPTION / CHARACTERISTICS | IMPACT ON EFFICIENCY (ENERGY & THROUGHPUT) | OER EDUCATIONAL MODULE / NOTES |
| 1. ORE HARDNESS (e.g., Bond Work Index, WI) | Resistance of the ore to breakage. Higher WI means harder ore. | **HIGH HARDNESS:** Decreases throughput, Increases specific energy consumption (kWh/t), Requires more grinding time / stages. | MODULE 2: ORE CHARACTERIZATION & BOND WORK INDEX |
| 2. MOISTURE CONTENT | Percentage of water in the feed ore. Can be dry, damp, or wet. | **OPTIMAL MOISTURE:** Varies by process (e.g., wet grinding is common). **EXCESSIVE MOISTURE:** Causes ball coating (sticking) in dry mills, reduces mill capacity, increases energy for drying. | MODULE 4: WET vs. DRY GRINDING |
| 3. FEED SIZE DISTRIBUTION | Size of ore particles entering the comminution circuit (F80). | **COARSE FEED:** Requires more energy in primary crushing/grinding, limits final product size. **FINE FEED:** Less energy needed, but can lead to over-grinding if not controlled. | MODULE 3: CRUSHING & GRINDING CIRCUITS |
| 4. EQUIPMENT DESIGN & OPERATING PARAMETERS | Specific machinery (e.g., mill type, size, liner design) and its operation (e.g., speed, ball load). | **OPTIMAL DESIGN:** Matches ore characteristics, maximizes throughput, minimizes energy loss. **POOR DESIGN:** Inefficient breakage, high wear rates, bottleneck in the circuit. | MODULE 5: MILL OPTIMIZATION & SCALE-UP |



Box 2.1: Key factors influencing comminution efficiency

**Pilot questions 2.2**

1. Name three types of crushing equipment and explain how each works.
2. Distinguish between ball mills, rod mills, and SAG mills.
3. What is the difference between open and closed grinding circuits?
4. State one factor that affects comminution efficiency.
5. Why is equipment design important in comminution?

## 2.3 Particle Sizing by Screening

### 2.3.1 Principles of screening

**Screening** is the process of separating particles according to size using a screen surface with openings of defined dimensions. Larger particles are retained on the screen, while smaller ones pass through. Screening is essential in mineral processing because it ensures that particles are appropriately sized for subsequent operations such as grinding or separation. The efficiency of screening depends on factors such as particle shape, moisture content, and screen design.

Fill in the blank: Screening separates particles according to ______ using a screen surface with openings of defined dimensions.

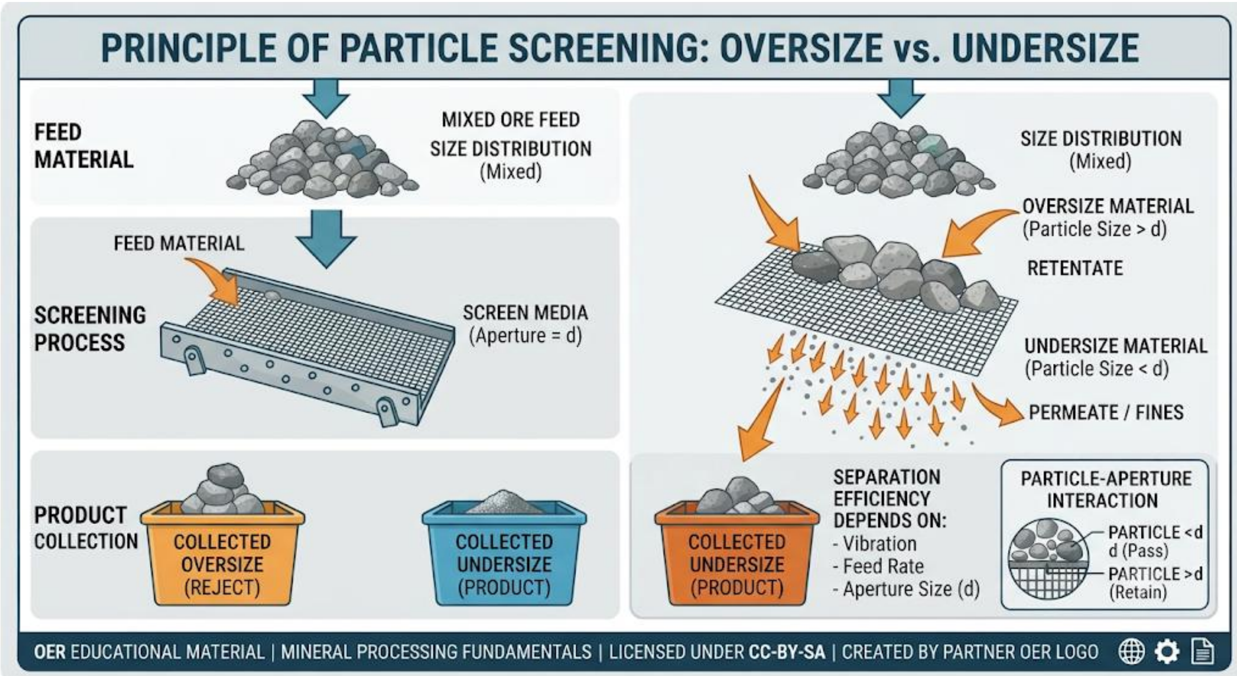
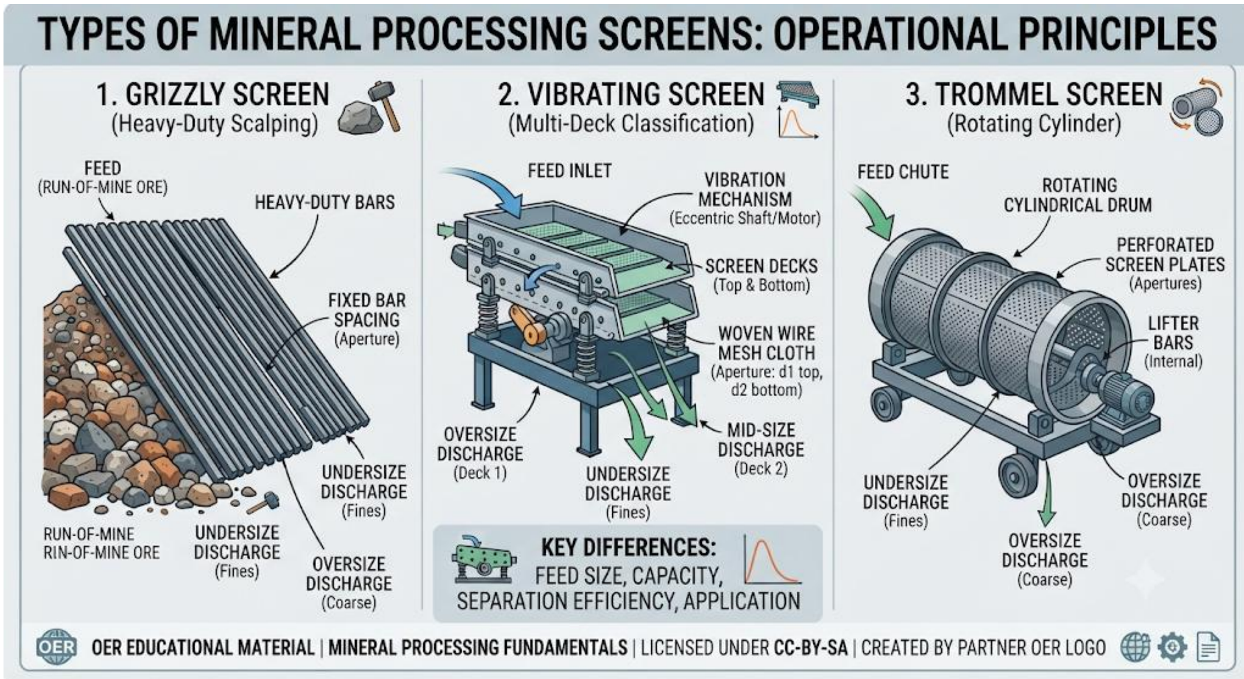



Diagram showing the principle of screening with oversized and undersized particles *Figure 2.3: Principle of particle screening*

### 2.3.2 Types of screens and applications

There are several types of **screens** used in mineral processing, including vibrating screens, trommel screens, and stationary grizzlies. Vibrating screens use mechanical vibration to improve efficiency, trommel screens are rotating cylindrical screens often used in coal and aggregate industries, and grizzlies are heavy-duty stationary screens used for coarse separation. Each type of screen is suited to specific applications depending on ore characteristics and processing requirements.

Fill in the blank: Trommel screens are rotating ______ screens often used in coal and aggregate industries.

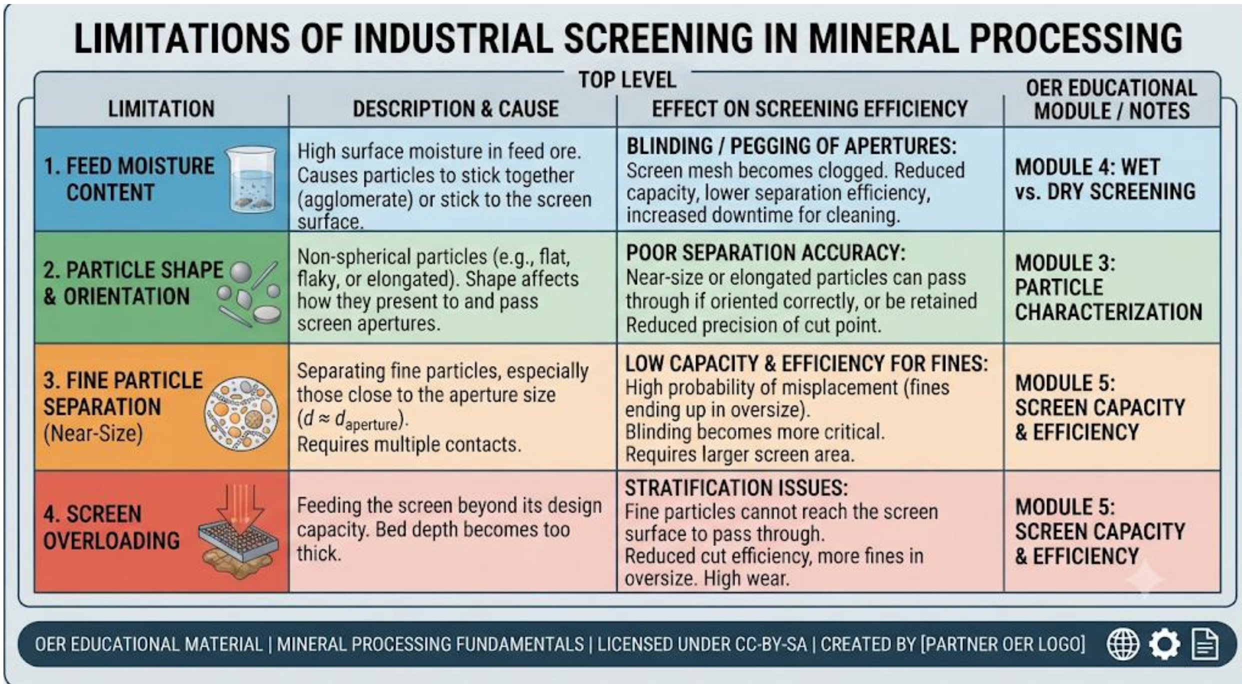



Photographs of vibrating screen, trommel screen, and grizzly screen *Plate 2.3: Types of screens used in mineral processing*

### 2.3.3 Limitations of screening methods

Despite its usefulness, screening has certain **limitations**. Moisture can cause particles to stick together, reducing efficiency. Irregular particle shapes may pass through openings incorrectly, leading to inaccurate sizing. Additionally, very fine particles are difficult to separate by screening alone, requiring classification methods instead. Engineers must therefore evaluate when screening is appropriate and when alternative methods are necessary.

Fill in the blank: Very fine particles are difficult to separate by screening alone and may require ______ methods instead.



LIMITATIONS OF INDUSTRIAL SCREENING IN MINERAL PROCESSING

| LIMITATION | DESCRIPTION & CAUSE | TOP LEVEL EFFECT ON SCREENING EFFICIENCY | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|
| 1. FEED MOISTURE CONTENT | High surface moisture in feed ore. Causes particles to stick together (agglomerate) or stick to the screen surface. | BLINDING / PEGGING OF APERTURES: Screen mesh becomes clogged. Reduced capacity, lower separation efficiency, increased downtime for cleaning. | MODULE 4: WET vs. DRY SCREENING |
| 2. PARTICLE SHAPE & ORIENTATION | Non-spherical particles (e.g., flat, flaky, or elongated). Shape affects how they present to and pass screen apertures. | POOR SEPARATION ACCURACY: Near-size or elongated particles can pass through if oriented correctly, or be retained Reduced precision of cut point. | MODULE 3: PARTICLE CHARACTERIZATION |
| 3. FINE PARTICLE SEPARATION (Near-Size) | Separating fine particles, especially those close to the aperture size ($d \approx d_{aperture}$). Requires multiple contacts. | LOW CAPACITY & EFFICIENCY FOR FINES: High probability of misplacement (fines ending up in oversize). Blinding becomes more critical. Requires larger screen area. | MODULE 5: SCREEN CAPACITY & EFFICIENCY |
| 4. SCREEN OVERLOADING | Feeding the screen beyond its design capacity. Bed depth becomes too thick. | STRATIFICATION ISSUES: Fine particles cannot reach the screen surface to pass through. Reduced cut efficiency, more fines in oversize. High wear. | MODULE 5: SCREEN CAPACITY & EFFICIENCY |

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Box 2.2: Limitations of screening in mineral processing

**Pilot questions 2.3**

1. Define screening and explain its purpose in mineral processing.
2. Name three types of screens and state one application for each.
3. What factor can reduce screening efficiency by causing particles to stick together?
4. Why are very fine particles difficult to separate by screening?
5. Explain one limitation of screening related to particle shape.

### 2.4 Particle Sizing by Classification

#### 2.4.1 Principles of classification

**Classification** is the process of separating particles based on size, shape, or density using a fluid medium such as water or air. Unlike screening, which relies on fixed openings, classification uses differences in settling velocity to separate fine and coarse particles. Coarse particles settle faster, while fine particles remain suspended longer. This principle is widely applied in mineral processing to control particle size distribution before further treatment.

Fill in the blank: Classification separates particles based on differences in ______ velocity in a fluid medium.

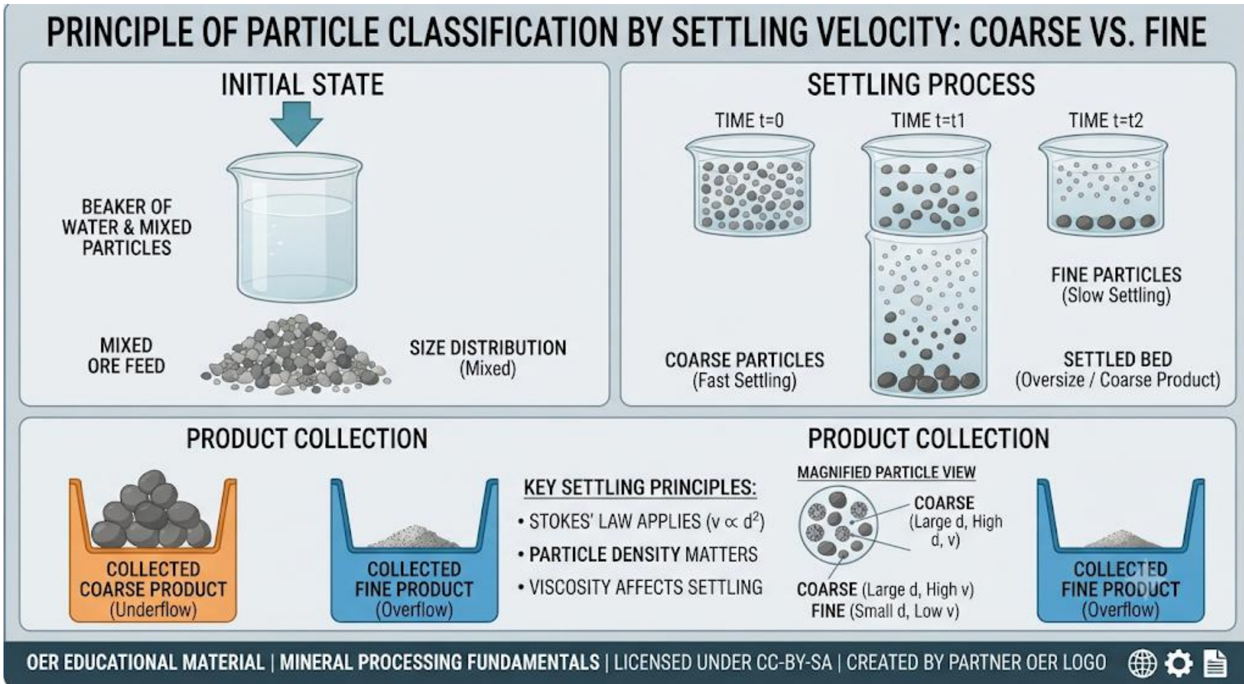
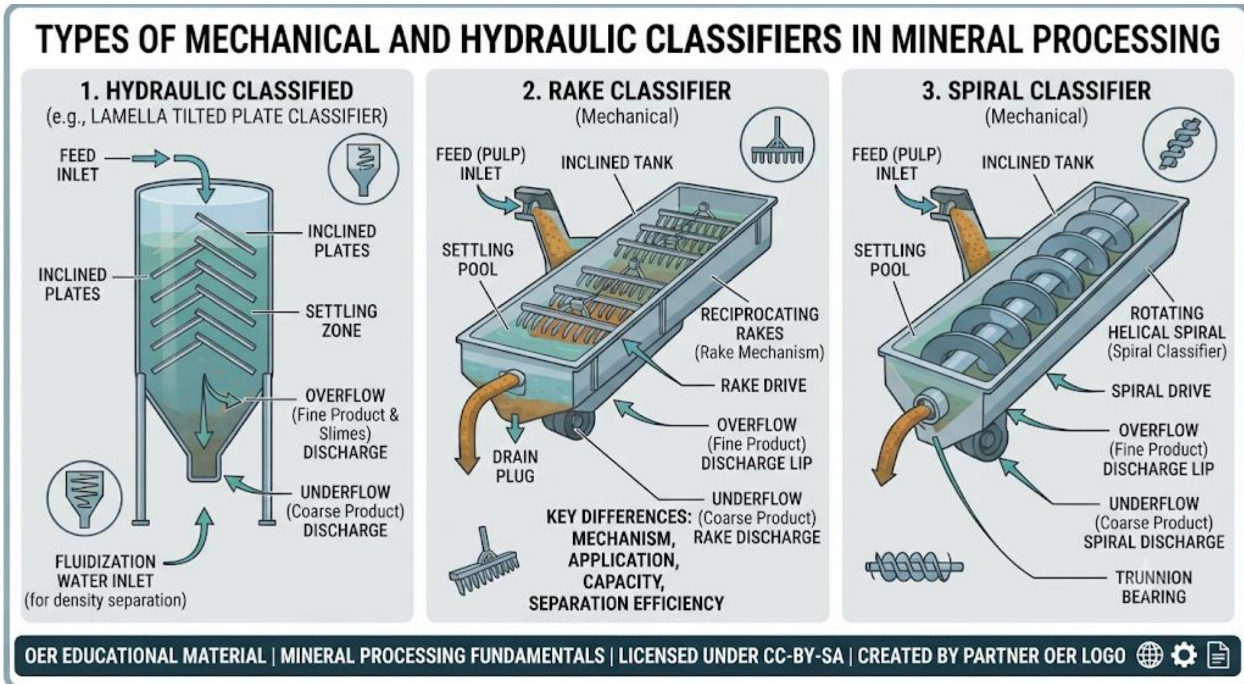



Diagram showing coarse particles settling faster than fine particles in water *Figure 2.4: Principle of particle classification*

### 2.4.2 Hydraulic and mechanical classifiers

**Hydraulic classifiers** use water flow to separate particles, with coarse particles settling at the bottom and fine particles carried away by the current. **Mechanical classifiers**, such as rake and spiral classifiers, use mechanical action to assist separation. Rake classifiers employ moving arms to lift coarse particles, while spiral classifiers use a rotating spiral to transport settled particles. These devices are commonly used in grinding circuits to control product size.

Fill in the blank: Spiral classifiers use a rotating ______ to transport settled particles.

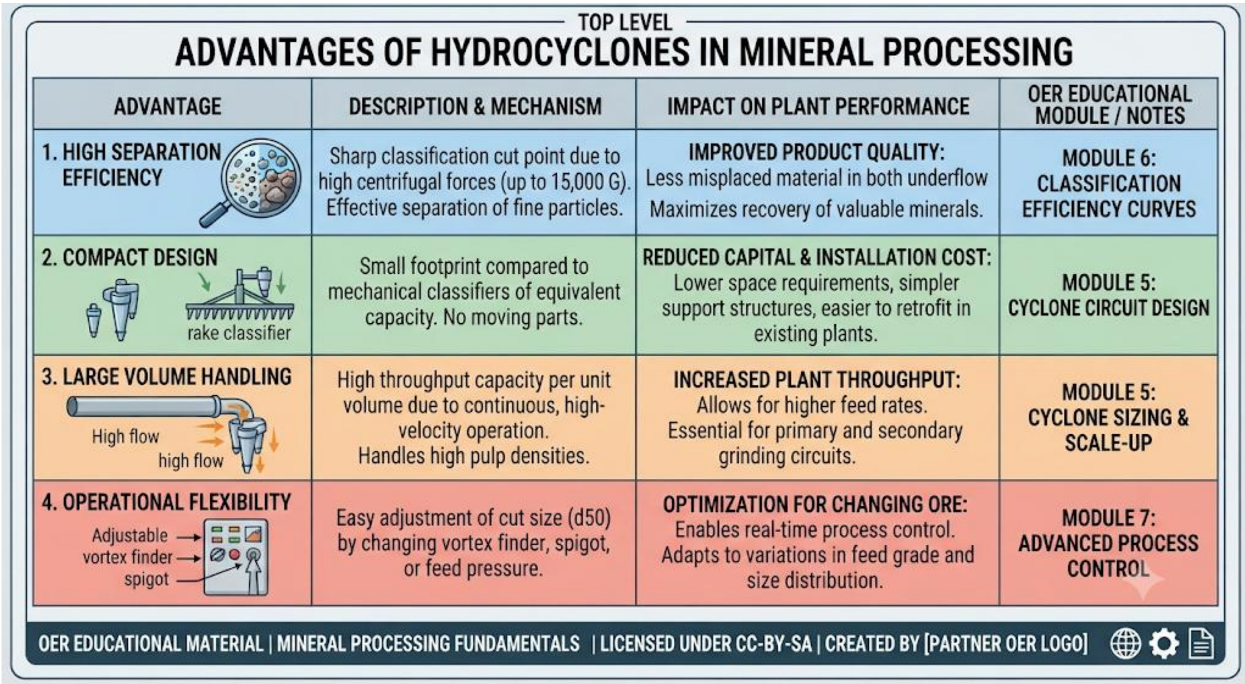



Photographs of hydraulic classifier, rake classifier, and spiral classifier *Plate 2.4: Types of hydraulic and mechanical classifiers*

#### 2.4.3 Cyclones and modern classifiers

**Cyclones** are widely used modern classifiers that separate particles by centrifugal force. Ore slurry is fed tangentially into the cyclone, creating a vortex. Coarse particles are forced to the wall and exit through the underflow, while fine particles are carried upward and exit through the overflow. Modern classifiers also include air classifiers, which separate particles using airflow. Cyclones are valued for their efficiency, compact design, and ability to handle large volumes.

Fill in the blank: In a cyclone, coarse particles exit through the ______, while fine particles leave through the overflow.



TOP LEVEL

ADVANTAGES OF HYDROCYCLONES IN MINERAL PROCESSING

| ADVANTAGE | DESCRIPTION & MECHANISM | IMPACT ON PLANT PERFORMANCE | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|
| 1. HIGH SEPARATION EFFICIENCY | Sharp classification cut point due to high centrifugal forces (up to 15,000 G). Effective separation of fine particles. | IMPROVED PRODUCT QUALITY: Less misplaced material in both underflow Maximizes recovery of valuable minerals. | MODULE 6: CLASSIFICATION EFFICIENCY CURVES |
| 2. COMPACT DESIGN (rake classifier) | Small footprint compared to mechanical classifiers of equivalent capacity. No moving parts. | REDUCED CAPITAL & INSTALLATION COST: Lower space requirements, simpler support structures, easier to retrofit in existing plants. | MODULE 5: CYCLONE CIRCUIT DESIGN |
| 3. LARGE VOLUME HANDLING (High flow, high flow) | High throughput capacity per unit volume due to continuous, high-velocity operation. Handles high pulp densities. | INCREASED PLANT THROUGHPUT: Allows for higher feed rates. Essential for primary and secondary grinding circuits. | MODULE 5: CYCLONE SIZING & SCALE-UP |
| 4. OPERATIONAL FLEXIBILITY (Adjustable vortex finder, spigot) | Easy adjustment of cut size (d50) by changing vortex finder, spigot, or feed pressure. | OPTIMIZATION FOR CHANGING ORE: Enables real-time process control. Adapts to variations in feed grade and size distribution. | MODULE 7: ADVANCED PROCESS CONTROL |

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Box 2.3: Advantages of cyclones in mineral processing

**Pilot questions 2.4**

1. Define classification and explain how it differs from screening.
2. Describe the principle behind hydraulic classifiers.
3. Explain the function of rake and spiral classifiers.
4. How do cyclones separate coarse and fine particles?
5. State one advantage of using cyclones in mineral processing.

### 2.5 Particle Size Analysis

#### 2.5.1 Methods of particle size measurement

**Particle size analysis** involves determining the distribution of particle sizes within a sample. Common methods include sieve analysis, sedimentation techniques, and modern instrumental methods such as laser diffraction. Sieve analysis is simple and widely used for coarse particles, while sedimentation relies on settling rates in a fluid. Laser diffraction provides rapid and precise measurements for fine particles.

Fill in the blank: Sieve analysis is most suitable for measuring ______ particles.

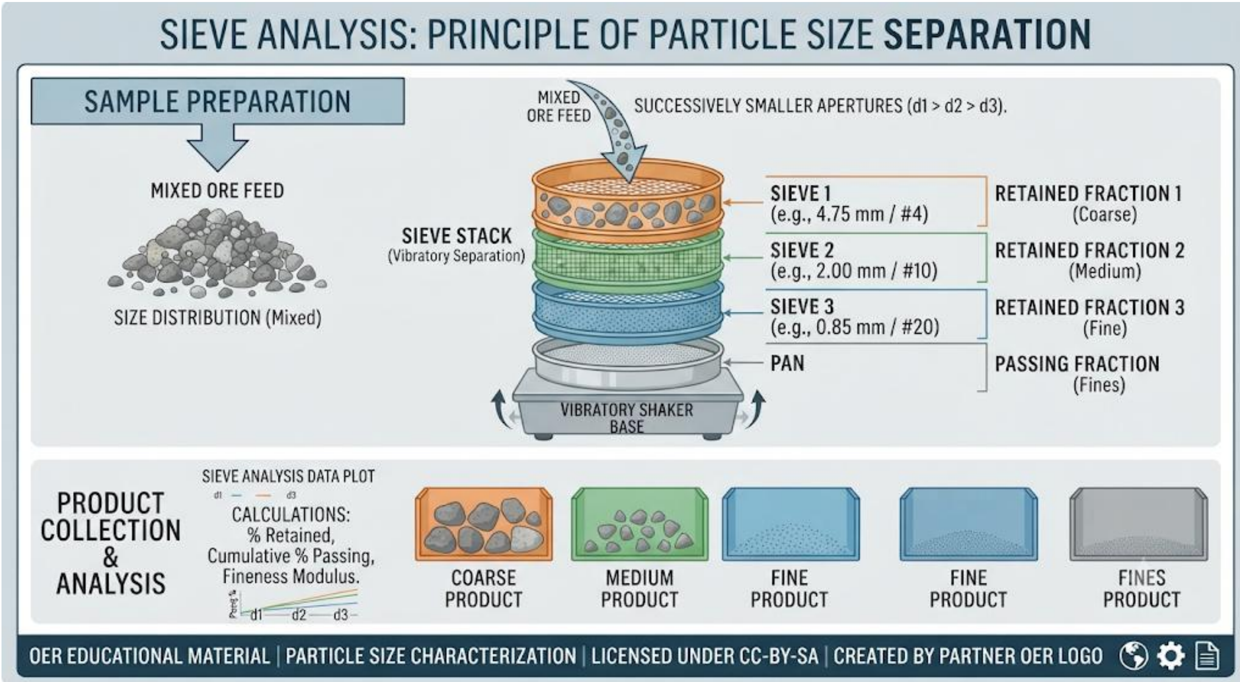



Diagram showing sieve analysis with stacked sieves of different mesh sizes *Figure 2.5: Principle of sieve analysis*

**2.5.2 Presentation of particle size data**

The results of particle size analysis are typically presented as size distribution curves or histograms. These show the proportion of particles within specific size ranges. Engineers use these data to evaluate grinding efficiency and to design separation processes. Cumulative curves are especially useful for understanding the percentage of particles finer than a given size.

Fill in the blank: Particle size distribution curves show the proportion of particles within specific ______ ranges.

## PARTICLE SIZE DISTRIBUTION PRESENTATION METHODS: HISTOGRAMS, CUMULATIVE CURVES, & SIZE DISTRIBUTION PLOTS

| PRESENTATION METHOD | ILLUSTRATION TYPE | KEY FEATURES | PRIMARY USES & INTERPRETATIONS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. HISTOGRAM | BAR CHART OF FREQUENCY | • Bars show frequency (e.g., % retained) within specific size intervals.<br>• Interval width can be linear or logarithmic. | • Visualizing the predominant size range (the "mode").<br>• Identifying symmetry or skewness in the distribution. | MODULE 3: DATA VISUALIZATION |
| 2. CUMULATIVE DISTRIBUTION CURVES (Passing / Retained) | SMOOTHED CUMULATIVE PERCENTAGE CURVE | • Y-axis is cumulative percentage (passing or<br>• X-axis is particle size (log scale).<br>• Represents the entire distribution. | • Determining percentiles (e.g., D10, D50, D90).<br>• Calculating uniformity coefficient.<br>• Comparing distributions. | MODULE 4: STATISTICAL ANALYSIS |
| 3. SIZE DISTRIBUTION PLOTS (Frequency & Cumulative) | COMBINED FREQUENCY HISTOGRAM & CUMULATIVE CURVE | • Overlaying frequency bars and cumulative curve on the same chart.<br>• Uses dual Y-axes (left for frequency, right for cumulative). | • Providing a comprehensive view of both the mode and percentiles simultaneously.<br>• Essential for detailed process control. | MODULE 5: PROCESS OPTIMIZATION |

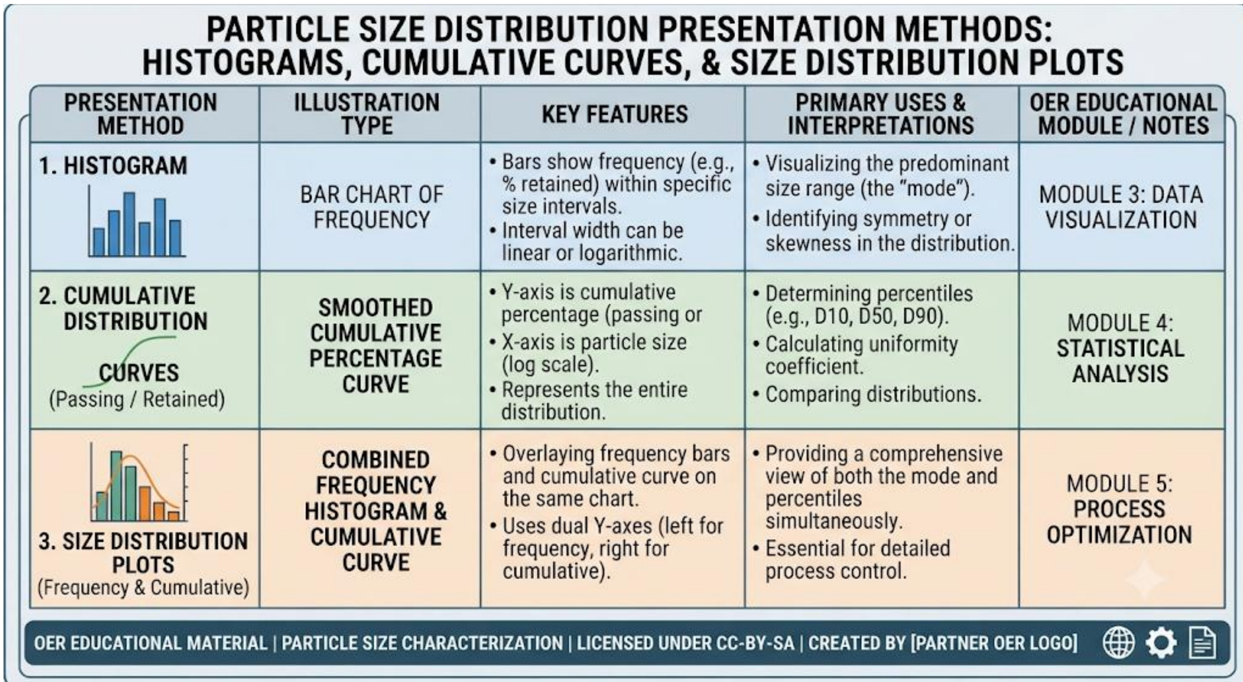


Table 2.2: Common ways of presenting particle size data

### 2.5.3 Applications in mineral processing

The **applications** of particle size analysis in mineral processing are extensive. It helps determine whether comminution has achieved the desired liberation, guides the selection of separation techniques, and ensures product quality. For example, flotation requires fine particles, while gravity separation is more effective with coarser particles. Accurate particle size data therefore supports both laboratory testing and industrial operations.

Fill in the blank: Flotation processes are more effective when treating ______ particles.



# PARTICLE SIZE DISTRIBUTION PRESENTATION METHODS: HISTOGRAMS, CUMULATIVE CURVES, & SIZE DISTRIBUTION PLOTS

| PRESENTATION METHOD | ILLUSTRATION TYPE | KEY FEATURES | PRIMARY USES & INTERPRETATIONS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. HISTOGRAM | BAR CHART OF FREQUENCY | • Bars show frequency (e.g., % retained) within specific size intervals.<br>• Interval width can be linear or logarithmic. | • Visualizing the predominant size range (the "mode").<br>• Identifying symmetry or skewness in the distribution. | MODULE 3: DATA VISUALIZATION |
| 2. CUMULATIVE DISTRIBUTION CURVES (Passing / Retained) | SMOOTHED CUMULATIVE PERCENTAGE CURVE | • Y-axis is cumulative percentage (passing or<br>• X-axis is particle size (log scale).<br>• Represents the entire distribution. | • Determining percentiles (e.g., D10, D50, D90).<br>• Calculating uniformity coefficient.<br>• Comparing distributions. | MODULE 4: STATISTICAL ANALYSIS |
| 3. SIZE DISTRIBUTION PLOTS (Frequency & Cumulative) | COMBINED FREQUENCY HISTOGRAM & CUMULATIVE CURVE | • Overlaying frequency bars and cumulative curve on the same chart.<br>• Uses dual Y-axes (left for frequency, right for cumulative). | • Providing a comprehensive view of both the mode and percentiles simultaneously.<br>• Essential for detailed process control. | MODULE 5: PROCESS OPTIMIZATION |

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Photograph of laboratory equipment used for particle size analysis *Plate 2.5: Laboratory setup for particle size analysis*

**Pilot questions 2.5**

1. Define particle size analysis and state its purpose.
2. Name three methods of particle size measurement.
3. How are particle size data typically presented?
4. Why are cumulative curves useful in particle size analysis?
5. Give one example of how particle size analysis guides mineral processing applications.

**Series Summary**

This Series has explored the essential concepts of comminution and particle analysis, which are central to mineral processing. We began with the basic theory of comminution, examining size reduction, energy requirements, and mineral liberation. We then studied comminution equipment and processes, including crushing and grinding operations, and the factors that influence efficiency. Following that, we looked at particle sizing by screening, considering its principles, types, and limitations. We continued with particle sizing by classification, focusing on hydraulic and mechanical classifiers as well as cyclones. Finally, we concluded with particle size analysis, covering measurement methods, data presentation, and practical applications.

By completing this Series, you should now be able to explain comminution principles, describe equipment and processes, demonstrate screening methods, apply classification techniques, and interpret particle size data. These skills align directly with the Series Learning Outcomes and provide the analytical foundation needed for effective mineral processing.

**Glossary of Terms**

- **Ball mill**: A grinding device that uses steel balls as media to reduce ore size.
- **Classification**: The process of separating particles based on differences in settling velocity in a fluid medium.
- **Comminution**: The process of reducing ore particle size to liberate valuable minerals.
- **Cyclone**: A modern classifier that separates particles using centrifugal force in a vortex.
- **Grinding**: The stage of comminution where ore is reduced to fine particles using mills.
- **Liberation**: The freeing of valuable minerals from gangue material during size reduction.
- **Screening**: The process of separating particles according to size using a screen surface.
- **Sieve analysis**: A particle size measurement method using stacked sieves of different mesh sizes.
- **Spiral classifier**: A mechanical classifier that uses a rotating spiral to transport settled particles.
- **Trommel screen**: A rotating cylindrical screen used for particle sizing, often in coal and aggregate industries.

**Concept Check Questions [Series 2]**

**Objective questions**

1. What is comminution? (Linked to SLO 2.1)
2. Which grinding device uses steel balls as media? (Linked to SLO 2.2)
3. In a cyclone, coarse particles exit through the ______. (Linked to SLO 2.4)

**Short-answer questions**

4. Explain the difference between screening and classification. (Linked to SLO 2.3, SLO 2.4)
5. State one limitation of screening methods. (Linked to SLO 2.3)
6. Give one example of how particle size analysis guides mineral processing applications. (Linked to SLO 2.5)

**Long-answer questions**

7. Analyse how energy laws (Kick's, Rittinger's, Bond's) contribute to understanding comminution requirements. (Linked to SLO 2.1)

8. Evaluate the role of particle size analysis in improving efficiency of mineral processing flowsheets. (Linked to SLO 2.5)

**Answers to Concept Check Questions [Series 2]**

**Objective questions**

1. Comminution is the process of reducing ore particle size to liberate valuable minerals.

2. Ball mill.

3. Underflow.

**Short-answer questions**

4. Screening separates particles using fixed openings, while classification uses settling velocity in a fluid medium.

5. Moisture can cause particles to stick together, reducing efficiency.

6. Particle size analysis helps determine whether comminution has achieved liberation and guides the choice of separation techniques.

**Long-answer questions**

7. **Basic response**: Kick's law relates energy to size reduction ratio, Rittinger's law to surface area created, and Bond's law provides practical estimates. **Value-added response**: Outstanding learners may discuss how these laws complement each other, with Bond's law bridging theoretical and industrial applications, ensuring accurate energy predictions for different ore types.

8. **Basic response**: Particle size analysis ensures that particles are appropriately sized for separation methods, improving efficiency. **Value-added response**: Outstanding learners may evaluate how integrating particle size data into flowsheet design reduces energy consumption, enhances recovery rates, and supports sustainable mineral processing.

**Answers to Pilot Questions [Series 2]**

1. Comminution is reducing ore particle size to liberate minerals.

2. Compression squeezes particles, impact strikes them, attrition grinds them.

3. Kick's law states energy is proportional to size reduction ratio.

4. Rittinger's law relates energy to new surface area.

5. Liberation is important for successful separation.

6. Jaw, gyratory, and cone crushers.
7. Ball mills use balls, rod mills use rods, SAG mills use ore plus media.
8. Open circuits lack classifiers, closed circuits use classifiers to control size.
9. Ore hardness, moisture, feed size, equipment design.
10. Equipment design influences throughput and product quality.
11. Screening separates particles by size using openings.
12. Vibrating screens, trommel screens, grizzlies.
13. Moisture causes particles to stick together.
14. Very fine particles are difficult to separate by screening.
15. Irregular shapes may pass incorrectly.
16. Classification separates particles by settling velocity.
17. Hydraulic classifiers use water flow.
18. Rake classifiers lift particles, spiral classifiers transport them.
19. Cyclones use centrifugal force; coarse particles exit underflow, fine particles overflow.
20. Cyclones are efficient, compact, and handle large volumes.
21. Particle size analysis determines distribution of particle sizes.
22. Sieve analysis, sedimentation, laser diffraction.
23. Data presented as histograms or cumulative curves.
24. Cumulative curves show percentage finer than a given size.
25. Particle size analysis guides flotation (fine particles) and gravity separation (coarse particles).

**References and Attributions [Series 2]**

- Figure 2.1: Principles of size reduction in comminution. Suggested AI prompt: "Create a labelled diagram showing compression, impact, and attrition forces breaking ore particles." Search string: "comminution forces compression impact attrition diagram OER."
- Table 2.1: Comparison of comminution energy laws. Suggested AI prompt: "Create a table comparing Kick's law, Rittinger's law, and Bond's law with their key principles." Search string: "comminution energy laws comparison table OER."

- Plate 2.1: Examples of mineral liberation in ores. Suggested AI prompt: “Generate images of ore samples showing liberated and unliberated mineral particles under a microscope.” Search string: “mineral liberation ore samples microscope OER.”
- Figure 2.2: Types of crushing equipment. Suggested AI prompt: “Create a labelled diagram comparing jaw crusher, gyratory crusher, and cone crusher.” Search string: “jaw gyratory cone crusher diagram OER.”
- Plate 2.2: Ball mill used in mineral processing. Suggested AI prompt: “Generate an image of a ball mill in operation inside a mineral processing plant.” Search string: “ball mill mineral processing plant OER.”
- Box 2.1: Key factors influencing comminution efficiency. Suggested AI prompt: “Create a table listing ore hardness, moisture content, feed size, and equipment design with their effects on efficiency.” Search string: “factors affecting comminution efficiency table OER.”
- Figure 2.3: Principle of particle screening. Suggested AI prompt: “Create a labelled diagram showing oversized particles retained on a screen and undersized particles passing through.” Search string: “principle of particle screening diagram OER.”
- Plate 2.3: Types of screens used in mineral processing. Suggested AI prompt: “Generate images of vibrating screen, trommel screen, and grizzly screen used in mineral processing.” Search string: “types of screens mineral processing OER.”
- Box 2.2: Limitations of screening in mineral processing. Suggested AI prompt: “Create a table listing limitations of screening such as moisture, particle shape, and fine particle separation.” Search string: “limitations of screening mineral processing table OER.”
- Figure 2.4: Principle of particle classification. Suggested AI prompt: “Create a labelled diagram showing coarse particles settling quickly and fine particles remaining suspended in water.” Search string: “principle of particle classification diagram OER.”
- Plate 2.4: Types of hydraulic and mechanical classifiers. Suggested AI prompt: “Generate images of hydraulic classifier, rake classifier, and spiral classifier used in mineral processing.” Search string: “hydraulic rake spiral classifier mineral processing OER.”
- Box 2.3: Advantages of cyclones in mineral processing. Suggested AI prompt: “Create a table listing advantages of cyclones such as efficiency, compact design, and large-volume handling.” Search string: “advantages of cyclones mineral processing table OER.”
- Figure 2.5: Principle of sieve analysis. Suggested AI prompt: “Create a labelled diagram showing stacked sieves separating coarse particles by size.” Search string: “sieve analysis particle size diagram OER.”
- Table 2.2: Common ways of presenting particle size data. Suggested AI prompt: “Create a table listing histograms, cumulative curves, and size distribution plots with their uses.” Search string: “particle size distribution presentation methods table OER.”

- Plate 2.5: Laboratory setup for particle size analysis. Suggested AI prompt: "Generate an image of laboratory equipment used for particle size analysis including sieves and laser diffraction instruments." Search string: "particle size analysis laboratory equipment OER."

## Series 3: Mineral Separation Techniques

**Series outline**

- **3.1 Principles of mineral separation**
  - 3.1.1 Fundamentals of separation processes
  - 3.1.2 Physical and chemical properties influencing separation
  - 3.1.3 Criteria for selecting separation methods
- **3.2 Gravity separation methods**
  - 3.2.1 Principles of gravity concentration
  - 3.2.2 Common equipment (jigs, shaking tables, spirals)
  - 3.2.3 Applications and limitations
- **3.3 Magnetic and electrostatic separation**
  - 3.3.1 Principles of magnetic separation
  - 3.3.2 Types of magnetic separators
  - 3.3.3 Principles of electrostatic separation and applications
- **3.4 Flotation techniques**
  - 3.4.1 Principles of flotation and reagents
  - 3.4.2 Flotation cells and circuits
  - 3.4.3 Industrial applications and challenges
- **3.5 Emerging and specialised separation methods**
  - 3.5.1 Advances in sensor-based sorting
  - 3.5.2 Bio-mineral separation approaches

- 3.5.3 Integration of separation methods in modern flowsheets

**Introduction**

Mineral separation is the stage of mineral processing where valuable minerals are separated from gangue materials after comminution and sizing. This step is critical because it determines the quality and recovery of the final product. Different separation techniques exploit variations in physical and chemical properties such as density, magnetism, surface chemistry, and conductivity.

The aim of this Series is to equip you with a clear understanding of the principles and applications of mineral separation techniques. You will learn how gravity, magnetic, electrostatic, and flotation methods are applied in practice, and explore emerging technologies that are shaping modern mineral processing. By mastering these concepts, you will be able to select appropriate separation methods and evaluate their effectiveness in different contexts.

We shall begin with the principles of mineral separation, focusing on the properties that influence method selection. Next, we will study gravity separation methods and their equipment. We will then examine magnetic and electrostatic separation, followed by flotation techniques, which are widely used for fine particles. Finally, we will conclude with emerging and specialised separation methods, including sensor-based sorting and bio-mineral approaches, highlighting their role in modern flowsheets.

**Series Learning Outcomes**

Upon completing **Series 3: Mineral Separation Techniques**, you should be able to:

- **SLO 3.1** explain the fundamental principles of mineral separation and identify the physical and chemical properties that influence method selection,
- **SLO 3.2** describe gravity separation methods, outline the operation of common equipment such as jigs, shaking tables, and spirals, and evaluate their applications and limitations,
- **SLO 3.3** analyse magnetic and electrostatic separation techniques, including their principles, equipment types, and industrial uses,
- **SLO 3.4** demonstrate understanding of flotation techniques, including the role of reagents, flotation cells, and circuits, and assess their industrial applications and challenges,
- **SLO 3.5** evaluate emerging and specialised separation methods such as sensor-based sorting and bio-mineral approaches, and explain how they integrate into modern mineral processing flowsheets.

**3.1 Principles of Mineral Separation**

### 3.1.1 Fundamentals of separation processes

**Mineral separation** is the stage in mineral processing where valuable minerals are separated from gangue based on differences in their physical or chemical properties. The fundamental principle is to exploit contrasts such as density, magnetism, conductivity, or surface chemistry. For example, gold can be concentrated by gravity methods due to its high density, while sulphide minerals are separated by flotation because of their surface properties.

Fill in the blank: Mineral separation exploits differences in physical or ______ properties between valuable minerals and gangue.

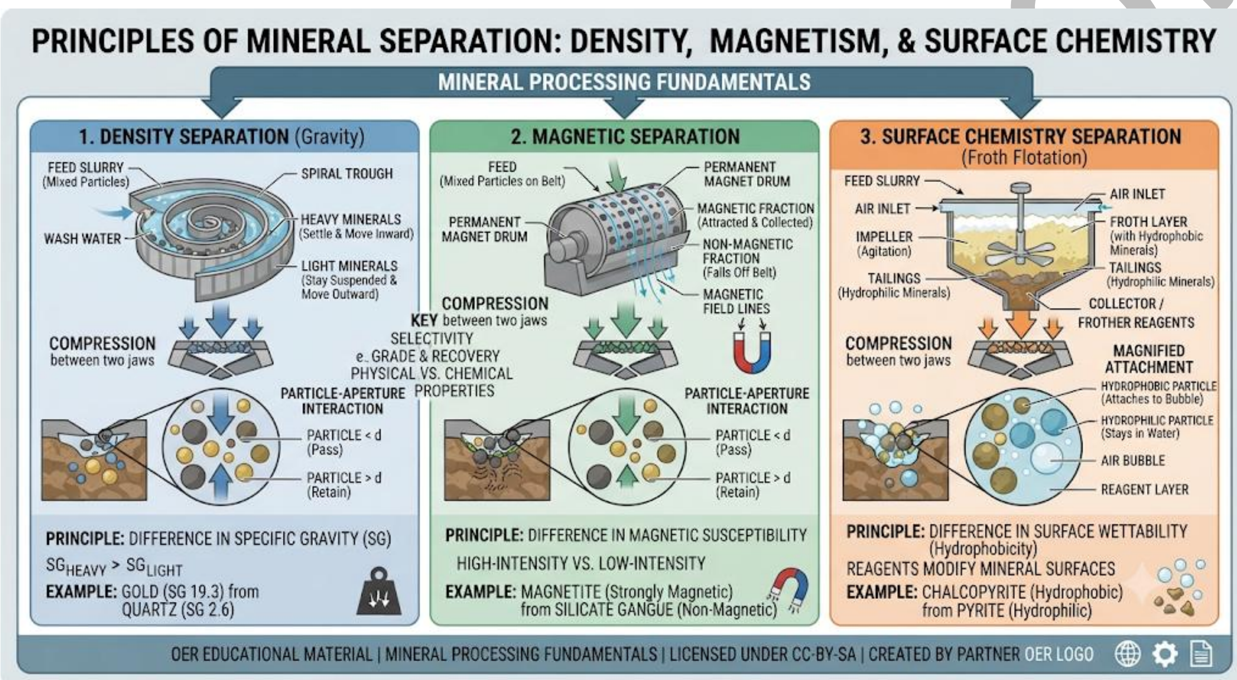



Diagram showing separation based on density, magnetism, and surface chemistry *Figure 3.1: Fundamental principles of mineral separation*

### 3.1.2 Physical and chemical properties influencing separation

The success of mineral separation depends on recognising and utilising key properties:

- **Density**: exploited in gravity separation.
- **Magnetism**: exploited in magnetic separation.
- **Conductivity**: exploited in electrostatic separation.
- **Surface chemistry**: exploited in flotation.

Each property determines which technique is most effective. For instance, minerals with strong magnetic susceptibility are best processed using magnetic separators, while differences in surface wettability guide flotation.

Fill in the blank: Differences in surface ______ are exploited in flotation processes.

**PROPERTIES INFLUENCING MINERAL SEPARATION: KEY PHYSICAL & CHEMICAL PROPERTIES**

| MINERAL PROPERTY | PROPERTY DESCRIPTION | CORRESPONDING SEPARATION TECHNIQUE | SEPARATION PRINCIPLE | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| B or (Specific Gravity) | Mass per unit volume. Significant difference between valuable mineral and gangue (waste). | GRAVITY CONCENTRATION e.g., Spiral, Jigs, Shaking Table | Differential settling velocity in a fluid (water or air) based on mass and size. Heavy particles sink, light particles are carried away. | MODULE 3: GRAVITY SEPARATION |
| 2. MAGNETIC SUSCEPTIBILITY | Degree to which a material is attracted to or repelled by a magnetic field. Can be strongly magnetic, weakly magnetic, or non-magnetic. | MAGNETIC SEPARATION e.g., Low-Intensity Magnetic Separator - LIMS High-Intensity Magnetic Separator - HIMS | Selective attraction of magnetic particles in a magnetic field. Non-magnetic particles follow a different path. | MODULE 4: MAGNETIC SEPARATION |
| 3. ELECTRICAL CONDUCTIVITY | Ability of a mineral to conduct an electric current. Varies from conductors (metals) to semiconductors insulators (most silicates). | ELECTROSTATIC SEPARATION e.g., High-Tension Roll Separator | Differential charging of particles in a high-voltage electrostatic field. . Conductors lose charge and are thrown off, insulators retain charge and adhere. | MODULE 5: ELECTROSTATIC SEPARATION |
| 4. SURFACE CHEMISTRY (Hydrophobicity / Wettability) | Ability of a mineral surface to be wetted by water. Hydrophobic (water-repelling) surfaces attach to air bubbles. | FROTH FLOTATION e.g., Flotation Cell | Selective attachment of hydrophobic particles to air bubbles, which rise to form a froth concentrate. Hydrophilic particles remain in the pulp (tailings). | MODULE 6: FROTH FLOTATION |



Table 3.1: Properties influencing mineral separation and corresponding techniques

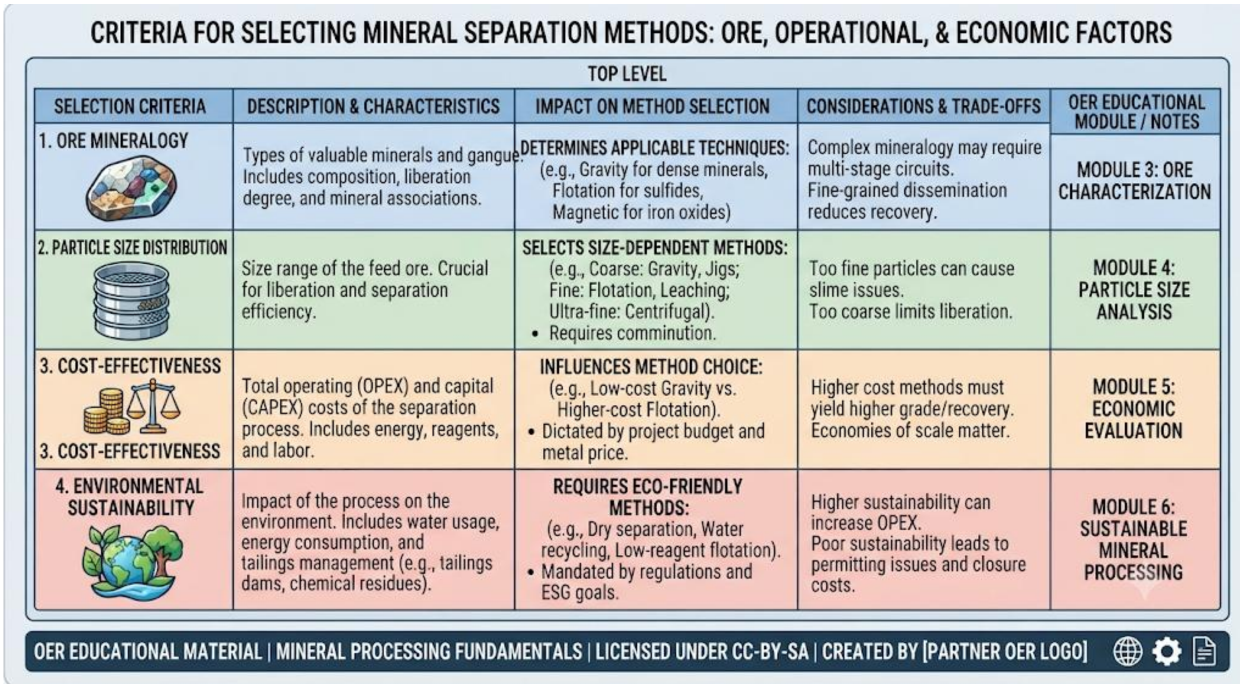
### 3.1.3 Criteria for selecting separation methods

Selecting the appropriate separation method requires considering ore characteristics, particle size, economic factors, and environmental impact. Engineers must evaluate:

- Ore mineralogy and texture.
- Degree of liberation achieved after comminution.
- Cost-effectiveness of the method.
- Environmental sustainability and waste management.

For example, flotation may be chosen for fine sulphide ores, while gravity separation may be more suitable for coarse, dense minerals.

Fill in the blank: The choice of separation method depends on ore characteristics, particle size, and ______ factors.



CRITERIA FOR SELECTING MINERAL SEPARATION METHODS: ORE, OPERATIONAL, & ECONOMIC FACTORS

TOP LEVEL

| SELECTION CRITERIA | DESCRIPTION & CHARACTERISTICS | IMPACT ON METHOD SELECTION | CONSIDERATIONS & TRADE-OFFS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. ORE MINERALOGY | Types of valuable minerals and gangue. Includes composition, liberation degree, and mineral associations. | DETERMINES APPLICABLE TECHNIQUES: (e.g., Gravity for dense minerals, Flotation for sulfides, Magnetic for iron oxides) | Complex mineralogy may require multi-stage circuits. Fine-grained dissemination reduces recovery. | MODULE 3: ORE CHARACTERIZATION |
| 2. PARTICLE SIZE DISTRIBUTION | Size range of the feed ore. Crucial for liberation and separation efficiency. | SELECTS SIZE-DEPENDENT METHODS: (e.g., Coarse: Gravity, Jigs; Fine: Flotation, Leaching; Ultra-fine: Centrifugal). • Requires comminution. | Too fine particles can cause slime issues. Too coarse limits liberation. | MODULE 4: PARTICLE SIZE ANALYSIS |
| 3. COST-EFFECTIVENESS 3. COST-EFFECTIVENESS | Total operating (OPEX) and capital (CAPEX) costs of the separation process. Includes energy, reagents, and labor. | INFLUENCES METHOD CHOICE: (e.g., Low-cost Gravity vs. Higher-cost Flotation). • Dictated by project budget and metal price. | Higher cost methods must yield higher grade/recovery. Economies of scale matter. | MODULE 5: ECONOMIC EVALUATION |
| 4. ENVIRONMENTAL SUSTAINABILITY | Impact of the process on the environment. Includes water usage, energy consumption, and tailings management (e.g., tailings dams, chemical residues). | REQUIRES ECO-FRIENDLY METHODS: (e.g., Dry separation, Water recycling, Low-reagent flotation). • Mandated by regulations and ESG goals. | Higher sustainability can increase OPEX. Poor sustainability leads to permitting issues and closure costs. | MODULE 6: SUSTAINABLE MINERAL PROCESSING |

OER EDUCATIONAL MATERIAL | MINERAL PROCESSING FUNDAMENTALS | LICENSED UNDER CC-BY-SA | CREATED BY [PARTNER OER LOGO]

Box 3.1: Criteria for selecting mineral separation methods

**Pilot questions 3.1**

1. Define mineral separation and explain its purpose in mineral processing.
2. Name three physical or chemical properties exploited in mineral separation.
3. Which property is exploited in flotation processes?
4. State one criterion used to select a separation method.
5. Why is ore mineralogy important in choosing a separation technique?

## 3.2 Gravity Separation Methods

### 3.2.1 Principles of gravity concentration

**Gravity separation** exploits differences in mineral density to achieve concentration. When particles are subjected to a fluid medium or mechanical motion, denser minerals settle faster than lighter gangue. This principle is widely used for minerals such as gold, tin, and iron ore. The efficiency of gravity concentration depends on particle size, shape, and liberation.

Fill in the blank: Gravity separation exploits differences in mineral ______ to achieve concentration.

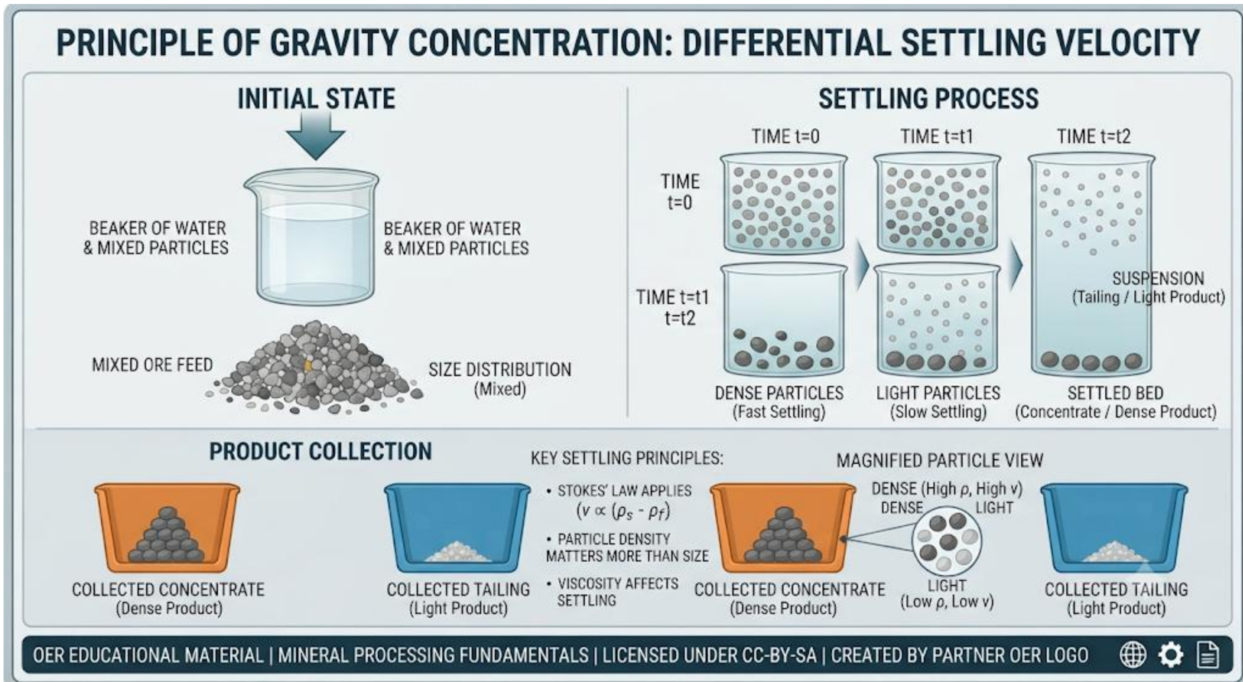


Diagram showing dense particles settling faster than lighter ones in a fluid medium *Figure 3.2: Principle of gravity concentration*

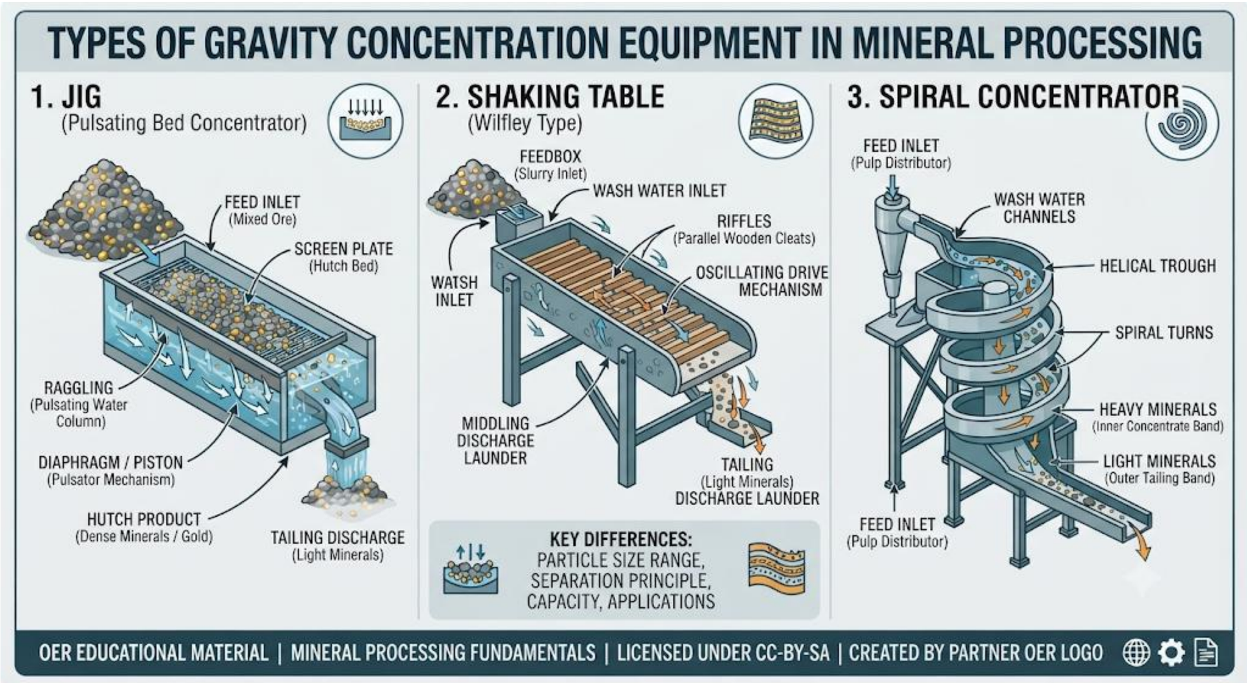
### 3.2.2 Common equipment (jigs, shaking tables, spirals)

Several types of equipment are used in gravity separation:

- **Jigs**: Pulsating water currents separate minerals by density.
- **Shaking tables**: Inclined tables with a shaking motion separate particles into bands according to density.
- **Spirals**: Helical troughs use flowing water to concentrate heavy minerals along the inner edge.

Each device is suited to particular particle sizes and ore types. For example, jigs are effective for coarse particles, while spirals and shaking tables are better for fine particles.

Fill in the blank: Shaking tables separate particles into bands according to differences in ______.

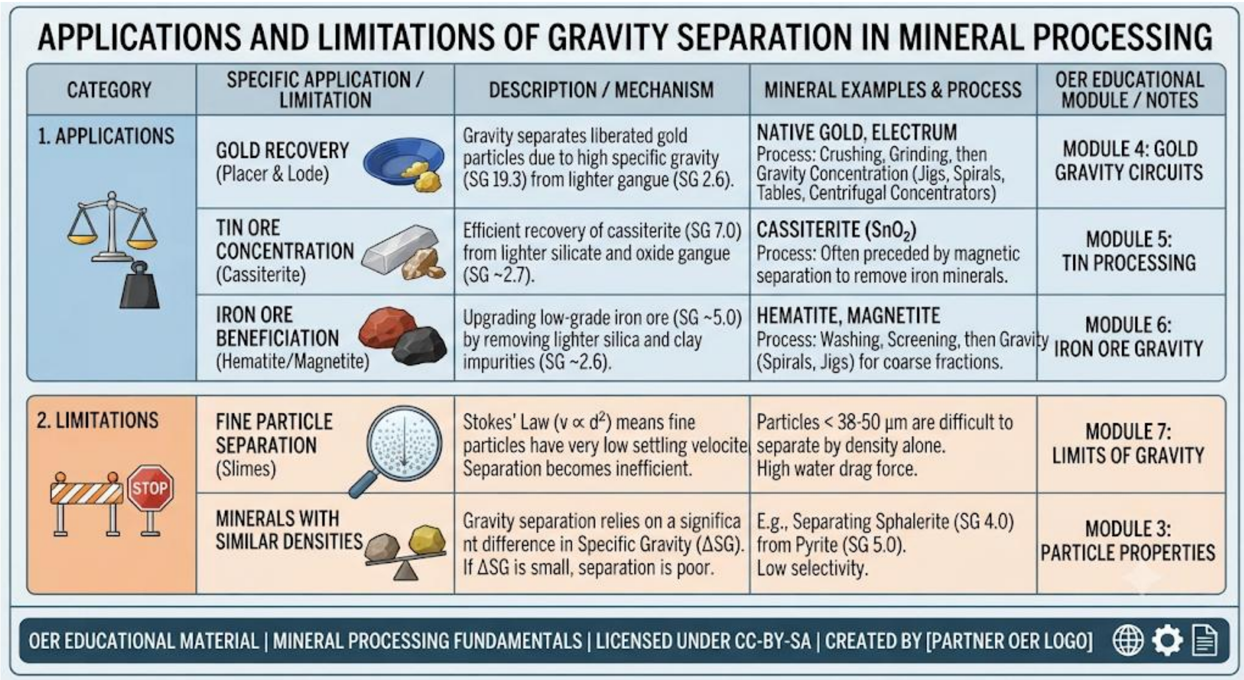



Photographs of jig, shaking table, and spiral concentrator *Plate 3.2: Common gravity separation equipment*

### 3.2.3 Applications and limitations

Gravity separation is widely applied in the recovery of gold, tin, and iron ores. It is cost-effective and environmentally friendly since it does not require chemical reagents. However, it has limitations: efficiency decreases with very fine particles, and ores with similar densities are difficult to separate. Engineers often combine gravity methods with other techniques to improve recovery.

Fill in the blank: Gravity separation is less effective when dealing with very ______ particles.



APPLICATIONS AND LIMITATIONS OF GRAVITY SEPARATION IN MINERAL PROCESSING

| CATEGORY | SPECIFIC APPLICATION / LIMITATION | DESCRIPTION / MECHANISM | MINERAL EXAMPLES & PROCESS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. APPLICATIONS | GOLD RECOVERY (Placer & Lode) | Gravity separates liberated gold particles due to high specific gravity (SG 19.3) from lighter gangue (SG 2.6). | NATIVE GOLD, ELECTRUM Process: Crushing, Grinding, then Gravity Concentration (Jigs, Spirals, Tables, Centrifugal Concentrators) | MODULE 4: GOLD GRAVITY CIRCUITS |
| | TIN ORE CONCENTRATION (Cassiterite) | Efficient recovery of cassiterite (SG 7.0) from lighter silicate and oxide gangue (SG ~2.7). | CASSITERITE ($SnO_2$) Process: Often preceded by magnetic separation to remove iron minerals. | MODULE 5: TIN PROCESSING |
| | IRON ORE BENEFICIATION (Hematite/Magnetite) | Upgrading low-grade iron ore (SG ~5.0) by removing lighter silica and clay impurities (SG ~2.6). | HEMATITE, MAGNETITE Process: Washing, Screening, then Gravity (Spirals, Jigs) for coarse fractions. | MODULE 6: IRON ORE GRAVITY |
| 2. LIMITATIONS | FINE PARTICLE SEPARATION (Slimes) | Stokes' Law ($v \propto d^2$) means fine particles have very low settling velocite Separation becomes inefficient. | Particles < 38-50 μm are difficult to separate by density alone. High water drag force. | MODULE 7: LIMITS OF GRAVITY |
| | MINERALS WITH SIMILAR DENSITIES | Gravity separation relies on a significa nt difference in Specific Gravity (ΔSG). If ΔSG is small, separation is poor. | E.g., Separating Sphalerite (SG 4.0) from Pyrite (SG 5.0). Low selectivity. | MODULE 3: PARTICLE PROPERTIES |



Box 3.2: Applications and limitations of gravity separation

**Pilot questions 3.2**

1. Define gravity separation and explain its principle.
2. Name three types of gravity separation equipment.
3. Which equipment uses pulsating water currents to separate minerals?
4. State one application of gravity separation.
5. Why is gravity separation less effective for very fine particles?

### 3.3 Magnetic and Electrostatic Separation

#### 3.3.1 Principles of magnetic separation

**Magnetic separation** exploits differences in magnetic susceptibility between minerals. Strongly magnetic minerals such as magnetite are easily separated from non-magnetic gangue using magnetic fields. Weakly magnetic minerals may require high-intensity separators. The principle is simple: magnetic particles are attracted to a magnetic field, while non-magnetic particles are not.

Fill in the blank: Magnetic separation exploits differences in mineral ______ susceptibility.

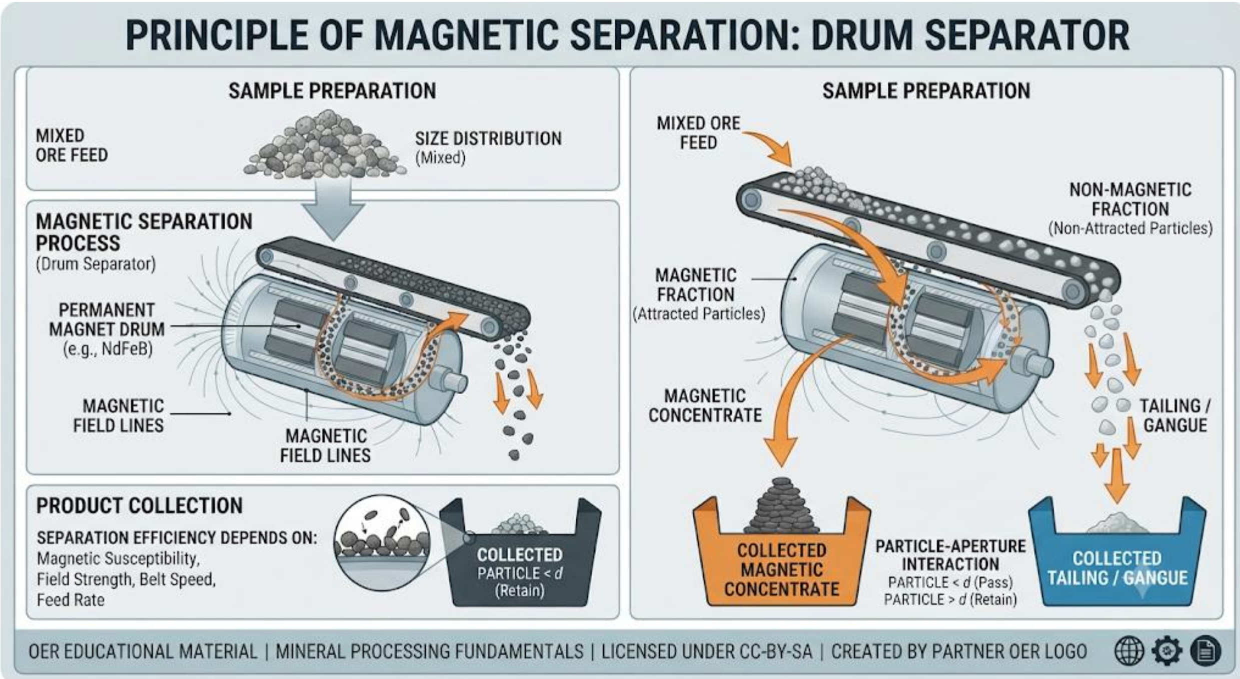


Diagram showing magnetic particles attracted to a magnetic drum while non-magnetic particles fall away *Figure 3.3: Principle of magnetic separation*

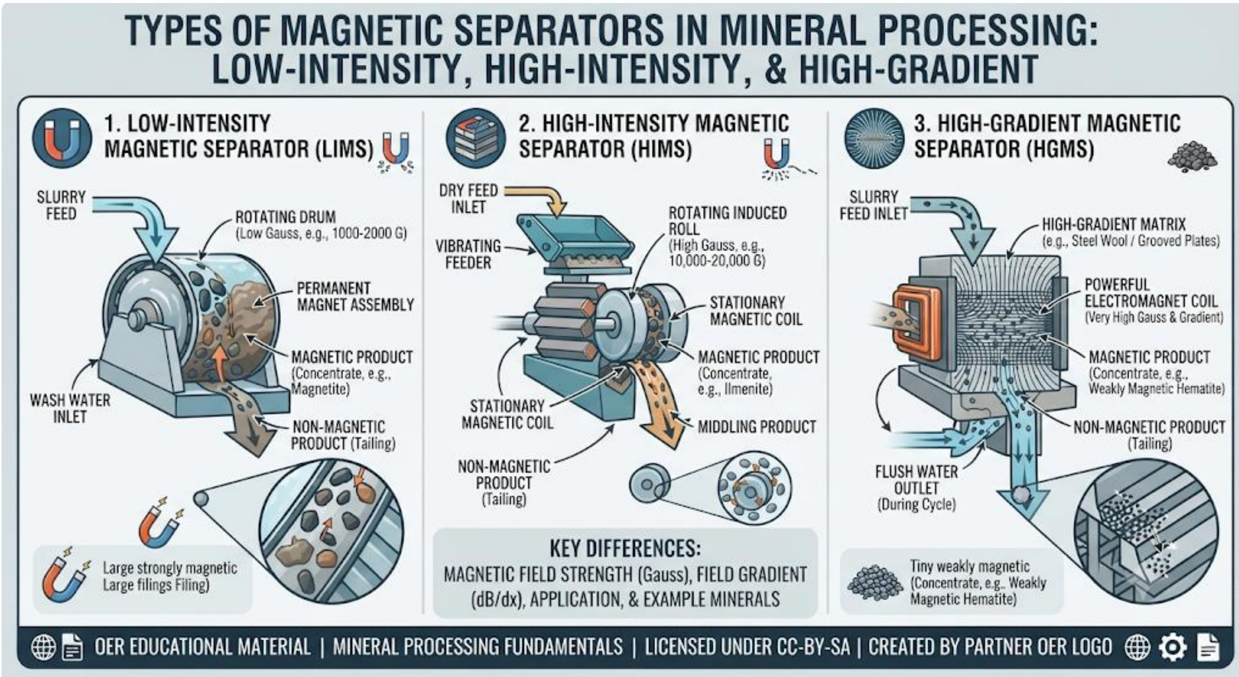
### 3.3.2 Types of magnetic separators

There are several types of magnetic separators:

- **Low-intensity magnetic separators (LIMS)**: Used for strongly magnetic minerals such as magnetite.
- **High-intensity magnetic separators (HIMS)**: Used for weakly magnetic minerals such as hematite.
- **High-gradient magnetic separators (HGMS)**: Employ fine wires to generate strong localised fields for very weakly magnetic minerals.

Each type is suited to specific ore types and particle sizes.

Fill in the blank: High-gradient magnetic separators employ fine ______ to generate strong localised fields.

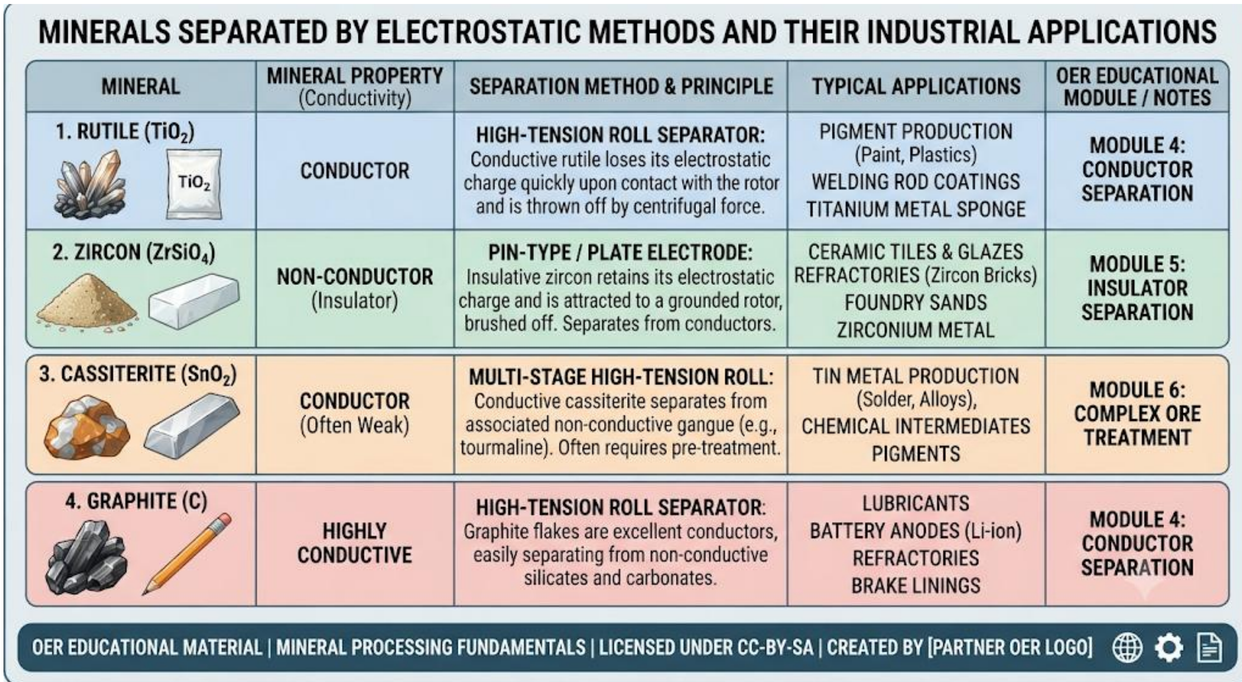



Photographs of LIMS, HIMS, and HGMS equipment *Plate 3.3: Types of magnetic separators*

### 3.3.3 Principles of electrostatic separation and applications

**Electrostatic separation** exploits differences in electrical conductivity between minerals. When particles are passed through an electric field, conductive minerals lose their charge quickly and are repelled, while non-conductive minerals retain charge and are attracted. This method is particularly useful for separating minerals such as rutile, zircon, and cassiterite. Electrostatic separation is often applied in dry processing environments.

Fill in the blank: Electrostatic separation exploits differences in mineral electrical ______.



MINERALS SEPARATED BY ELECTROSTATIC METHODS AND THEIR INDUSTRIAL APPLICATIONS

| MINERAL | MINERAL PROPERTY (Conductivity) | SEPARATION METHOD & PRINCIPLE | TYPICAL APPLICATIONS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. RUTILE ($TiO_2$) | CONDUCTOR | HIGH-TENSION ROLL SEPARATOR: Conductive rutile loses its electrostatic charge quickly upon contact with the rotor and is thrown off by centrifugal force. | PIGMENT PRODUCTION (Paint, Plastics) WELDING ROD COATINGS TITANIUM METAL SPONGE | MODULE 4: CONDUCTOR SEPARATION |
| 2. ZIRCON ($ZrSiO_4$) | NON-CONDUCTOR (Insulator) | PIN-TYPE / PLATE ELECTRODE: Insulative zircon retains its electrostatic charge and is attracted to a grounded rotor, brushed off. Separates from conductors. | CERAMIC TILES & GLAZES REFRACTORIES (Zircon Bricks) FOUNDRY SANDS ZIRCONIUM METAL | MODULE 5: INSULATOR SEPARATION |
| 3. CASSITERITE ($SnO_2$) | CONDUCTOR (Often Weak) | MULTI-STAGE HIGH-TENSION ROLL: Conductive cassiterite separates from associated non-conductive gangue (e.g., tourmaline). Often requires pre-treatment. | TIN METAL PRODUCTION (Solder, Alloys), CHEMICAL INTERMEDIATES PIGMENTS | MODULE 6: COMPLEX ORE TREATMENT |
| 4. GRAPHITE (C) | HIGHLY CONDUCTIVE | HIGH-TENSION ROLL SEPARATOR: Graphite flakes are excellent conductors, easily separating from non-conductive silicates and carbonates. | LUBRICANTS BATTERY ANODES (Li-ion) REFRACTORIES BRAKE LININGS | MODULE 4: CONDUCTOR SEPARATION |



Box 3.3: Applications of electrostatic separation

**Pilot questions 3.3**

1. Define magnetic separation and explain its principle.
2. Name three types of magnetic separators.
3. Which minerals are commonly separated using low-intensity magnetic separators?
4. Explain the principle of electrostatic separation.
5. State one mineral that can be separated using electrostatic methods.

## 3.4 Flotation Techniques

### 3.4.1 Principles of flotation and reagents

**Flotation** is a separation technique that exploits differences in surface chemistry between minerals. Valuable minerals are made hydrophobic (water-repelling) by reagents, allowing them to attach to air bubbles and float, while gangue remains hydrophilic and sinks. Reagents include collectors (which modify mineral surfaces), frothers (which stabilize bubbles), and modifiers (which control selectivity).

Fill in the blank: In flotation, valuable minerals attach to ______ bubbles and float.

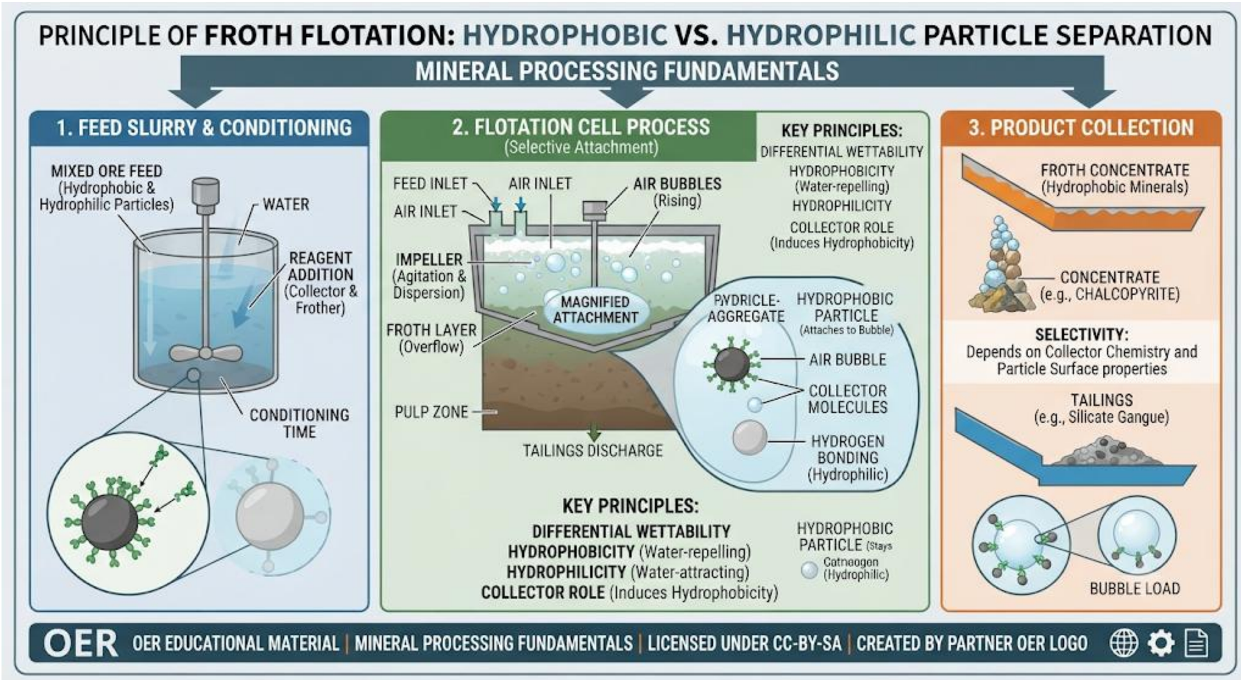
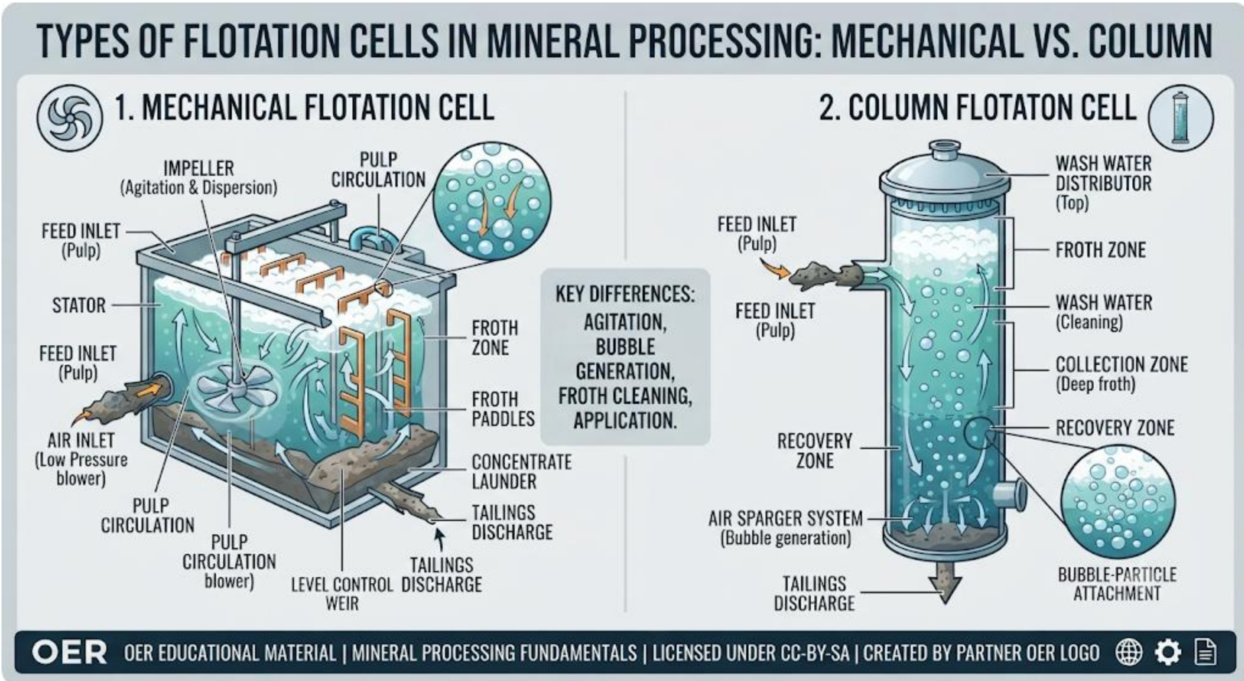



Diagram showing hydrophobic particles attaching to bubbles and floating, while hydrophilic particles sink *Figure 3.4: Principle of flotation separation*

### 3.4.2 Flotation cells and circuits

Flotation is carried out in **flotation cells**, which are tanks where air is introduced to create bubbles. Mechanical cells use impellers to disperse air, while column cells rely on natural air dispersion and are more efficient for fine particles. Flotation circuits may be simple (single stage) or complex (multi-stage cleaning and scavenging). Circuit design depends on ore type and desired product quality.

Fill in the blank: Column flotation cells are especially efficient for separating very ______ particles.




Photographs of mechanical flotation cell and column flotation cell *Plate 3.4: Types of flotation cells used in mineral processing*

### 3.4.3 Industrial applications and challenges

Flotation is widely applied in the beneficiation of sulphide ores (e.g., copper, lead, zinc) and in the recovery of precious metals. It is also used in coal cleaning and phosphate processing. However, challenges include reagent costs, environmental concerns, and difficulties in treating very fine or complex ores. Engineers must balance efficiency, cost, and sustainability when applying flotation.

Fill in the blank: Flotation is widely applied in the beneficiation of ______ ores such as copper and zinc.

**APPLICATIONS AND CHALLENGES OF FROTH FLOTATION IN MINERAL PROCESSING**

| CATEGORY | SPECIFIC APPLICATION / CHALLENGE | DESCRIPTION / MECHANISM | MINERAL / MATERIAL EXAMPLES & PROCESS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. APPLICATIONS | 1.1 SULPHIDE ORES (e.g., Copper, Lead, Zinc) | Selective separation of valuable sulphide minerals from gangue (silicates, carbonate) on natural hydrophobicity or induced by collectors. | CHALCOPYRITE ($CuFeS_2$), GALENA ($PbS$), SPHALERITE ($ZnS$) Process: Grinding, pH adjustment, collectors (Xanthates), frothers. | MODULE 6: SULPHIDE FLOTATION |
| | 1.2 COAL BENEFICIATION | Selective removal of ash-forming minerals and pyritic sulfur from fine coal to increase calorific value. | BITUMINOUS COAL, ANTHRACITE Process: Oil agglomeration (sometimes), collectors (Kerosene/Diesel), frothers (MIBC). | MODULE 7: COAL FLOTATION |
| | 1.3 PHOSPHATE ROCK PROCESSING | Separation of phosphate minerals (Apatite) from siliceous (sand) or calcareous (limestone) gangue. | APATITE ($Ca_3(PO_4)_3(F,Cl,OH)$) Process: Reverse flotation (silicate/calcite floats, phosphate sinks), fatty acid collectors. | MODULE 8: INDUSTRIAL MINERALS FLOTATION |
| 2. CHALLENGES | | | | |
| | 2.1 REAGENT COST & CONSUMPTION | Significant operational cost due to the high volume of collectors, frothers, depressants, and activators required. | Cost optimization vs. recovery/grade. Finding cost-effective, biodegradable alternatives. | MODULE 9: REAGENT ECONOMICS |
| | 2.2 ENVIRONMENTAL IMPACT | Management of tailings storage facilities (TSF) and potential contamination from residual flotation reagents in process water. | Water recycling, detoxification of effluents, reducing reagent footprint. Regulatory compliance. | MODULE 10: ENVIRONMENTAL SUSTAINABILITY |
| | 2.3 FINE ORE TREATMENT (SLIMES) | Inefficiency of flotation for ultra-fine particles (<10-20 μm) due to low collision probability and high reagent consumption. | High specific surface area, excessive water drag, non-selective bubble attachment. Requires specialized techniques (e.g., carrier flotation, Jameson cell). | MODULE 11: FINE PARTICLE PROCESSING |



Box 3.4: Applications and challenges of flotation

**Pilot questions 3.4**

1. Define flotation and explain its principle.
2. Name three types of flotation reagents and their functions.
3. Which flotation cell type is more efficient for fine particles?
4. State one industrial application of flotation.
5. What is one challenge associated with flotation processes?

### 3.5 Emerging and Specialised Separation Methods

#### 3.5.1 Advances in sensor-based sorting

**Sensor-based sorting** uses modern technologies such as X-ray transmission (XRT), near-infrared (NIR), and optical sensors to detect differences in mineral properties. Particles are scanned as they pass through the system, and automated jets or mechanical devices separate valuable minerals from waste. This method is efficient, reduces processing costs, and minimises environmental impact by rejecting waste early.

Fill in the blank: Sensor-based sorting uses modern ______ to detect differences in mineral properties.

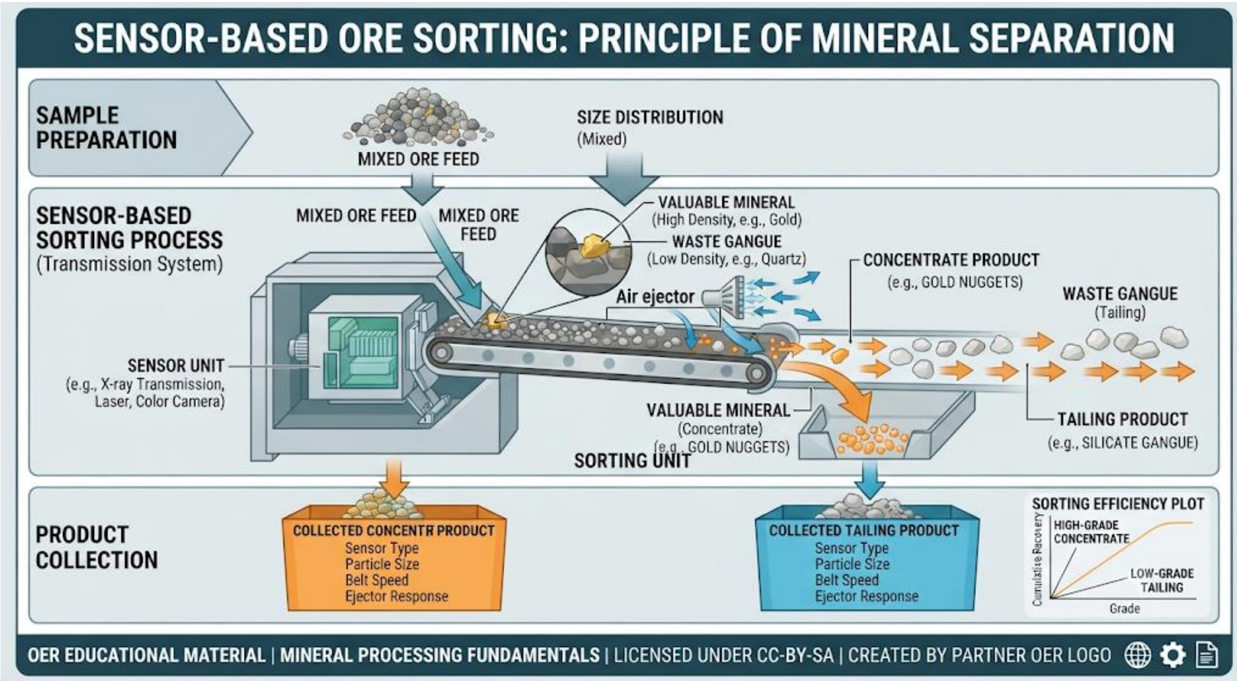
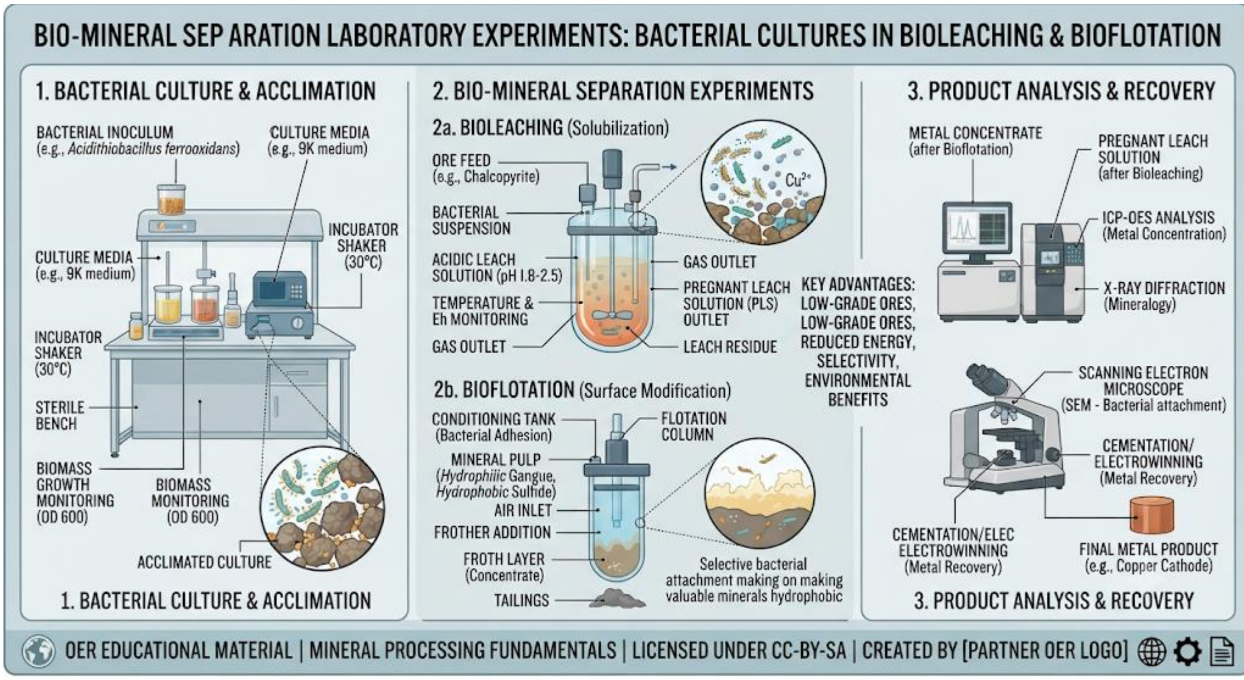


Diagram showing ore particles passing through a sensor-based sorter with valuable minerals separated from waste *Figure 3.5: Principle of sensor-based sorting*

### 3.5.2 Bio-mineral separation approaches

**Bio-mineral separation** applies biological agents such as bacteria, fungi, or biomolecules to modify mineral surfaces and enhance separation. For example, certain bacteria can selectively attach to sulphide minerals, making them more amenable to flotation. This approach is environmentally friendly and offers potential for treating complex ores that are difficult to process using conventional methods.

Fill in the blank: Bio-mineral separation uses biological ______ to modify mineral surfaces and enhance separation.

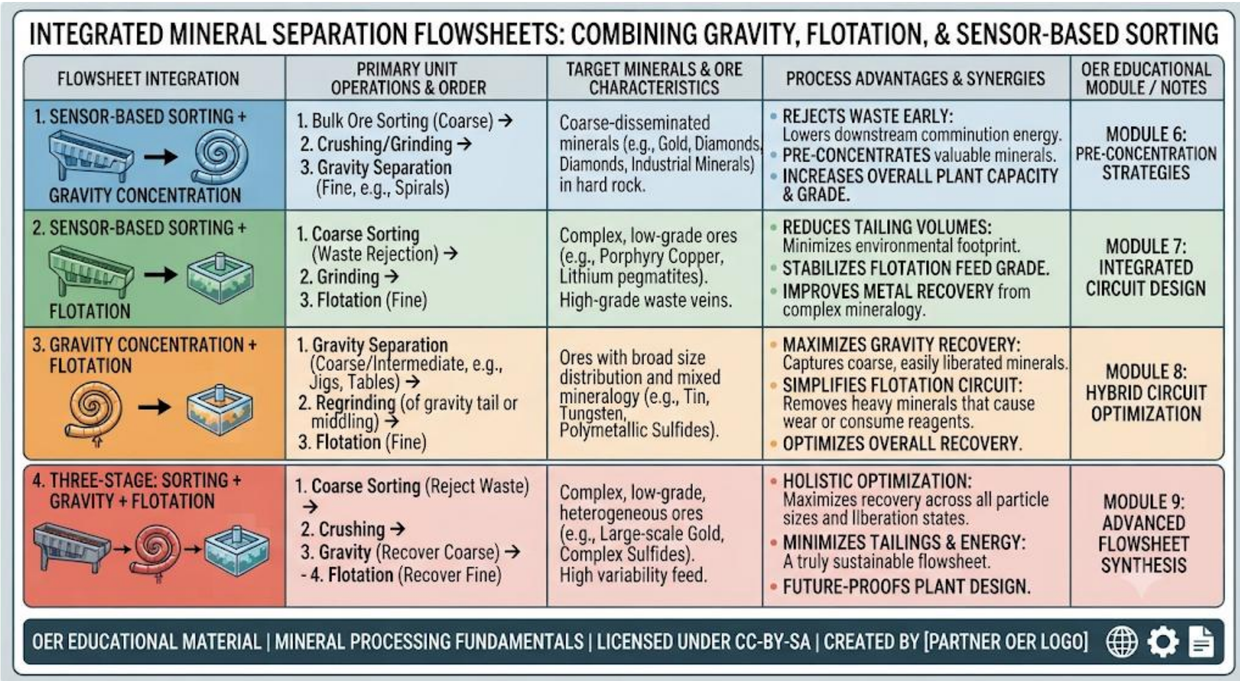


Photograph of laboratory setup for bio-mineral separation experiments *Plate 3.5: Laboratory research in bio-mineral separation*

### 3.5.3 Integration of separation methods in modern flowsheets

Modern mineral processing flowsheets often integrate multiple separation methods to maximise recovery and efficiency. For example, gravity separation may be used first to recover coarse dense minerals, followed by flotation for fine particles, and sensor-based sorting to remove waste. Integration ensures that each method complements the others, resulting in higher product quality and reduced costs.

Fill in the blank: Modern mineral processing flowsheets often integrate multiple ______ methods to maximise recovery.



INTEGRATED MINERAL SEPARATION FLOWSHEETS: COMBINING GRAVITY, FLOTATION, & SENSOR-BASED SORTING

| FLOWSHEET INTEGRATION | PRIMARY UNIT OPERATIONS & ORDER | TARGET MINERALS & ORE CHARACTERISTICS | PROCESS ADVANTAGES & SYNERGIES | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. SENSOR-BASED SORTING + GRAVITY CONCENTRATION | 1. Bulk Ore Sorting (Coarse) → 2. Crushing/Grinding → 3. Gravity Separation (Fine, e.g., Spirals) | Coarse-disseminated minerals (e.g., Gold, Diamonds, Diamonds, Industrial Minerals) in hard rock. | • REJECTS WASTE EARLY: Lowers downstream comminution energy. • PRE-CONCENTRATES valuable minerals. • INCREASES OVERALL PLANT CAPACITY & GRADE. | MODULE 6: PRE-CONCENTRATION STRATEGIES |
| 2. SENSOR-BASED SORTING + FLOTATION | 1. Coarse Sorting (Waste Rejection) → 2. Grinding → 3. Flotation (Fine) | Complex, low-grade ores (e.g., Porphyry Copper, Lithium pegmatites). High-grade waste veins. | • REDUCES TAILING VOLUMES: Minimizes environmental footprint. • STABILIZES FLOTATION FEED GRADE. • IMPROVES METAL RECOVERY from complex mineralogy. | MODULE 7: INTEGRATED CIRCUIT DESIGN |
| 3. GRAVITY CONCENTRATION + FLOTATION | 1. Gravity Separation (Coarse/Intermediate, e.g., Jigs, Tables) → 2. Regrinding (of gravity tail or middling) → 3. Flotation (Fine) | Ores with broad size distribution and mixed mineralogy (e.g., Tin, Tungsten, Polymetallic Sulfides). | • MAXIMIZES GRAVITY RECOVERY: Captures coarse, easily liberated minerals. • SIMPLIFIES FLOTATION CIRCUIT: Removes heavy minerals that cause wear or consume reagents. • OPTIMIZES OVERALL RECOVERY. | MODULE 8: HYBRID CIRCUIT OPTIMIZATION |
| 4. THREE-STAGE: SORTING + GRAVITY + FLOTATION | 1. Coarse Sorting (Reject Waste) → 2. Crushing → 3. Gravity (Recover Coarse) → - 4. Flotation (Recover Fine) | Complex, low-grade, heterogeneous ores (e.g., Large-scale Gold, Complex Sulfides). High variability feed. | • HOLISTIC OPTIMIZATION: Maximizes recovery across all particle sizes and liberation states. • MINIMIZES TAILINGS & ENERGY: A truly sustainable flowsheet. • FUTURE-PROOFS PLANT DESIGN. | MODULE 9: ADVANCED FLOWSHEET SYNTHESIS |

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Box 3.5: Examples of integrated mineral separation flowsheets

**Pilot questions 3.5**

1. Define sensor-based sorting and explain its principle.
2. Name two types of sensors used in mineral sorting.
3. What biological agents are used in bio-mineral separation?
4. State one advantage of bio-mineral separation.
5. Why is integration of separation methods important in modern flowsheets?

**Series Summary**

This Series has examined the major **mineral separation techniques** used in mineral processing. We began with the principles of separation, focusing on the physical and chemical properties that influence method selection. We then studied gravity separation methods and their equipment, followed by magnetic and electrostatic separation techniques. Next, we explored flotation, which is widely applied for fine particles, and finally we looked at emerging and specialised methods such as sensor-based sorting and bio-mineral approaches.

By completing this Series, you should now be able to explain the principles of mineral separation, describe and evaluate gravity, magnetic, electrostatic, and flotation methods, and assess the role of emerging technologies in modern flowsheets. These skills align directly with the Series Learning Outcomes and provide a comprehensive foundation for understanding mineral beneficiation.

**Glossary of Terms**

- **Collector**: A flotation reagent that modifies mineral surfaces to make them hydrophobic.
- **Cyclone**: A classifier that separates particles using centrifugal force.
- **Electrostatic separation**: A technique exploiting differences in electrical conductivity between minerals.
- **Flotation**: A separation method based on differences in surface chemistry, using air bubbles.
- **Frother**: A flotation reagent that stabilises bubbles.
- **Gravity separation**: A method exploiting differences in mineral density.
- **Jig**: Gravity separation equipment using pulsating water currents.
- **Magnetic separation**: A method exploiting differences in magnetic susceptibility.
- **Sensor-based sorting**: Modern separation using sensors such as XRT or NIR to detect mineral properties.
- **Spiral concentrator**: Gravity separation equipment using a helical trough.

**Concept Check Questions [Series 3]**

**Objective questions**

1. What property is exploited in gravity separation? (Linked to SLO 3.2)
2. Which flotation reagent stabilises bubbles? (Linked to SLO 3.4)
3. Sensor-based sorting uses modern ______ to detect mineral properties. (Linked to SLO 3.5)

**Short-answer questions**

4. Explain the difference between magnetic and electrostatic separation. (Linked to SLO 3.3)
5. State one limitation of gravity separation. (Linked to SLO 3.2)
6. Give one example of an emerging separation method. (Linked to SLO 3.5)

**Long-answer questions**

7. Analyse how flotation reagents (collectors, frothers, modifiers) contribute to successful mineral separation. (Linked to SLO 3.4)
8. Evaluate the role of integrating multiple separation methods in modern flowsheets. (Linked to SLO 3.5)

**Answers to Concept Check Questions [Series 3]**

**Objective questions**

1. Density.
2. Frother.
3. Sensors.

**Short-answer questions**

4. Magnetic separation exploits magnetic susceptibility, while electrostatic separation exploits electrical conductivity.
5. Gravity separation is less effective for very fine particles.
6. Sensor-based sorting or bio-mineral separation.

**Long-answer questions**

7. **Basic response**: Collectors make minerals hydrophobic, frothers stabilise bubbles, and modifiers control selectivity. **Value-added response**: Outstanding learners may discuss how reagent combinations are tailored to ore mineralogy, balancing recovery and selectivity, and how reagent costs and environmental impacts influence industrial practice.
8. **Basic response**: Integration ensures each method complements the others, improving recovery. **Value-added response**: Outstanding learners may evaluate how flowsheets combining gravity, flotation, and sensor-based sorting reduce energy consumption, enhance product quality, and support sustainable mineral processing.

**Answers to Pilot Questions [Series 3]**

1. Mineral separation exploits differences in physical or chemical properties.
2. Density, magnetism, conductivity, surface chemistry.
3. Surface chemistry.
4. Ore characteristics, particle size, economic factors.
5. Mineralogy determines which properties can be exploited.
6. Gravity separation exploits density differences.
7. Jigs, shaking tables, spirals.
8. Jigs.
9. Gold, tin, iron ores.
10. Fine particles reduce efficiency.
11. Magnetic separation exploits magnetic susceptibility.

12. LIMS, HIMS, HGMS.
13. Magnetite.
14. Electrostatic separation exploits conductivity differences.
15. Rutile, zircon, cassiterite.
16. Flotation exploits surface chemistry differences.
17. Collectors, frothers, modifiers.
18. Column cells.
19. Sulphide ores (copper, zinc, lead).
20. Reagent costs, environmental concerns.
21. Sensor-based sorting uses sensors to detect mineral properties.
22. XRT, NIR.
23. Bacteria, fungi, biomolecules.
24. Environmentally friendly.
25. Integration improves recovery and efficiency.

**References and Attributions [Series 3]**

- Figure 3.1: Principles of mineral separation. Suggested AI prompt: “Create a labelled diagram showing mineral separation based on density, magnetism, and surface chemistry.” Search string: “principles of mineral separation diagram OER.”
- Table 3.1: Properties influencing mineral separation. Suggested AI prompt: “Create a table listing density, magnetism, conductivity, and surface chemistry with their corresponding separation techniques.” Search string: “properties influencing mineral separation table OER.”
- Box 3.1: Criteria for selecting mineral separation methods. Suggested AI prompt: “Create a table listing ore mineralogy, particle size, cost-effectiveness, and environmental sustainability.” Search string: “criteria for selecting mineral separation methods table OER.”
- Figure 3.2: Principle of gravity concentration. Suggested AI prompt: “Create a labelled diagram showing dense particles settling faster than lighter particles in water.” Search string: “principle of gravity concentration diagram OER.”
- Plate 3.2: Gravity separation equipment. Suggested AI prompt: “Generate images of jig, shaking table, and spiral concentrator.” Search string: “jig shaking table spiral concentrator mineral processing OER.”

- Box 3.2: Applications and limitations of gravity separation. Suggested AI prompt: "Create a table listing applications (gold, tin, iron) and limitations (fine particles, similar densities)." Search string: "applications limitations gravity separation table OER."
- Figure 3.3: Principle of magnetic separation. Suggested AI prompt: "Create a labelled diagram showing magnetic particles attracted to a drum." Search string: "principle of magnetic separation diagram OER."
- Plate 3.3: Types of magnetic separators. Suggested AI prompt: "Generate images of LIMS, HIMS, and HGMS." Search string: "types of magnetic separators mineral processing OER."
- Box 3.3: Applications of electrostatic separation. Suggested AI prompt: "Create a table listing minerals separated by electrostatic methods such as rutile, zircon, cassiterite." Search string: "applications of electrostatic separation mineral processing table OER."
- Figure 3.4: Principle of flotation. Suggested AI prompt: "Create a labelled diagram showing hydrophobic particles attaching to bubbles." Search string: "principle of flotation mineral processing diagram OER."
- Plate 3.4: Types of flotation cells. Suggested AI prompt: "Generate images of mechanical and column flotation cells." Search string: "mechanical flotation cell column flotation cell mineral processing OER."
- Box 3.4: Applications and challenges of flotation. Suggested AI prompt: "Create a table listing applications (sulphide ores, coal, phosphate) and challenges (reagent cost, environmental impact)." Search string: "applications challenges flotation mineral processing table OER."
- Figure 3.5: Principle of sensor-based sorting. Suggested AI prompt: "Create a labelled diagram showing ore particles passing through a sensor-based sorter." Search string: "sensor-based sorting mineral processing diagram OER."
- Plate 3.5: Laboratory research in bio-mineral separation. Suggested AI prompt: "Generate an image of laboratory setup showing bio-mineral separation experiments." Search string: "bio-mineral separation laboratory experiments OER."
- Box 3.5: Integrated mineral separation flowsheets. Suggested AI prompt: "Create a table showing flowsheets combining gravity, flotation, and sensor-based sorting." Search string: "integrated mineral separation flowsheets examples table OER."

## Series 4: Hydrometallurgical and Biological Recovery

**Series outline**

- **4.1 Principles of hydrometallurgy**
  - 4.1.1 Fundamentals of aqueous processing
  - 4.1.2 Leaching mechanisms and kinetics
  - 4.1.3 Factors influencing hydrometallurgical recovery
- **4.2 Leaching techniques**
  - 4.2.1 Heap leaching
  - 4.2.2 Tank leaching
  - 4.2.3 In-situ leaching
- **4.3 Solution purification and metal recovery**
  - 4.3.1 Solvent extraction
  - 4.3.2 Ion exchange
  - 4.3.3 Electrowinning and precipitation
- **4.4 Biological recovery methods**
  - 4.4.1 Bioleaching principles
  - 4.4.2 Microorganisms used in bioleaching
  - 4.4.3 Applications and limitations of biological recovery
- **4.5 Integration and sustainability**
  - 4.5.1 Combining hydrometallurgical and biological methods
  - 4.5.2 Environmental considerations and waste management
  - 4.5.3 Future trends in sustainable recovery

**Introduction**

Hydrometallurgy is a branch of extractive metallurgy that uses aqueous solutions to recover metals from ores, concentrates, and recycled materials. It is widely applied in the production of copper, gold, uranium, and other metals. Biological recovery, often referred to as biohydrometallurgy, complements hydrometallurgy by using microorganisms to enhance leaching and metal extraction. Together, these approaches provide environmentally friendly alternatives to traditional pyrometallurgical methods.

The aim of this Series is to provide you with a clear understanding of hydrometallurgical and biological recovery techniques. You will learn the principles of aqueous processing, leaching methods, solution purification, and metal recovery. In addition, you will explore how microorganisms contribute to bioleaching, and how these processes can be integrated to achieve sustainable mineral recovery.

We shall begin with the principles of hydrometallurgy, focusing on leaching mechanisms and influencing factors. Next, we will study leaching techniques such as heap, tank, and in-situ leaching. We will then examine solution purification and metal recovery methods, including solvent extraction, ion exchange, and electrowinning. Following this, we will explore biological recovery methods, highlighting bioleaching principles and applications. Finally, we will conclude with integration and sustainability, considering environmental impacts and future trends in mineral recovery.

**Series Learning Outcomes**

Upon completing **Series 4: Hydrometallurgical and Biological Recovery**, you should be able to:

- **SLO 4.1** explain the fundamental principles of hydrometallurgy, including aqueous processing, leaching mechanisms, and factors influencing recovery,
- **SLO 4.2** describe and compare leaching techniques such as heap, tank, and in-situ leaching, and evaluate their applications,
- **SLO 4.3** analyse solution purification and metal recovery methods, including solvent extraction, ion exchange, electrowinning, and precipitation,
- **SLO 4.4** demonstrate understanding of biological recovery methods, including bioleaching principles, microorganisms involved, and industrial applications,
- **SLO 4.5** evaluate the integration of hydrometallurgical and biological methods, considering environmental sustainability, waste management, and future trends in mineral recovery.

## 4.1 Principles of Hydrometallurgy

### 4.1.1 Fundamentals of aqueous processing

**Hydrometallurgy** is the recovery of metals from ores, concentrates, or recycled materials using aqueous solutions. The process typically involves three stages: leaching (dissolving the metal into solution), solution purification (removing impurities), and metal recovery (precipitating or electrowinning the metal). It is widely used for copper, gold, uranium, and zinc.

Fill in the blank: Hydrometallurgy recovers metals using ______ solutions.

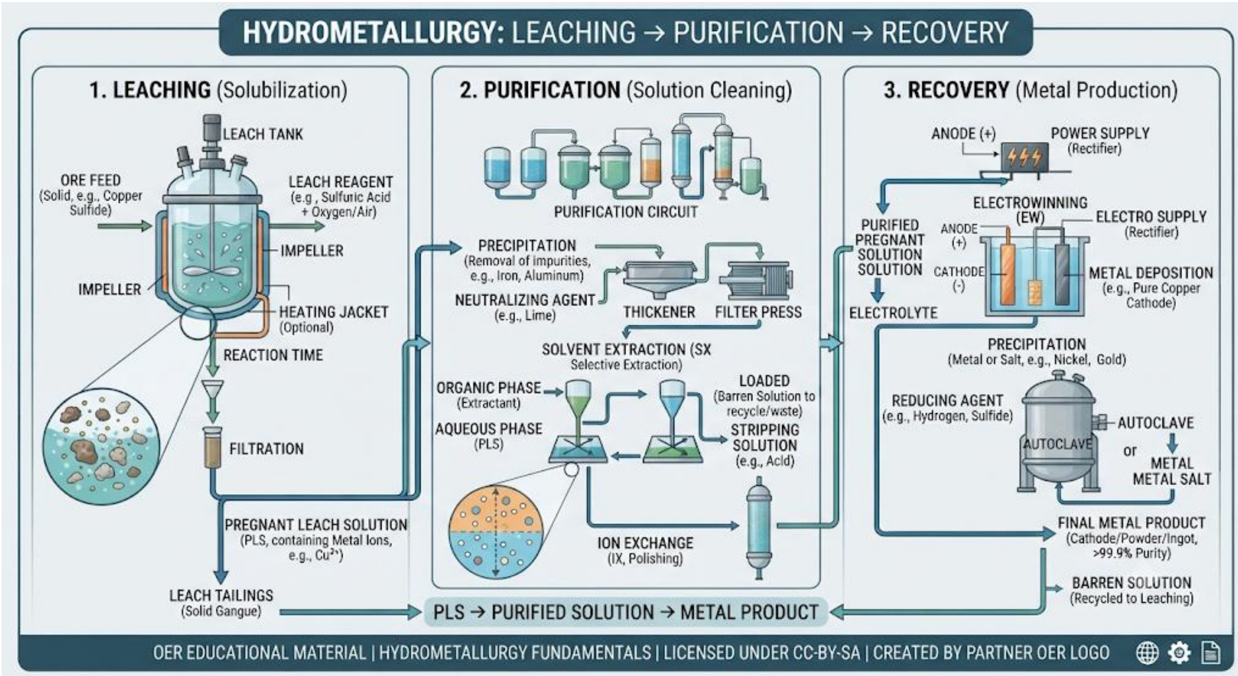



Diagram showing the three stages of hydrometallurgy: leaching, purification, recovery *Figure 4.1: Fundamental stages of hydrometallurgy*

### 4.1.2 Leaching mechanisms and kinetics

**Leaching** is the process of dissolving metals into solution using chemical reagents such as acids, bases, or cyanide. The rate of leaching depends on factors such as reagent concentration, temperature, particle size, and agitation. Kinetics are often controlled by diffusion through particle boundaries or chemical reaction rates.

Fill in the blank: The rate of leaching depends on reagent concentration, temperature, particle size, and ______.

**FACTORS INFLUENCING LEACHING KINETICS IN HYDROMETALLURGY**

| FACTOR | DESCRIPTION & MECHANISM | EFFECT ON LEACHING RATE (Kinetics) | CONSIDERATIONS & TRADE-OFFS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. REAGENT CONCENTRATION | Amount of active reagent (e.g., $H_2SO_4$, NaOH, NaCN) per unit volume of solution. Affects chemical reaction rate at the surface. | **INCREASES RATE:** Higher concentration generally leads to more frequent collisions between reagent and mineral surface (proportional to $C^n$). | Optimum concentration exists; too high may cause side reactions, passivation, or high reagent cost. Mass transfer limits can dominate. | MODULE 4: LEACHING CHEMISTRY |
| 2. TEMPERATURE | Measure of thermal energy. Increases kinetic energy of molecules and lowers activation energy barrier (Arrhenius equation) | **INCREASES RATE:** Significant exponential increase with temperature ($k = Ae^{-Ea/RT}$). | High temperatures require more energy (heating costs), can increase corrosion, and may cause unwanted precipitation or reagent degradation. | MODULE 5: TEMPERATURE EFFECTS |
| 3. PARTICLE SIZE DISTRIBUTION | Size range of ore particles. Determines the available reactive surface area per unit mass (Specific Surface Area ∝ 1/d). | **INCREASES RATE** (with finer size): Larger surface area allows more simultaneous reactions (shrinking core model). | Requires more energy for grinding (comminution costs). Very fine particles can cause solid-liquid separation problems (slimes) or reagent loss. | MODULE 3: ORE CHARACTERIZATION |
| 4. AGITATION (Mixing Intensity) | Degree of mixing of the pulp (solid-liquid slurry). Controls mass transfer of reagent to the particle surface and products away. | **INCREASES RATE** (up to a limit): Enhances diffusion through the liquid boundary layer and keeps particles suspended. | Excessive agitation wastes energy (power costs) and can cause particle attrition or equipment wear. | MODULE 6: MASS TRANSFER |



Table 4.1: Factors influencing leaching kinetics

### 4.1.3 Factors influencing hydrometallurgical recovery

The efficiency of hydrometallurgical recovery depends on ore mineralogy, reagent choice, operating conditions, and environmental considerations. For example, sulphide ores may require oxidation before leaching, while refractory ores may need pretreatment. Engineers must balance recovery rates with cost and sustainability.

Fill in the blank: The efficiency of hydrometallurgical recovery depends on ore mineralogy, reagent choice, operating conditions, and ______ considerations.

## FACTORS INFLUENCING HYDROMETALLURGICAL RECOVERY

| FACTOR | DESCRIPTION & MECHANISM | IMPACT ON RECOVERY & EFFICIENCY | CONSIDERATIONS & TRADE-OFFS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|
| 1. ORE MINERALOGY | Type of valuable mineral (e.g., sulfide, oxide, native) and associated gangue (host rock, deleterious elements). Determines liberation and reactivity. | DIRECTLY CONTROLS ULTIMATE RECOVERY: Determines the amenability to specific leaching agents and the extent of mineral dissolution. | Complex mineralogy (e.g., refractory gold) requires pre-treatment (roasting, autoclave). Deleterious elements (As, Sb) consume reagents or poison solutions. | MODULE 3: ORE CHARACTERIZATION |
| 2. REAGENT CHOICE (Lixiviant & Additives) | Type and concentration of the chemical agent (e.g., Sulfuric Acid, Cyanide, Ammonia) used to dissolve the valuable metal. Includes oxidants, pH modifiers. | DEFINES SELECTIVITY & KINETICS: The right reagent ensures high dissolution rate of the target metal while minimizing gangue dissolution. | Reagent cost is a major factor. Toxicity (e.g., cyanide) requires strict environmental control. Oxidation potential (Eh) and pH must be optimized. | MODULE 4: LEACHING CHEMISTRY |
| 3. OPERATING CONDITIONS (Temperature, Pressure, Agitation) | Physical parameters of the leaching process. Temperature affects reaction rate (Arrhenius); Pressure enables high-temperature leaching; Agitation controls mass transfer. | OPTIMIZES KINETICS & YIELD: High T/P increases reaction rate but also energy costs. Proper agitation ensures uniform reaction. | High T/P requires robust equipment (autoclaves) and higher energy input. Excessive agitation wastes power and causes attrition. | MODULE 5: PROCESS OPTIMIZATION |
| 4. ENVIRONMENTAL CONSIDERATIONS | Management of process waste (tailings, effluents, gases). Includes recycling, detoxification, and regulatory compliance. | ENSURES SUSTAINABILITY & SOCIAL LICENSE: Proper waste management prevents environmental contamination and maintains operational legality. | Cost of effluent treatment (e.g., cyanide detoxification, acid neutralization) is significant. Strict regulations must be met to avoid fines and shutdowns. | MODULE 6: ENVIRONMENTAL SUSTAINABILITY |



Box 4.1: Key factors influencing hydrometallurgical recovery

**Pilot questions 4.1**

1. Define hydrometallurgy and state its three main stages.
2. What is leaching in hydrometallurgy?
3. Name four factors influencing leaching kinetics.
4. Why might sulphide ores require oxidation before leaching?
5. State one environmental consideration in hydrometallurgical recovery.

### 4.2 Leaching Techniques

#### 4.2.1 Heap leaching

**Heap leaching** involves stacking crushed ore on impermeable pads and irrigating it with leaching solutions (e.g., cyanide for gold, acid for copper). The solution percolates through the heap, dissolving metals, which are then collected at the base. Heap leaching is cost-effective and suitable for low-grade ores, though it requires large areas and careful environmental management.

Fill in the blank: Heap leaching is especially suitable for processing ______-grade ores.

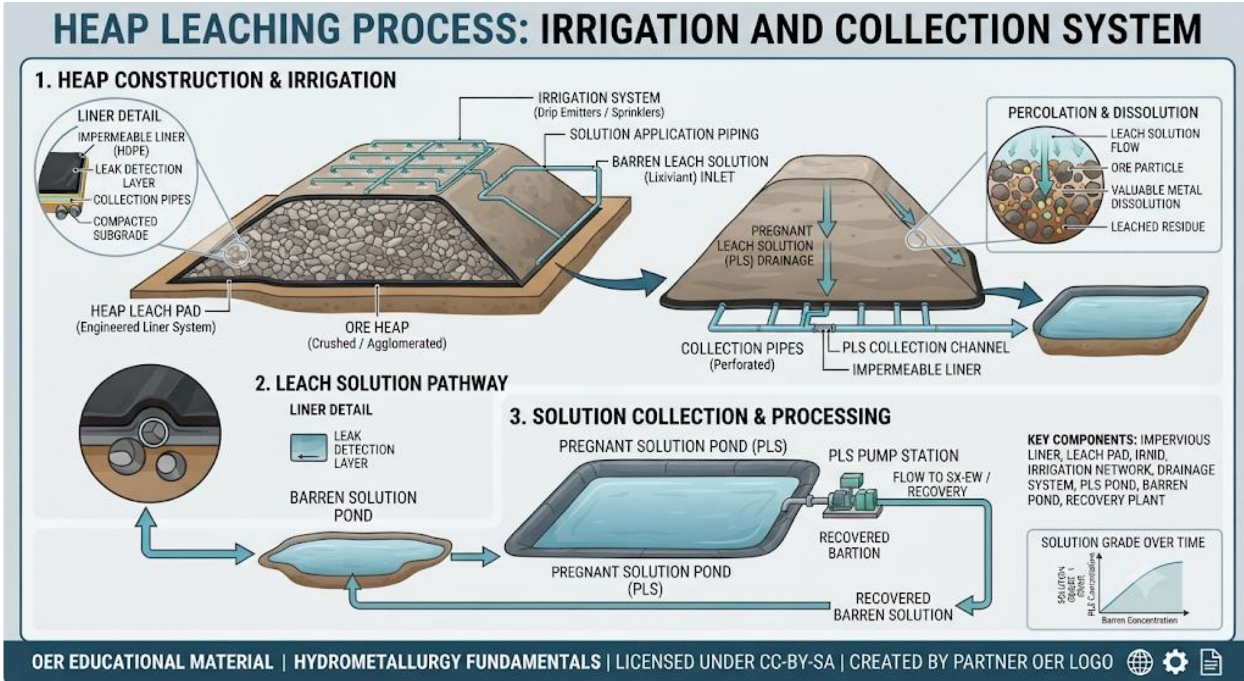
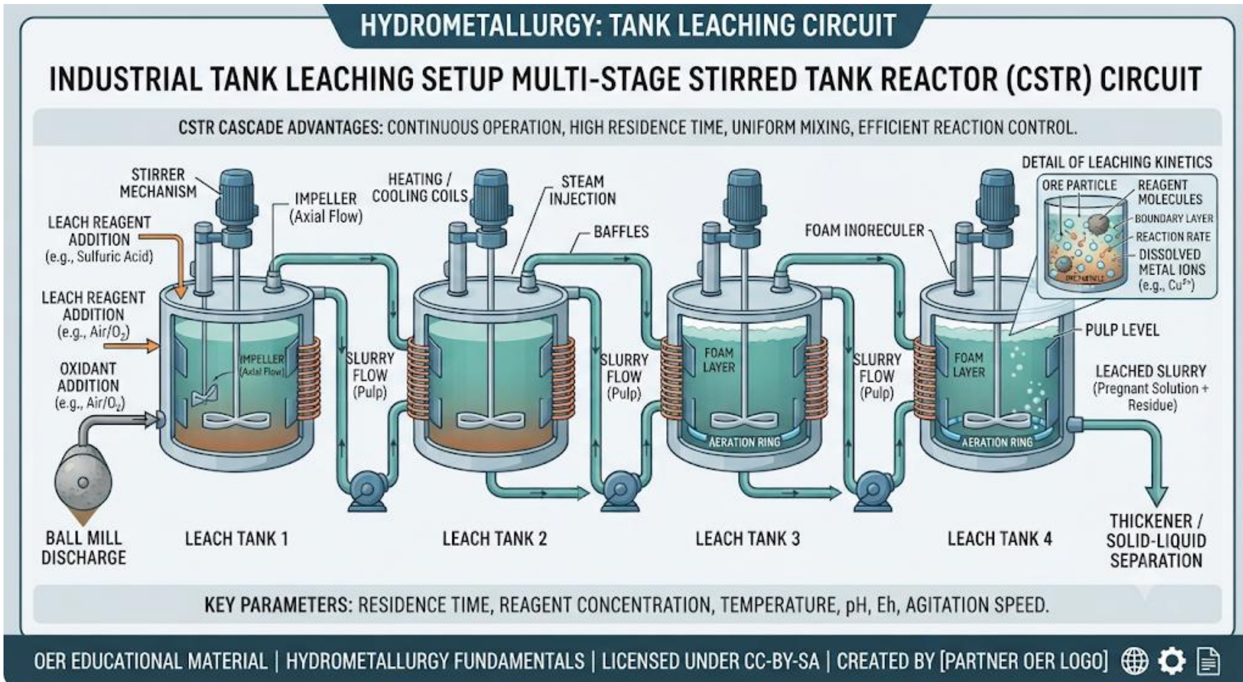


Diagram showing ore heaps irrigated with leaching solution and collection at the base *Figure 4.2: Principle of heap leaching*

### 4.2.2 Tank leaching

**Tank leaching** is carried out in large, controlled tanks where finely ground ore is mixed with leaching solutions under agitation. This method allows precise control of temperature, reagent concentration, and reaction time, leading to higher recovery rates. Tank leaching is commonly used for gold and uranium ores.

Fill in the blank: Tank leaching allows precise control of temperature, reagent concentration, and ______ time.

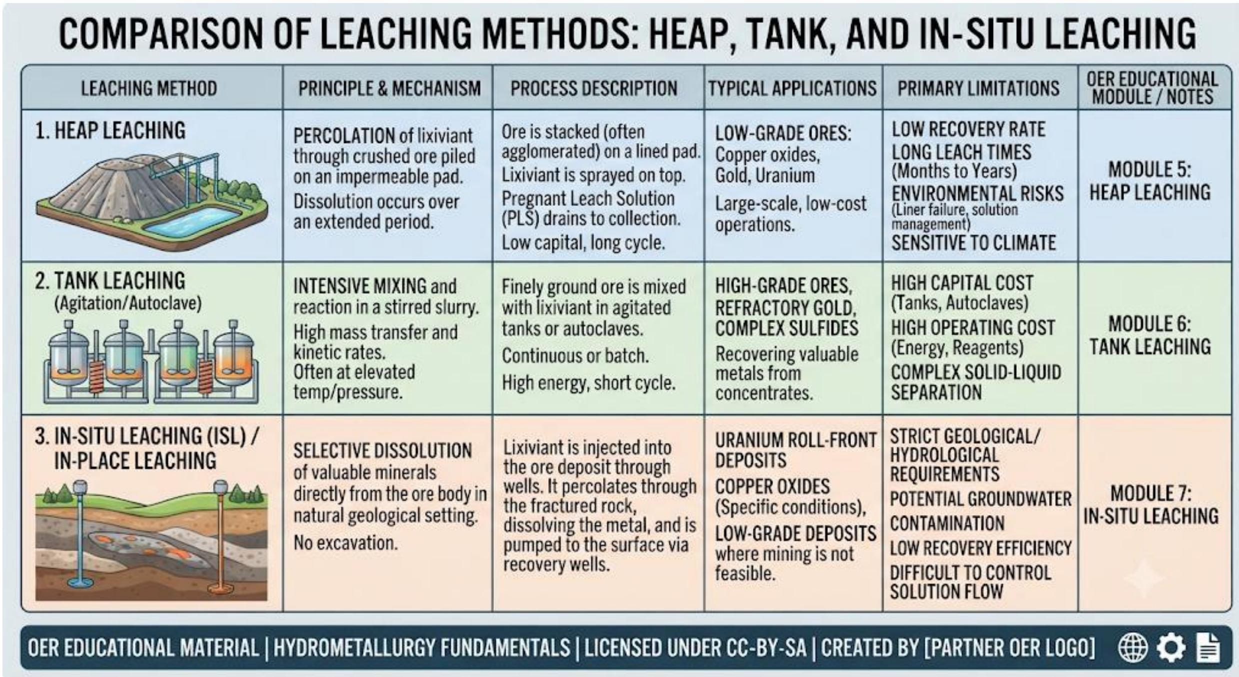



Photograph of industrial tank leaching setup *Plate 4.2: Tank leaching equipment in mineral processing*

#### 4.2.3 In-situ leaching

**In-situ leaching** (also called solution mining) involves injecting leaching solutions directly into ore deposits underground. Metals dissolve in place and are pumped to the surface for recovery. This method reduces the need for mining and crushing, but requires suitable geology and careful monitoring to avoid environmental contamination. It is widely used for uranium and copper recovery.

Fill in the blank: In-situ leaching involves injecting leaching solutions directly into ______ deposits underground.



COMPARISON OF LEACHING METHODS: HEAP, TANK, AND IN-SITU LEACHING

| LEACHING METHOD | PRINCIPLE & MECHANISM | PROCESS DESCRIPTION | TYPICAL APPLICATIONS | PRIMARY LIMITATIONS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|---|
| 1. HEAP LEACHING | PERCOLATION of lixiviant through crushed ore piled on an impermeable pad. Dissolution occurs over an extended period. | Ore is stacked (often agglomerated) on a lined pad. Lixiviant is sprayed on top. Pregnant Leach Solution (PLS) drains to collection. Low capital, long cycle. | LOW-GRADE ORES: Copper oxides, Gold, Uranium. Large-scale, low-cost operations. | LOW RECOVERY RATE. LONG LEACH TIMES (Months to Years). ENVIRONMENTAL RISKS (Liner failure, solution management). SENSITIVE TO CLIMATE | MODULE 5: HEAP LEACHING |
| 2. TANK LEACHING (Agitation/Autoclave) | INTENSIVE MIXING and reaction in a stirred slurry. High mass transfer and kinetic rates. Often at elevated temp/pressure. | Finely ground ore is mixed with lixiviant in agitated tanks or autoclaves. Continuous or batch. High energy, short cycle. | HIGH-GRADE ORES, REFRACTORY GOLD, COMPLEX SULFIDES. Recovering valuable metals from concentrates. | HIGH CAPITAL COST (Tanks, Autoclaves). HIGH OPERATING COST (Energy, Reagents). COMPLEX SOLID-LIQUID SEPARATION | MODULE 6: TANK LEACHING |
| 3. IN-SITU LEACHING (ISL) / IN-PLACE LEACHING | SELECTIVE DISSOLUTION of valuable minerals directly from the ore body in natural geological setting. No excavation. | Lixiviant is injected into the ore deposit through wells. It percolates through the fractured rock, dissolving the metal, and is pumped to the surface via recovery wells. | URANIUM ROLL-FRONT DEPOSITS. COPPER OXIDES (Specific conditions). LOW-GRADE DEPOSITS where mining is not feasible. | STRICT GEOLOGICAL/ HYDROLOGICAL REQUIREMENTS. POTENTIAL GROUNDWATER CONTAMINATION. LOW RECOVERY EFFICIENCY. DIFFICULT TO CONTROL SOLUTION FLOW | MODULE 7: IN-SITU LEACHING |

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Box 4.2: Comparison of leaching techniques

**Pilot questions 4.2**

1. Define heap leaching and state one of its applications.
2. Why is heap leaching suitable for low-grade ores?
3. What advantage does tank leaching offer compared to heap leaching?
4. Explain the principle of in-situ leaching.
5. State one environmental concern associated with in-situ leaching.

### 4.3 Solution Purification and Metal Recovery

#### 4.3.1 Solvent extraction

**Solvent extraction (SX)** is a technique where metals are selectively transferred from an aqueous solution into an organic solvent. The loaded solvent is then stripped to recover the metal in a purified form. SX is widely used for copper, uranium, and rare earth elements. It offers high selectivity and efficiency but requires careful handling of organic solvents.

Fill in the blank: In solvent extraction, metals are transferred from aqueous solution into an ______ solvent.

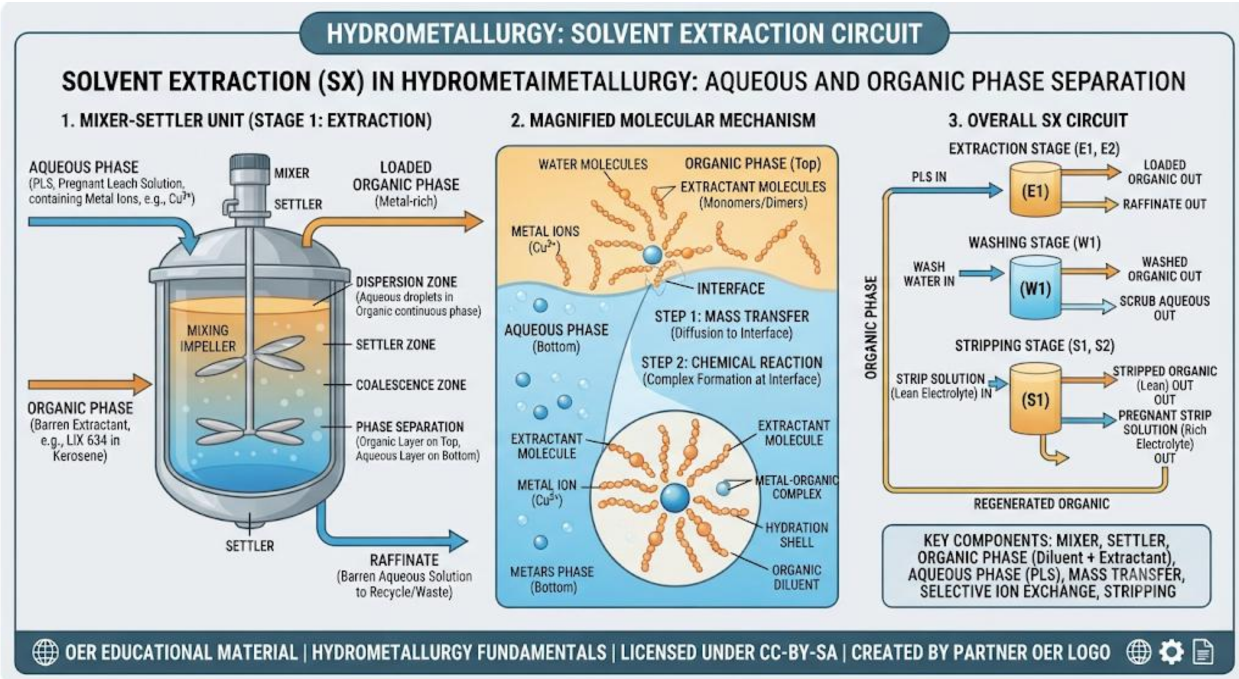
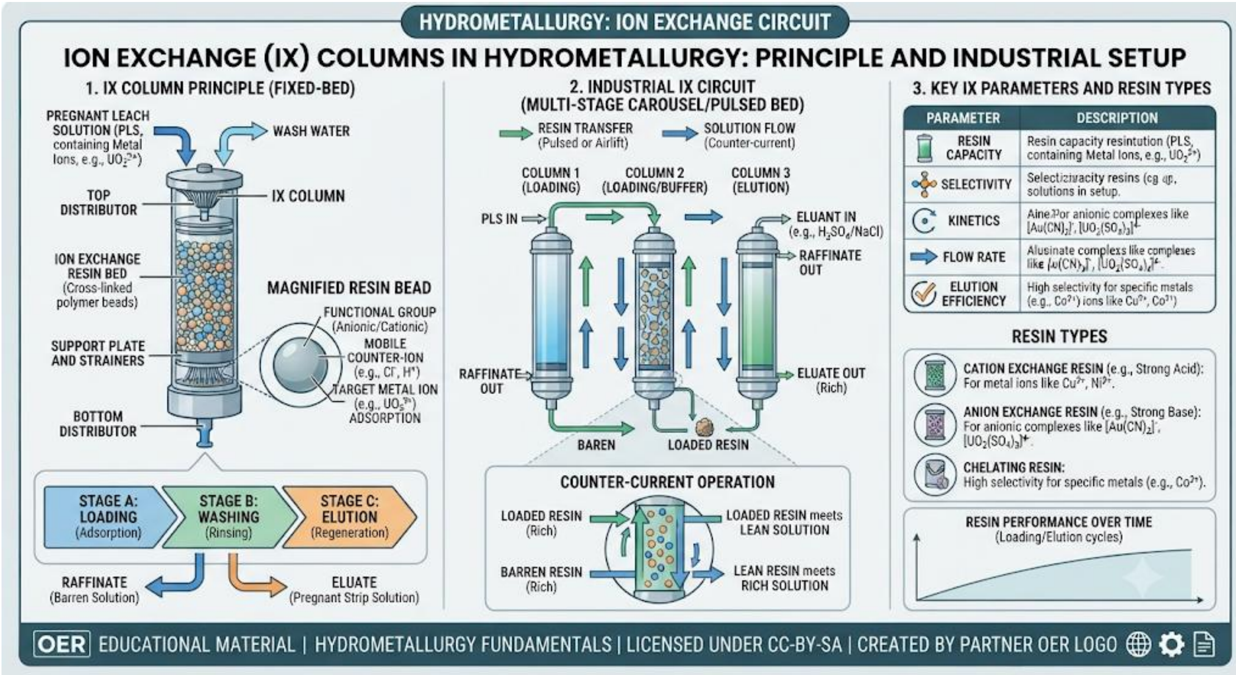


Diagram showing aqueous solution, organic solvent, and metal transfer between phases *Figure 4.3: Principle of solvent extraction*

### 4.3.2 Ion exchange

**Ion exchange** uses resins or membranes to selectively adsorb metal ions from solution and release them under controlled conditions. It is particularly useful for recovering metals from dilute solutions and for purifying rare elements. Ion exchange resins can be tailored for specific ions, making the method versatile.

Fill in the blank: Ion exchange uses resins to selectively adsorb ______ ions from solution.

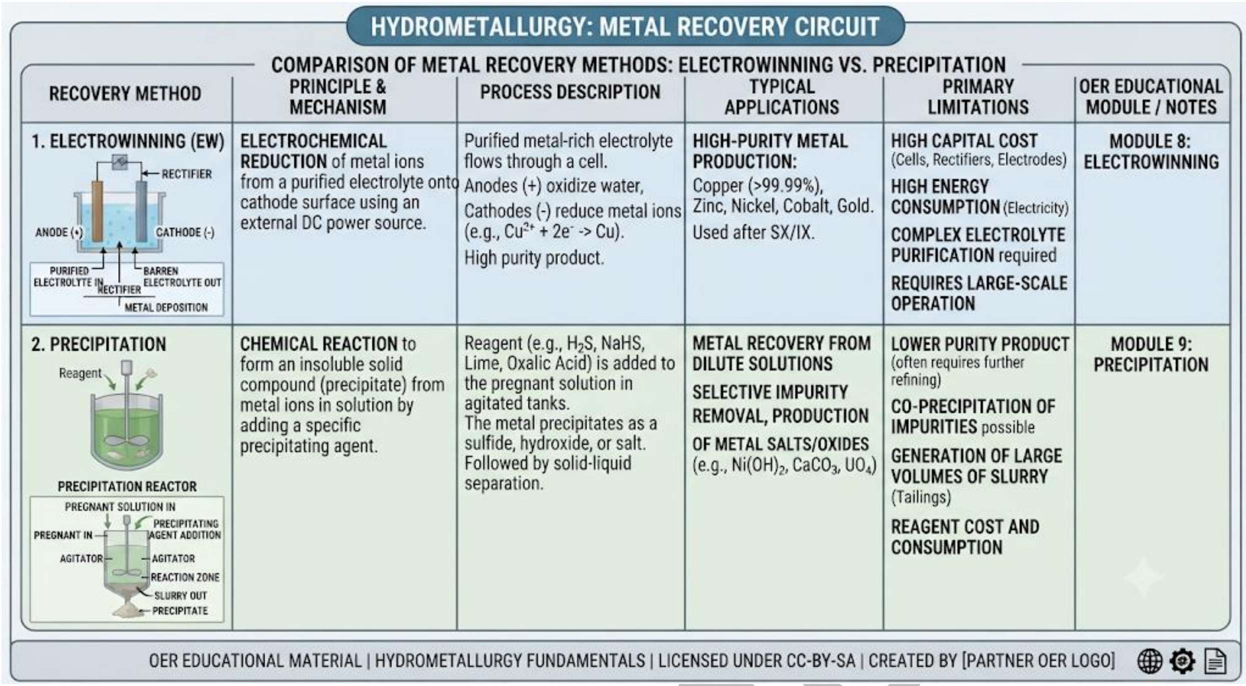



Photograph of ion exchange columns in operation *Plate 4.3: Ion exchange equipment in hydrometallurgy*

### 4.3.3 Electrowinning and precipitation

**Electrowinning** involves passing an electric current through a solution to deposit pure metal onto cathodes. It is commonly used for copper, zinc, and gold. **Precipitation** involves adding reagents to cause metals to form insoluble compounds, which are then filtered and recovered. Both methods are final steps in hydrometallurgical recovery, producing market-ready metals.

Fill in the blank: In electrowinning, pure metal is deposited onto ______ by passing an electric current.



HYDROMETALLURGY: METAL RECOVERY CIRCUIT

COMPARISON OF METAL RECOVERY METHODS: ELECTROWINNING VS. PRECIPITATION

| RECOVERY METHOD | PRINCIPLE & MECHANISM | PROCESS DESCRIPTION | TYPICAL APPLICATIONS | PRIMARY LIMITATIONS | OER EDUCATIONAL MODULE / NOTES |
|---|---|---|---|---|---|
| 1. ELECTROWINNING (EW) | ELECTROCHEMICAL REDUCTION of metal ions from a purified electrolyte onto cathode surface using an external DC power source. | Purified metal-rich electrolyte flows through a cell. Anodes (+) oxidize water, Cathodes (-) reduce metal ions (e.g., $Cu^{2+} + 2e^- \rightarrow Cu$). High purity product. | HIGH-PURITY METAL PRODUCTION: Copper (>99.99%), Zinc, Nickel, Cobalt, Gold. Used after SX/IX. | HIGH CAPITAL COST (Cells, Rectifiers, Electrodes) HIGH ENERGY CONSUMPTION (Electricity) COMPLEX ELECTROLYTE PURIFICATION required REQUIRES LARGE-SCALE OPERATION | MODULE 8: ELECTROWINNING |
| 2. PRECIPITATION | CHEMICAL REACTION to form an insoluble solid compound (precipitate) from metal ions in solution by adding a specific precipitating agent. | Reagent (e.g., $H_2S$, NaHS, Lime, Oxalic Acid) is added to the pregnant solution in agitated tanks. The metal precipitates as a sulfide, hydroxide, or salt. Followed by solid-liquid separation. | METAL RECOVERY FROM DILUTE SOLUTIONS SELECTIVE IMPURITY REMOVAL, PRODUCTION OF METAL SALTS/OXIDES (e.g., $Ni(OH)_2$, $CaCO_3$, $UO_4$) | LOWER PURITY PRODUCT (often requires further refining) CO-PRECIPITATION OF IMPURITIES possible GENERATION OF LARGE VOLUMES OF SLURRY (Tailings) REAGENT COST AND CONSUMPTION | MODULE 9: PRECIPITATION |



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Box 4.3: Comparison of electrowinning and precipitation

**Pilot questions 4.3**

1. Define solvent extraction and state one of its applications.
2. What material is used in ion exchange to adsorb metal ions?
3. Which method deposits pure metal onto cathodes using electricity?
4. State one advantage of ion exchange.
5. Why is precipitation used in hydrometallurgy?

### 4.4 Biological Recovery Methods

#### 4.4.1 Bioleaching principles

**Bioleaching** is the process of using microorganisms to facilitate the extraction of metals from ores. Certain bacteria and fungi produce acids or oxidising agents that dissolve metals into solution. This technique is particularly effective for sulphide ores, where microorganisms oxidise sulphur compounds, enhancing leaching efficiency. Bioleaching is considered environmentally friendly compared to traditional chemical methods.

Fill in the blank: Bioleaching uses ______ to facilitate the extraction of metals from ores.

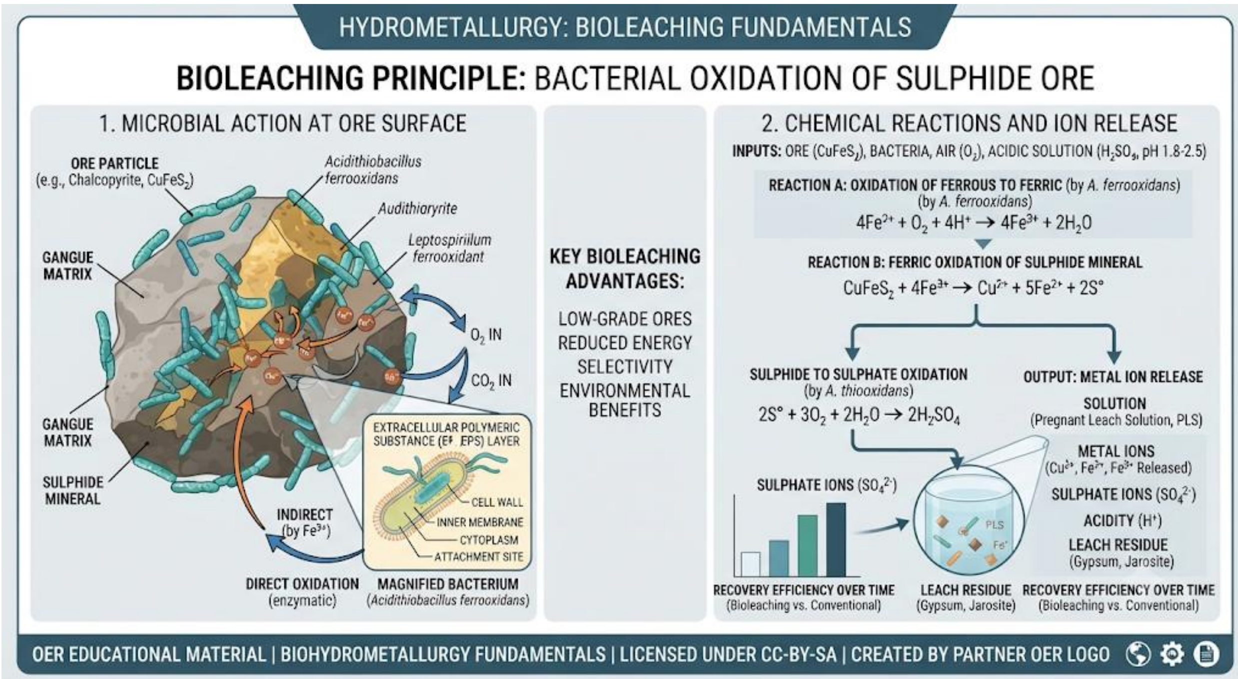


Diagram showing bacteria acting on sulphide ore to release metal ions into solution *Figure 4.4: Principle of bioleaching*

### 4.4.2 Microorganisms used in bioleaching

Several microorganisms are commonly used in bioleaching:

- **Acidithiobacillus ferrooxidans**: Oxidises ferrous iron and sulphur compounds.
- **Leptospirillum ferrooxidans**: Specialises in iron oxidation.
- **Fungi and other bacteria**: Produce organic acids that dissolve metals.

These organisms thrive in acidic environments and play a critical role in breaking down mineral structures to release valuable metals.

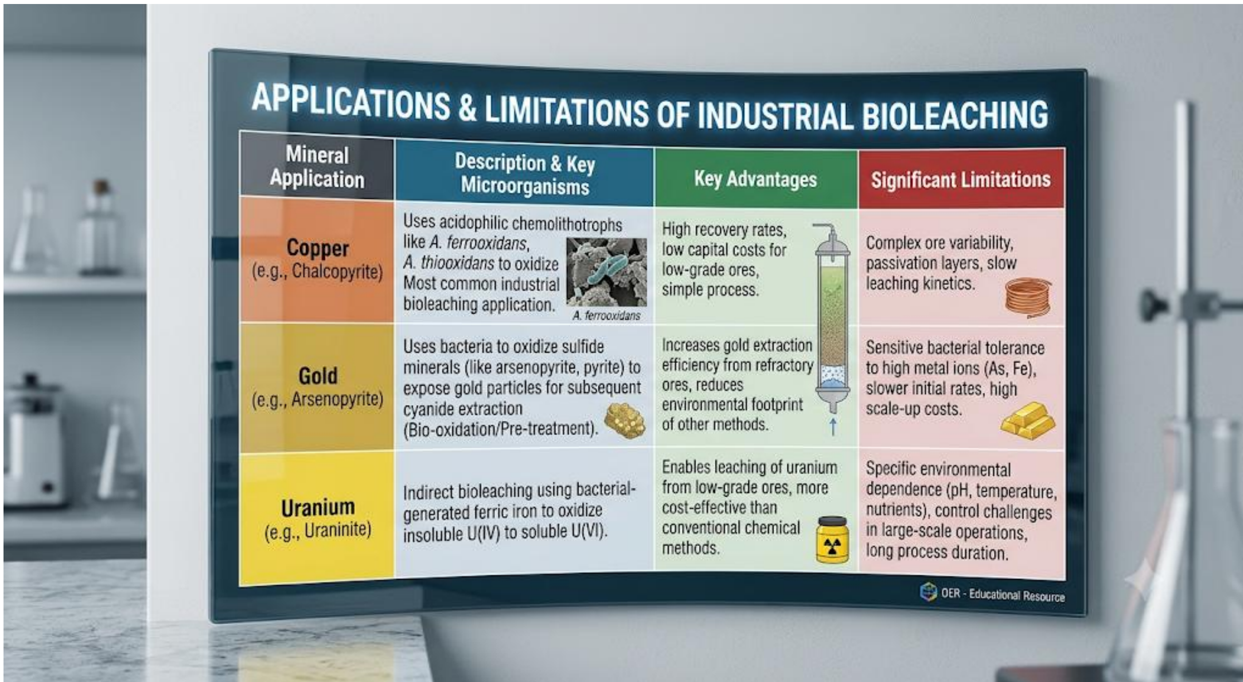
Fill in the blank: Acidithiobacillus ferrooxidans oxidises ferrous ______ and sulphur compounds.

Photographs of microbial cultures used in bioleaching experiments *Plate 4.4: Microorganisms used in bioleaching*

**4.4.3 Applications and limitations of biological recovery**

Bioleaching is applied in the recovery of copper, gold, and uranium from low-grade ores. It is cost-effective, requires less energy, and reduces environmental impact compared to pyrometallurgy. However, limitations include slower reaction rates, dependence on suitable environmental conditions, and challenges in scaling up for large operations. Engineers often combine bioleaching with hydrometallurgical techniques to improve efficiency.

Fill in the blank: Bioleaching is especially useful for recovering metals from ______-grade ores.



Box 4.4: Applications and limitations of bioleaching

**Pilot questions 4.4**

1. Define bioleaching and explain its principle.
2. Name two microorganisms commonly used in bioleaching.
3. Which microorganism oxidises ferrous iron and sulphur compounds?
4. State one application of bioleaching.
5. What is one limitation of bioleaching compared to chemical leaching?

### 4.5 Integration and Sustainability

#### 4.5.1 Combining hydrometallurgical and biological methods

Modern mineral recovery often integrates **hydrometallurgical** and **biological methods** to maximise efficiency. For example, bioleaching may be used to dissolve metals from low-grade ores, followed by solvent extraction or electrowinning to purify and recover the metals. This integration allows engineers to exploit the strengths of each method while compensating for their limitations.

Fill in the blank: Modern mineral recovery often integrates hydrometallurgical and ______ methods to maximise efficiency.

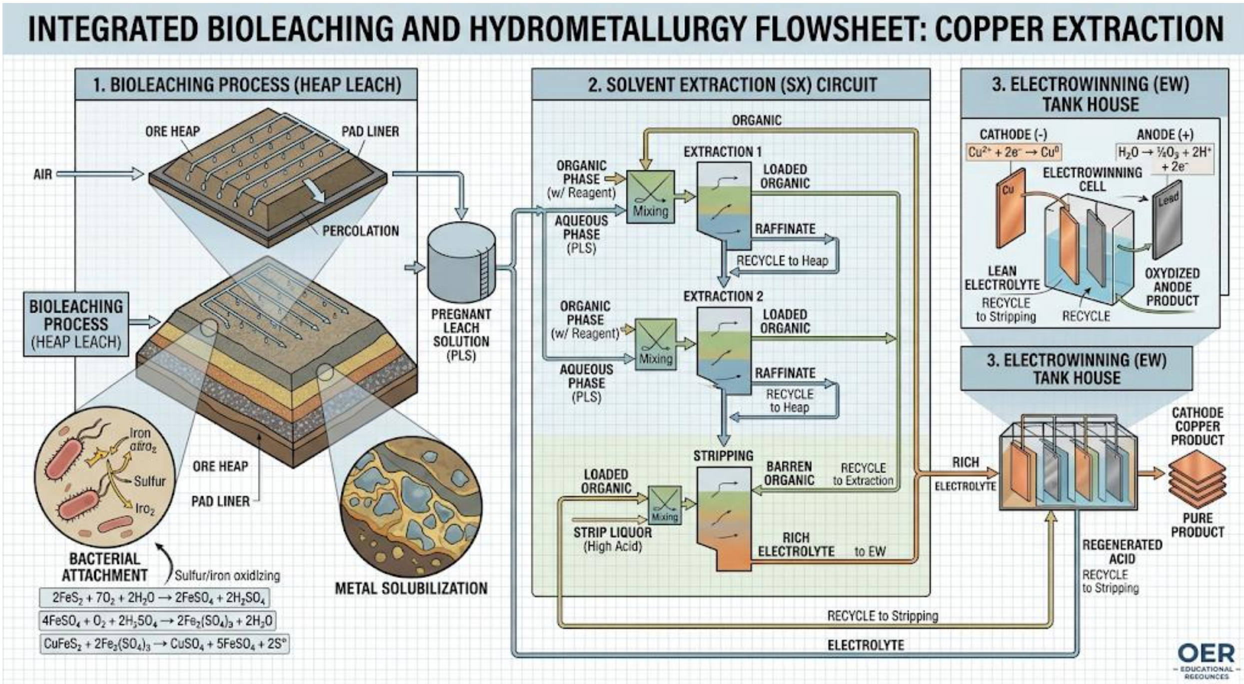
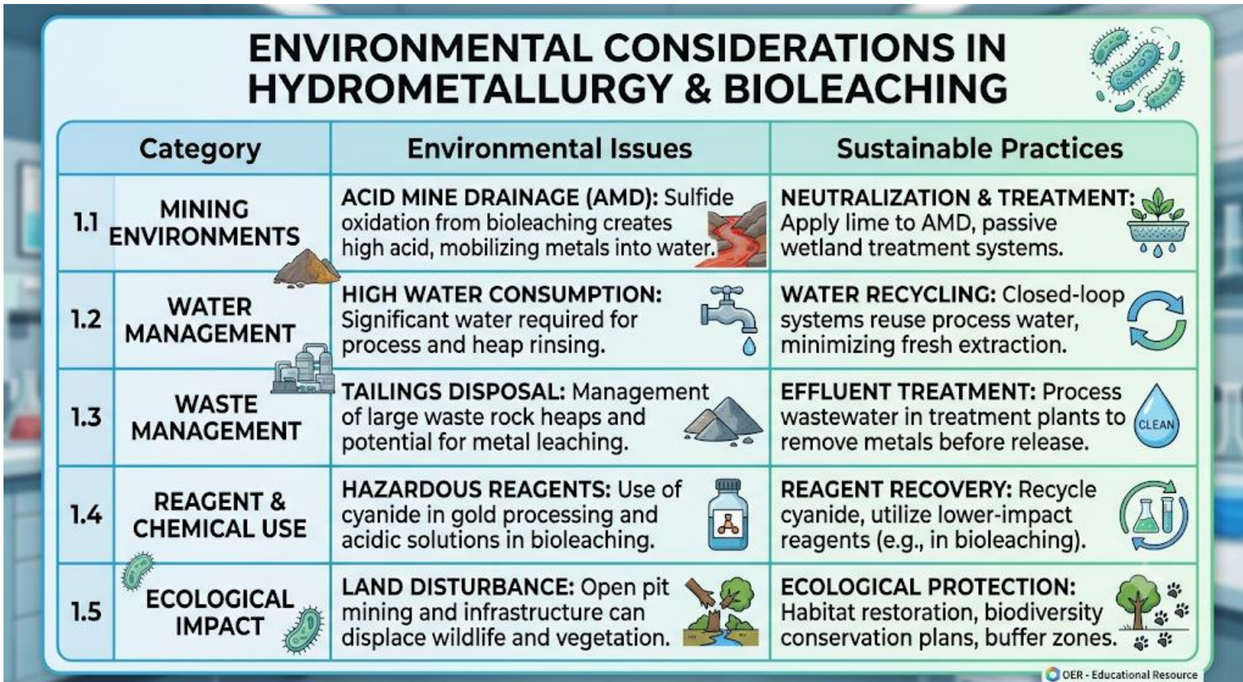



Diagram showing combined bioleaching and solvent extraction/electrowinning flowsheet *Figure 4.5: Integration of biological and hydrometallurgical methods*

### 4.5.2 Environmental considerations and waste management

Hydrometallurgical and biological recovery methods are generally more environmentally friendly than pyrometallurgy, but they still require careful management. Issues include reagent consumption, acid drainage, and disposal of tailings. Biological methods reduce chemical use but depend on maintaining suitable microbial environments. Sustainable practice involves recycling reagents, treating effluents, and minimising ecological disruption.

Fill in the blank: Sustainable hydrometallurgy involves recycling reagents, treating effluents, and minimising ______ disruption.



## ENVIRONMENTAL CONSIDERATIONS IN HYDROMETALLURGY & BIOLEACHING

| | Category | Environmental Issues | Sustainable Practices |
|---|---|---|---|
| 1.1 | MINING ENVIRONMENTS | **ACID MINE DRAINAGE (AMD):** Sulfide oxidation from bioleaching creates high acid, mobilizing metals into water. | **NEUTRALIZATION & TREATMENT:** Apply lime to AMD, passive wetland treatment systems. |
| 1.2 | WATER MANAGEMENT | **HIGH WATER CONSUMPTION:** Significant water required for process and heap rinsing. | **WATER RECYCLING:** Closed-loop systems reuse process water, minimizing fresh extraction. |
| 1.3 | WASTE MANAGEMENT | **TAILINGS DISPOSAL:** Management of large waste rock heaps and potential for metal leaching. | **EFFLUENT TREATMENT:** Process wastewater in treatment plants to remove metals before release. |
| 1.4 | REAGENT & CHEMICAL USE | **HAZARDOUS REAGENTS:** Use of cyanide in gold processing and acidic solutions in bioleaching. | **REAGENT RECOVERY:** Recycle cyanide, utilize lower-impact reagents (e.g., in bioleaching). |
| 1.5 | ECOLOGICAL IMPACT | **LAND DISTURBANCE:** Open pit mining and infrastructure can displace wildlife and vegetation. | **ECOLOGICAL PROTECTION:** Habitat restoration, biodiversity conservation plans, buffer zones. |



Box 4.5: Environmental considerations in hydrometallurgical and biological recovery

**4.5.3 Future trends in sustainable recovery**

Future trends in mineral recovery include the use of advanced sensors, artificial intelligence, and biotechnology to improve efficiency and reduce environmental impact. Research is focusing on genetically engineered microorganisms for enhanced bioleaching, closed-loop hydrometallurgical systems, and integration with renewable energy. These innovations aim to make mineral recovery more sustainable and adaptable to complex ore deposits.

Fill in the blank: Future trends in mineral recovery include genetically engineered ______ for enhanced bioleaching.


Photograph of laboratory research on bio-mineral recovery and sustainable hydrometallurgy *Plate 4.5: Future trends in sustainable mineral recovery*

**Pilot questions 4.5**

1. Why is integration of hydrometallurgical and biological methods important?
2. State one environmental issue associated with hydrometallurgical recovery.
3. What sustainable practice helps minimise ecological disruption?
4. Name one future trend in mineral recovery.
5. How can biotechnology contribute to sustainable mineral recovery?

**Series Summary**

This Series explored **Hydrometallurgical and Biological Recovery** methods, focusing on aqueous and microbial processes for extracting metals. We began with the principles of hydrometallurgy, covering leaching mechanisms and influencing factors. We then studied leaching techniques such as heap, tank, and in-situ leaching. Next, we examined solution purification and metal recovery methods, including solvent extraction, ion exchange, electrowinning, and precipitation. Following this, we explored biological recovery methods, highlighting bioleaching principles, microorganisms involved, and applications. Finally, we discussed integration and sustainability, considering environmental impacts and future trends.

By completing this Series, you should now be able to explain hydrometallurgical principles, describe leaching techniques, analyse purification and recovery methods, demonstrate understanding of biological recovery, and evaluate integration for sustainable mineral processing.

**Glossary of Terms**

- **Bioleaching**: Use of microorganisms to dissolve metals from ores.
- **Electrowinning**: Recovery of metals by depositing them onto cathodes using electricity.
- **Heap leaching**: Irrigation of crushed ore heaps with leaching solution.
- **Hydrometallurgy**: Recovery of metals using aqueous solutions.
- **Ion exchange**: Use of resins to selectively adsorb and release metal ions.
- **Leaching**: Dissolution of metals into solution using reagents.
- **Solvent extraction (SX)**: Transfer of metals between aqueous and organic phases.
- **Tank leaching**: Controlled leaching in stirred tanks.
- **In-situ leaching**: Injection of leaching solutions directly into ore deposits underground.
- **Sustainability**: Practices that minimise environmental impact in mineral recovery.

**Concept Check Questions [Series 4]**

**Objective questions**

1. Hydrometallurgy recovers metals using ______ solutions. (Linked to SLO 4.1)
2. Heap leaching is especially suitable for processing ______-grade ores. (Linked to SLO 4.2)
3. In solvent extraction, metals are transferred into an ______ solvent. (Linked to SLO 4.3)

**Short-answer questions**

4. Explain the principle of tank leaching. (Linked to SLO 4.2)
5. Name two microorganisms used in bioleaching. (Linked to SLO 4.4)
6. State one environmental issue associated with hydrometallurgical recovery. (Linked to SLO 4.5)

**Long-answer questions**

7. Analyse the advantages and limitations of heap, tank, and in-situ leaching. (Linked to SLO 4.2)
8. Evaluate how integrating hydrometallurgical and biological methods contributes to sustainable mineral recovery. (Linked to SLO 4.5)

**Answers to Concept Check Questions [Series 4]**

**Objective questions**

1. Aqueous.
2. Low.
3. Organic.

**Short-answer questions**

4. Tank leaching involves finely ground ore mixed with leaching solution in stirred tanks under controlled conditions.
5. *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*.
6. Acid drainage or reagent consumption.

**Long-answer questions**

7. **Basic response**: Heap leaching is cost-effective for low-grade ores but slow; tank leaching offers higher recovery but is more expensive; in-situ leaching avoids mining but risks contamination. **Value-added response**: Outstanding learners may compare kinetics, environmental impacts, and scalability, highlighting how ore type and grade influence method choice.
8. **Basic response**: Integration improves efficiency and reduces chemical use. **Value-added response**: Outstanding learners may discuss flowsheets combining bioleaching with solvent extraction/electrowinning, emphasising reduced energy consumption, improved recovery, and sustainability.

**Answers to Pilot Questions [Series 4]**

1. Hydrometallurgy involves leaching, purification, and recovery.
2. Leaching dissolves metals into solution using reagents.
3. Reagent concentration, temperature, particle size, agitation.
4. Sulphide ores may need oxidation to enhance leaching.
5. Environmental considerations include effluent treatment.
6. Heap leaching irrigates crushed ore heaps with solution.
7. Heap leaching is suitable for low-grade ores.
8. Tank leaching offers precise control of conditions.
9. In-situ leaching injects solutions into ore deposits underground.
10. Risk of groundwater contamination.

11. Solvent extraction transfers metals into organic solvent.
12. Ion exchange uses resins to adsorb metal ions.
13. Electrowinning deposits metals onto cathodes.
14. Ion exchange is versatile for dilute solutions.
15. Precipitation recovers metals as insoluble compounds.
16. Bioleaching uses microorganisms to dissolve metals.
17. *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*.
18. *Acidithiobacillus ferrooxidans* oxidises ferrous iron and sulphur.
19. Copper, gold, uranium recovery.
20. Slow reaction rates.
21. Integration combines hydrometallurgical and biological methods.
22. Acid drainage.
23. Effluent treatment minimises ecological disruption.
24. Genetically engineered microorganisms.
25. Biotechnology enhances bioleaching efficiency.

**References and Attributions [Series 4]**

- Figure 4.1: Stages of hydrometallurgy. Suggested AI prompt: "Create a labelled diagram showing leaching, purification, and recovery stages." Search string: "hydrometallurgy stages diagram OER."
- Table 4.1: Factors influencing leaching kinetics. Suggested AI prompt: "Create a table listing reagent concentration, temperature, particle size, agitation." Search string: "leaching kinetics factors table OER."
- Box 4.1: Factors influencing hydrometallurgical recovery. Suggested AI prompt: "Create a table listing ore mineralogy, reagent choice, operating conditions, environmental considerations." Search string: "hydrometallurgical recovery factors table OER."
- Figure 4.2: Heap leaching principle. Suggested AI prompt: "Create a labelled diagram showing heap leaching." Search string: "heap leaching diagram OER."
- Plate 4.2: Tank leaching equipment. Suggested AI prompt: "Generate image of industrial tank leaching setup." Search string: "tank leaching equipment OER."

- Box 4.2: Comparison of leaching techniques. Suggested AI prompt: “Create a table comparing heap, tank, in-situ leaching.” Search string: “comparison leaching techniques table OER.”
- Figure 4.3: Solvent extraction principle. Suggested AI prompt: “Create a labelled diagram showing aqueous and organic phases.” Search string: “solvent extraction diagram OER.”
- Plate 4.3: Ion exchange columns. Suggested AI prompt: “Generate image of ion exchange columns.” Search string: “ion exchange columns OER.”
- Box 4.3: Comparison of electrowinning and precipitation. Suggested AI prompt: “Create a table comparing electrowinning and precipitation.” Search string: “electrowinning precipitation comparison table OER.”
- Figure 4.4: Bioleaching principle. Suggested AI prompt: “Create a labelled diagram showing bacteria acting on sulphide ore.” Search string: “bioleaching principle diagram OER.”
- Plate 4.4: Microorganisms used in bioleaching. Suggested AI prompt: “Generate images of Acidithiobacillus ferrooxidans and Leptospirillum ferrooxidans.” Search string: “bioleaching microorganisms OER.”
- Box 4.4: Applications and limitations of bioleaching. Suggested AI prompt: “Create a table listing applications and limitations.” Search string: “bioleaching applications limitations table OER.”
- Figure 4.5: Integration flowsheet. Suggested AI prompt: “Create a labelled diagram showing bioleaching + solvent extraction/electrowinning.” Search string: “integration bioleaching hydrometallurgy flowsheet OER.”
- Box 4.5: Environmental considerations. Suggested AI prompt: “Create a table listing issues and sustainable practices.” Search string: “environmental considerations hydrometallurgy bioleaching table OER.”
- Plate 4.5: Future trends. Suggested AI prompt: “Generate image of laboratory research on genetically engineered microorganisms.” Search string: “future trends bioleaching hydrometallurgy OER.”

# Series 5: Metallurgical Balances and Laboratory Practice

**Series outline**

- **5.1 Principles of metallurgical balances**

- 5.1.1 Mass balance fundamentals
- 5.1.2 Metal accounting and recovery calculations
- 5.1.3 Importance of balances in plant performance

- **5.2 Sampling and assay methods**
  - 5.2.1 Principles of representative sampling
  - 5.2.2 Assay techniques for mineral content
  - 5.2.3 Errors and bias in sampling and assays
- **5.3 Laboratory practice in mineral processing**
  - 5.3.1 Laboratory equipment and safety protocols
  - 5.3.2 Experimental procedures for separation tests
  - 5.3.3 Data recording and interpretation
- **5.4 Application of balances in process evaluation**
  - 5.4.1 Calculating recovery, grade, and yield
  - 5.4.2 Evaluating circuit efficiency
  - 5.4.3 Case studies in metallurgical accounting



**Introduction**

Metallurgical balances are fundamental tools in mineral processing, providing a quantitative framework for tracking material and metal flows through a plant. They ensure accountability, help identify inefficiencies, and support decision-making in process optimisation. Laboratory practice complements this by generating reliable data through sampling, assays, and controlled experiments, which form the basis for accurate balances.

The aim of this Series is to equip you with the knowledge and skills to perform metallurgical balances and conduct laboratory practice effectively. You will learn the principles of mass and metal accounting, representative sampling, assay techniques, and laboratory procedures. In addition, you will explore how balances are applied to evaluate process performance and efficiency.

We shall begin with the principles of metallurgical balances, focusing on mass balance fundamentals and recovery calculations. Next, we will study sampling and assay methods, including sources of error and bias. We will then examine laboratory practice in mineral processing, covering equipment, safety, and data interpretation. Finally, we will apply balances in process evaluation, calculating recovery, grade, and yield, and analysing circuit efficiency through case studies.

**Series Learning Outcomes**

Upon completing **Series 5: Metallurgical Balances and Laboratory Practice**, you should be able to:

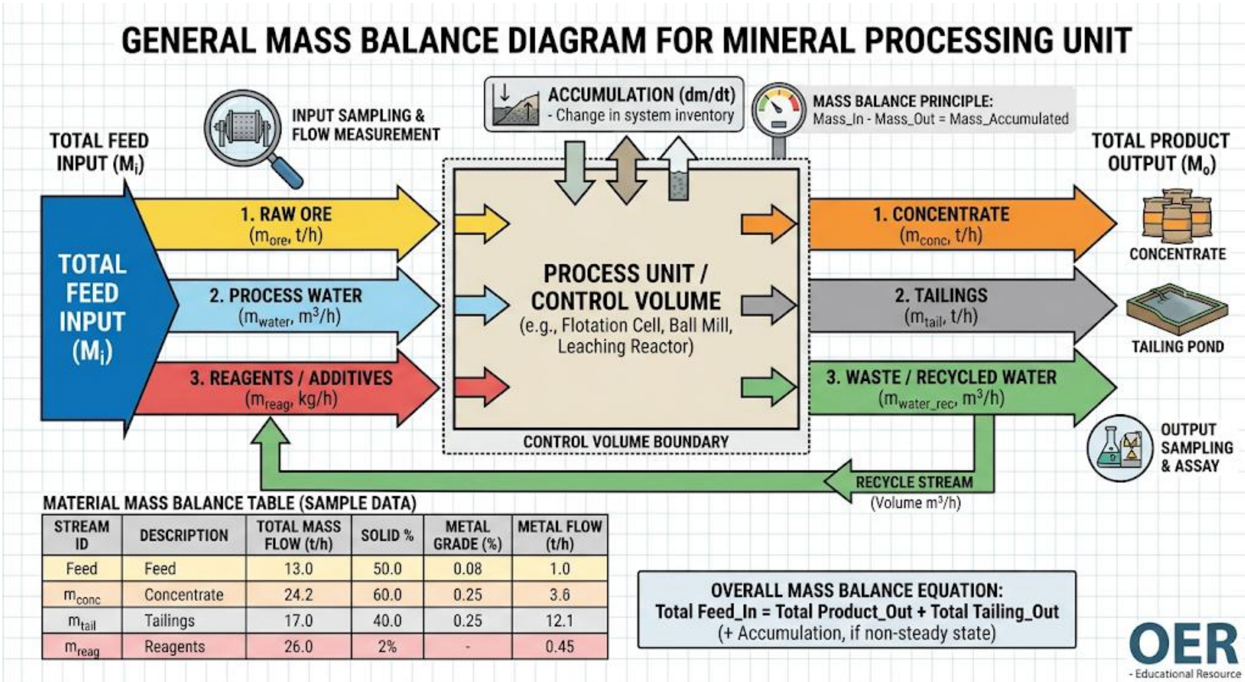
- **SLO 5.1** explain the principles of metallurgical balances, including mass balance fundamentals, metal accounting, and their role in evaluating plant performance,
- **SLO 5.2** describe representative sampling and assay methods, identify sources of error and bias, and apply techniques to obtain reliable data,
- **SLO 5.3** demonstrate laboratory practice in mineral processing, including safe use of equipment, conducting separation experiments, and interpreting data,
- **SLO 5.4** apply metallurgical balances to process evaluation, calculating recovery, grade, and yield, and assessing circuit efficiency through case studies.

**5.1 Principles of Metallurgical Balances**

**5.1.1 Mass balance fundamentals**

A **mass balance** is the accounting of material entering and leaving a process. It ensures that the total input equals the total output plus any accumulation. In mineral processing, mass balances are used to track ore, concentrate, and tailings streams. They provide the foundation for evaluating plant performance and efficiency.

Fill in the blank: A mass balance ensures that total input equals total ______ plus accumulation.




| STREAM ID | DESCRIPTION | TOTAL MASS FLOW (t/h) | SOLID % | METAL GRADE (%) | METAL FLOW (t/h) |
|---|---|---|---|---|---|
| Feed | Feed | 13.0 | 50.0 | 0.08 | 1.0 |
| $m_{conc}$ | Concentrate | 24.2 | 60.0 | 0.25 | 3.6 |
| $m_{tail}$ | Tailings | 17.0 | 40.0 | 0.25 | 12.1 |
| $m_{reag}$ | Reagents | 26.0 | 2% | - | 0.45 |

Diagram showing input, output, and accumulation in a mass balance system *Figure 5.1: Principle of mass balance in mineral processing*

### 5.1.2 Metal accounting and recovery calculations

**Metal accounting** involves quantifying the amount of valuable metal recovered compared to the amount present in the feed. Recovery is calculated as:

$$\text{Recovery (\%)} = \frac{\text{Metal in concentrate}}{\text{Metal in feed}} \times 100$$

This calculation is essential for determining the efficiency of separation processes and for reporting production figures.

Fill in the blank: Recovery (%) is calculated as metal in concentrate divided by metal in ______, multiplied by 100.

## COPPER ORE RECOVERY CALCULATION & GRADE TABLE

| Stream Description | Mass (kg) | Grade (%) | Metal Content (kg) $M = m * G/100$ | Recovery (%) $R = \frac{M_{conc}}{M_{feed}} * 100$ |
|---|---|---|---|---|
| Feed | 1,000 | 0.80 | 8.0 | |
| Concentrate | 25 | 28.0 | 7.0 | |
| Tailings | 975 | 0.10 | 1.0 | |
| | | | | 87.5 |

**RECOVERY CALCULATION EXAMPLE**

1. Metal in Feed ($M_{feed}$) = $\frac{Mass_{feed} * Grade_{feed}}{100} = \frac{1{,}000 * 0.8}{100}$ = **8.0 kg**
2. Metal in Concentrate ($M_{conc}$) = $\frac{Mass_{conc} * Grade_{conc}}{100} = \frac{25 * 28.0}{100}$ = **7.0 kg**
3. Recovery (%) = $\frac{M_{conc}}{M_{feed}} * 100 = \frac{7.0}{8.0} * 100$ = **87.5 %**

**OVERALL RECOVERY FOR THIS ORE: 87.5%**

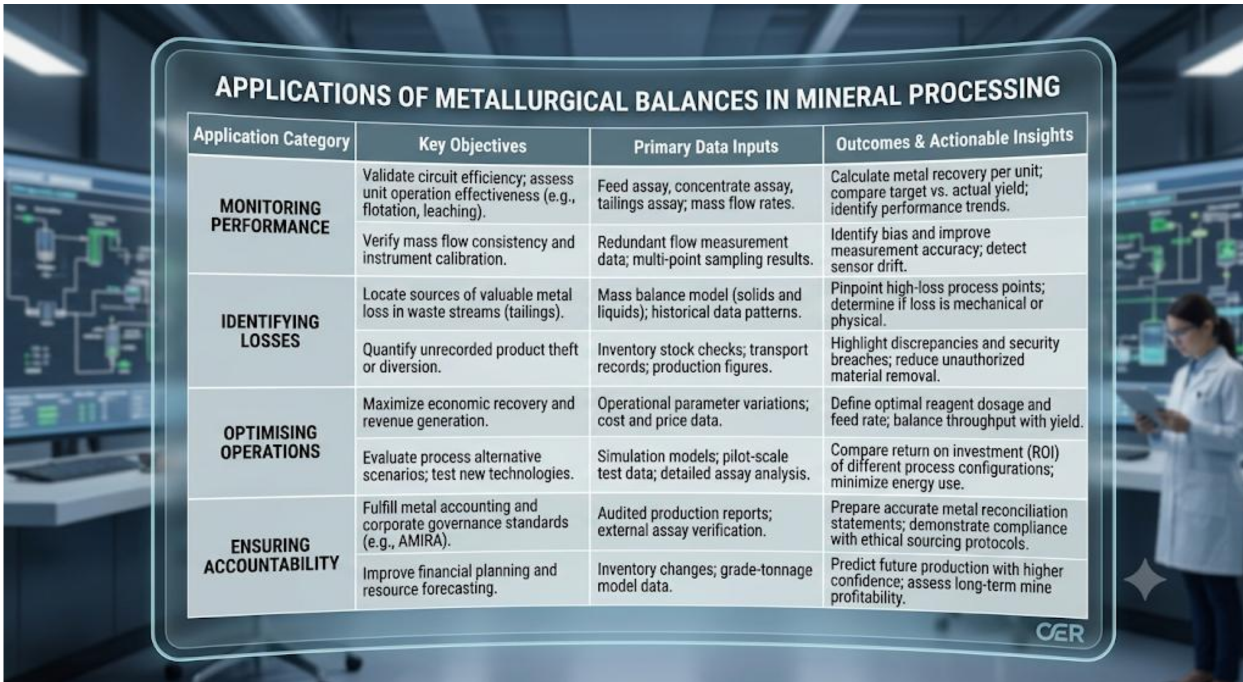
OER

Table 5.1: Example of recovery calculation for copper ore

### 5.1.3 Importance of balances in plant performance

Metallurgical balances are critical for monitoring plant performance, identifying losses, and optimising operations. They help engineers detect inefficiencies, such as poor recovery or excessive losses to tailings. Accurate balances also ensure accountability in production reporting and compliance with industry standards.

Fill in the blank: Metallurgical balances are critical for monitoring plant performance, identifying losses, and optimising ______.



APPLICATIONS OF METALLURGICAL BALANCES IN MINERAL PROCESSING

| Application Category | Key Objectives | Primary Data Inputs | Outcomes & Actionable Insights |
|---|---|---|---|
| MONITORING PERFORMANCE | Validate circuit efficiency; assess unit operation effectiveness (e.g., flotation, leaching). | Feed assay, concentrate assay, tailings assay; mass flow rates. | Calculate metal recovery per unit; compare target vs. actual yield; identify performance trends. |
| | Verify mass flow consistency and instrument calibration. | Redundant flow measurement data; multi-point sampling results. | Identify bias and improve measurement accuracy; detect sensor drift. |
| IDENTIFYING LOSSES | Locate sources of valuable metal loss in waste streams (tailings). | Mass balance model (solids and liquids); historical data patterns. | Pinpoint high-loss process points; determine if loss is mechanical or physical. |
| | Quantify unrecorded product theft or diversion. | Inventory stock checks; transport records; production figures. | Highlight discrepancies and security breaches; reduce unauthorized material removal. |
| OPTIMISING OPERATIONS | Maximize economic recovery and revenue generation. | Operational parameter variations; cost and price data. | Define optimal reagent dosage and feed rate; balance throughput with yield. |
| | Evaluate process alternative scenarios; test new technologies. | Simulation models; pilot-scale test data; detailed assay analysis. | Compare return on investment (ROI) of different process configurations; minimize energy use. |
| ENSURING ACCOUNTABILITY | Fulfill metal accounting and corporate governance standards (e.g., AMIRA). | Audited production reports; external assay verification. | Prepare accurate metal reconciliation statements; demonstrate compliance with ethical sourcing protocols. |
| | Improve financial planning and resource forecasting. | Inventory changes; grade-tonnage model data. | Predict future production with higher confidence; assess long-term mine profitability. |

Box 5.1: Applications of metallurgical balances in plant performance

**Pilot questions 5.1**

1. Define a mass balance in mineral processing.
2. What does a mass balance ensure about input and output?
3. Write the formula for recovery (%) in metal accounting.
4. Why are metallurgical balances important for plant performance?
5. State one application of metallurgical balances in industry.

## 5.2 Sampling and Assay Methods

### 5.2.1 Principles of representative sampling

**Sampling** is the process of collecting a portion of material that accurately reflects the whole. In mineral processing, representative sampling is critical because ore deposits are heterogeneous. Poor sampling leads to biased results and unreliable metallurgical balances. Techniques such as grab sampling, channel sampling, and composite sampling are used to ensure accuracy.

Fill in the blank: Sampling must be ______ to ensure results accurately reflect the whole material.

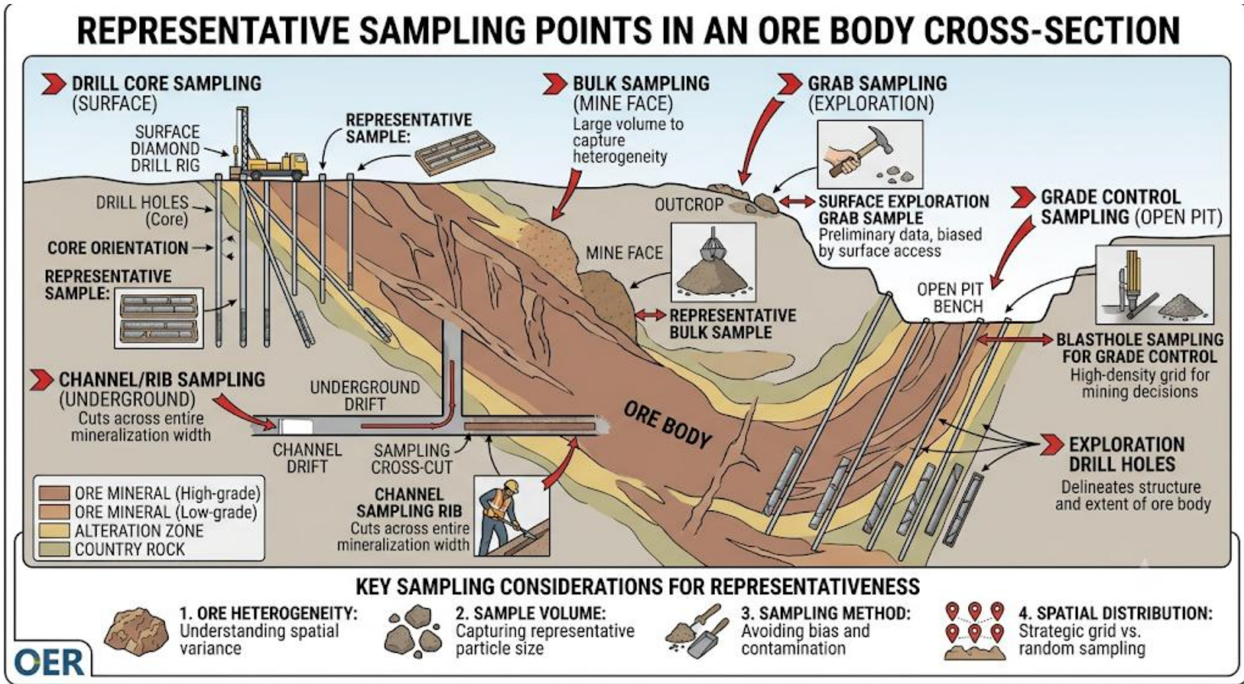
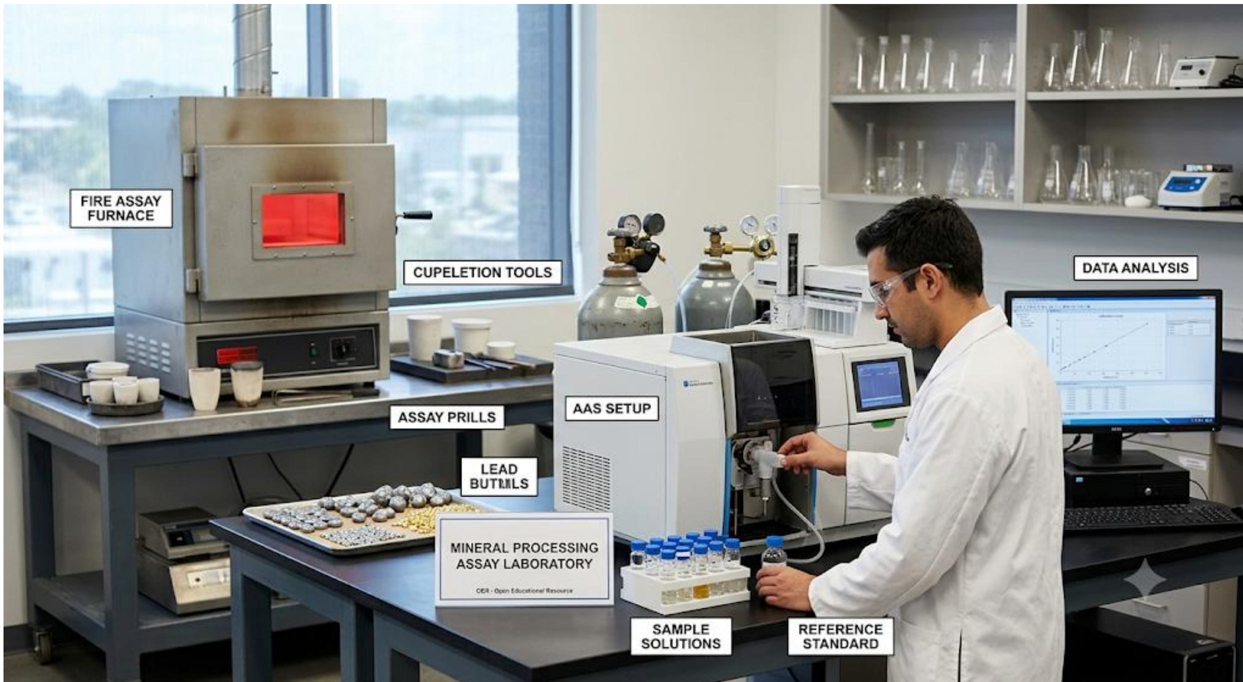


Diagram showing ore body with representative sampling points *Figure 5.2: Principle of representative sampling*

#### 5.2.2 Assay techniques for mineral content

**Assays** determine the concentration of valuable metals in ore, concentrate, or tailings. Common techniques include fire assay (for precious metals), atomic absorption spectroscopy (AAS), inductively coupled plasma (ICP), and X-ray fluorescence (XRF). Accurate assays are essential for calculating grades and recoveries in metallurgical balances.

Fill in the blank: Fire assay is commonly used to determine the concentration of ______ metals.



Photograph of laboratory assay equipment (fire assay furnace, AAS setup) *Plate 5.2: Assay techniques in mineral processing laboratories*

**5.2.3 Errors and bias in sampling and assays**

Errors in sampling and assays can arise from poor technique, equipment limitations, or human bias. Sampling errors include segregation, size bias, and contamination. Assay errors may result from improper calibration or sample preparation. Minimising errors requires strict protocols, quality control, and repeated measurements.

Fill in the blank: Sampling errors may include segregation, size bias, and ______.

| 1. ERRORS IN SAMPLING MINERAL PROCESSING | | |
|---|---|---|
| Type of Error | | Description & Causes |
| 1.1 | SEGREGATION | Particles with different physical properties (size, shape, density) distribute unevenly in a material stream. Causes include differential settling, flow patterns, and improper sample cutting. |
| 1.2 | SIZE BIAS | A sampling device selectively collects or excludes certain particle sizes, leading to a sample not representative of the bulk material. Causes include sampler gap width or speed. |
| 1.3 | CONTAMINATION | The introduction of foreign material into the sample after collection. Causes include uncleaned equipment, improper sample containers, and environmental dust. |

| 2. ERRORS IN ASSAYS MINERAL PROCESSING | | |
|---|---|---|
| Type of Error | | Description & Causes |
| 2.1 | CALIBRATION | Inaccurate or infrequent calibration of assay instruments leads to consistent systematic errors in measurements. Causes include drifted standards and improper procedures. |
| 2.2 | PREPARATION | Errors introduced during the sample preparation stages before analysis (grinding, digestion, fusion). Causes include incomplete sample recovery, sample cross-contamination, and volatile loss. |
| 2.3 | HUMAN BIAS | Errors introduced by the laboratory technician during visual observation or manual steps, affecting results. Causes include subjective interpretation of endpoints, color changes, and reading scales. |

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Box 5.2: Sources of error in sampling and assays

**Pilot questions 5.2**

1. Why is representative sampling important in mineral processing?
2. Name two common assay techniques.
3. Which assay method is widely used for precious metals?
4. State one source of sampling error.
5. How can errors in assays be minimised?

## 5.3 Laboratory Practice in Mineral Processing

### 5.3.1 Laboratory equipment and safety protocols

Laboratory practice in mineral processing requires the use of specialised equipment such as crushers, grinders, flotation cells, magnetic separators, and assay furnaces. Safety protocols are essential to protect personnel from chemical, mechanical, and electrical hazards. Standard measures include wearing personal protective equipment (PPE), proper ventilation, and adherence to handling procedures for reagents and samples.

Fill in the blank: Laboratory safety protocols require the use of personal ______ equipment (PPE).

Photograph of mineral processing laboratory with flotation cells, crushers, and PPE in use *Plate 5.3: Laboratory equipment and safety protocols*

### 5.3.2 Experimental procedures for separation tests

Laboratory experiments simulate industrial processes on a smaller scale to evaluate ore characteristics and separation efficiency. Common procedures include gravity concentration tests, magnetic separation trials, and flotation experiments. These tests provide data on recovery, grade, and yield, which are essential for designing plant flowsheets.

Fill in the blank: Laboratory experiments provide data on recovery, grade, and ______.

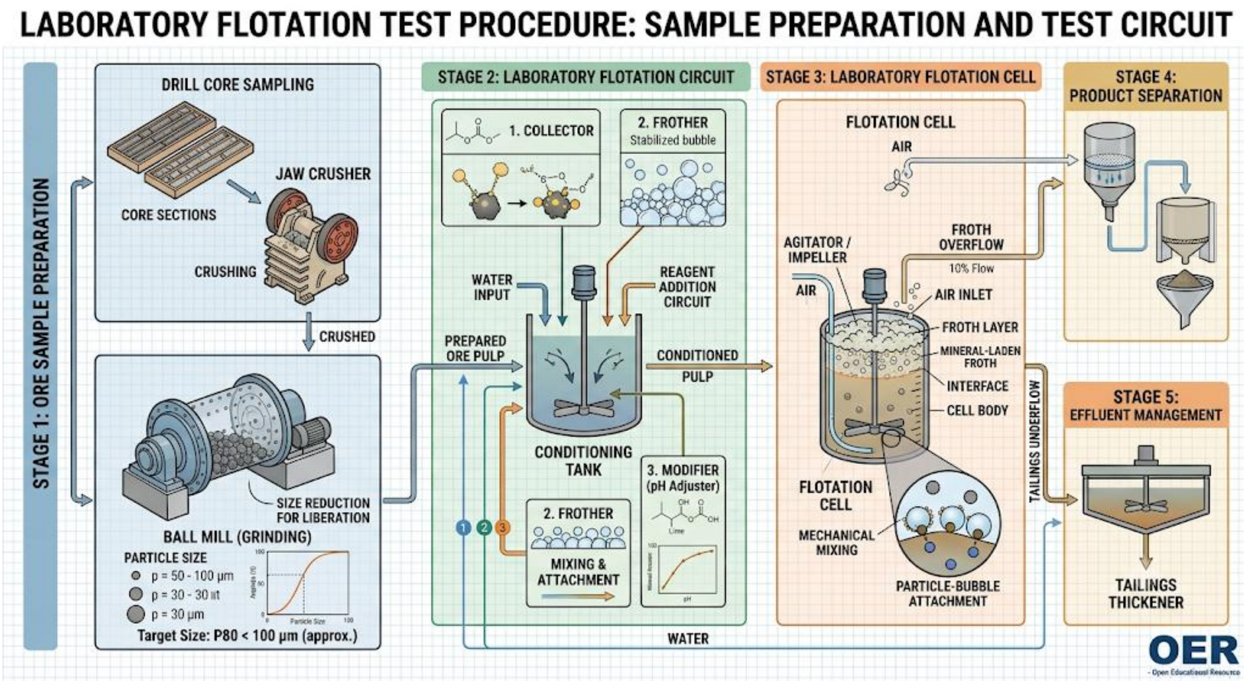
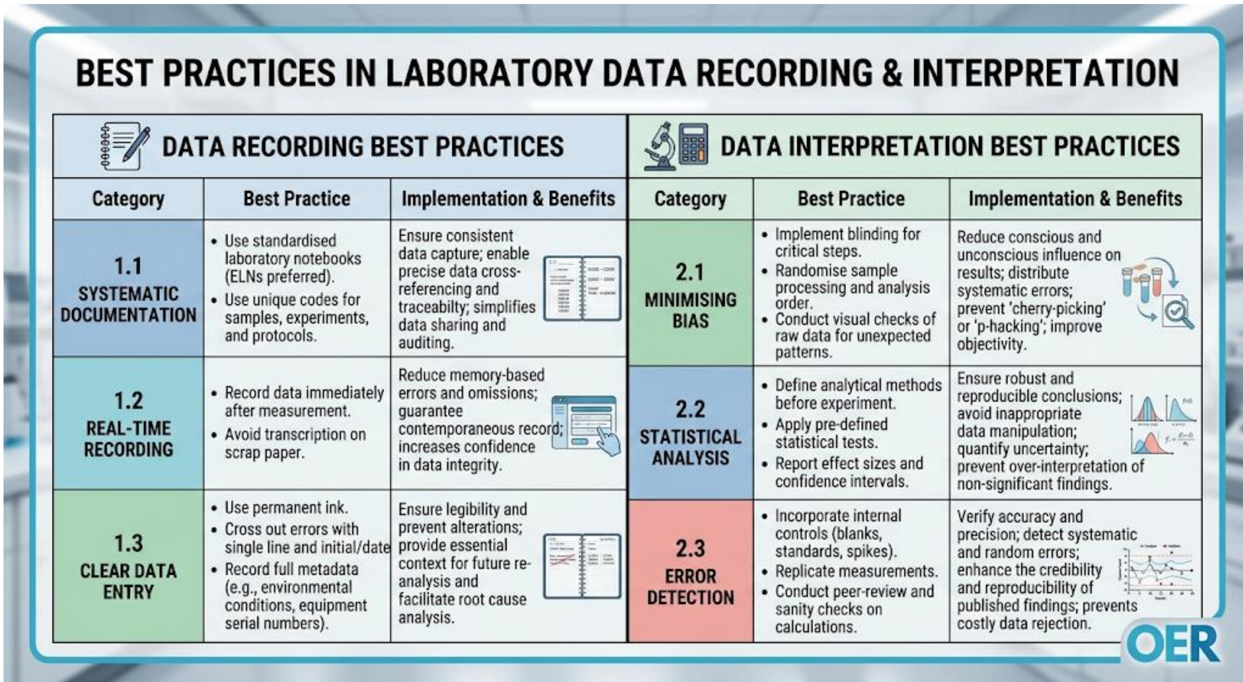



Diagram showing laboratory-scale flotation test procedure *Figure 5.3: Laboratory flotation experiment setup*

### 5.3.3 Data recording and interpretation

Accurate data recording is vital in laboratory practice. Results from sampling, assays, and separation tests must be documented systematically. Interpretation involves analysing recovery, grade, and yield to assess ore behaviour and predict plant performance. Statistical methods are often applied to ensure reliability and minimise bias.

Fill in the blank: Accurate laboratory practice requires systematic data ______ and interpretation.



BEST PRACTICES IN LABORATORY DATA RECORDING & INTERPRETATION

**DATA RECORDING BEST PRACTICES**

| Category | Best Practice | Implementation & Benefits |
|---|---|---|
| 1.1 SYSTEMATIC DOCUMENTATION | • Use standardised laboratory notebooks (ELNs preferred). • Use unique codes for samples, experiments, and protocols. | Ensure consistent data capture; enable precise data cross-referencing and traceabilty; simplifies data sharing and auditing. |
| 1.2 REAL-TIME RECORDING | • Record data immediately after measurement. • Avoid transcription on scrap paper. | Reduce memory-based errors and omissions; guarantee contemporaneous record; increases confidence in data integrity. |
| 1.3 CLEAR DATA ENTRY | • Use permanent ink. • Cross out errors with single line and initial/date • Record full metadata (e.g., environmental conditions, equipment serial numbers). | Ensure legibility and prevent alterations; provide essential context for future re-analysis and facilitate root cause analysis. |

**DATA INTERPRETATION BEST PRACTICES**

| Category | Best Practice | Implementation & Benefits |
|---|---|---|
| 2.1 MINIMISING BIAS | • Implement blinding for critical steps. • Randomise sample processing and analysis order. • Conduct visual checks of raw data for unexpected patterns. | Reduce conscious and unconscious influence on results; distribute systematic errors; prevent 'cherry-picking' or 'p-hacking'; improve objectivity. |
| 2.2 STATISTICAL ANALYSIS | • Define analytical methods before experiment. • Apply pre-defined statistical tests. • Report effect sizes and confidence intervals. | Ensure robust and reproducible conclusions; avoid inappropriate data manipulation; quantify uncertainty; prevent over-interpretation of non-significant findings. |
| 2.3 ERROR DETECTION | • Incorporate internal controls (blanks, standards, spikes). • Replicate measurements. • Conduct peer-review and sanity checks on calculations. | Verify accuracy and precision; detect systematic and random errors; enhance the credibility and reproducibility of published findings; prevents costly data rejection. |

OER

Box 5.3: Best practices in laboratory data recording and interpretation

**Pilot questions 5.3**

1. Name two pieces of equipment commonly used in mineral processing laboratories.
2. Why are safety protocols essential in laboratory practice?
3. State one type of separation test conducted in laboratories.
4. What three key parameters are measured in laboratory experiments?
5. Why is systematic data recording important in laboratory practice?

### 5.4 Application of Balances in Process Evaluation

#### 5.4.1 Calculating recovery, grade, and yield

In mineral processing, **recovery** measures the proportion of valuable metal recovered from the feed, **grade** indicates the concentration of valuable metal in a product stream, and **yield** represents the mass of product obtained relative to feed. Together, these parameters provide a comprehensive picture of process efficiency.

Fill in the blank: Recovery, grade, and ______ are key parameters in evaluating process performance.

Table 5.4: Example calculation of recovery, grade, and yield for a flotation circuit

### 5.4.2 Evaluating circuit efficiency

Circuit efficiency is assessed by comparing actual recovery and grade against theoretical or expected values. Inefficiencies may arise from poor liberation, inadequate reagent use, or equipment malfunction. Metallurgical balances help identify where losses occur in the circuit, enabling corrective actions such as adjusting grind size or reagent dosage.

Fill in the blank: Circuit efficiency is assessed by comparing actual recovery and grade against ______ values.

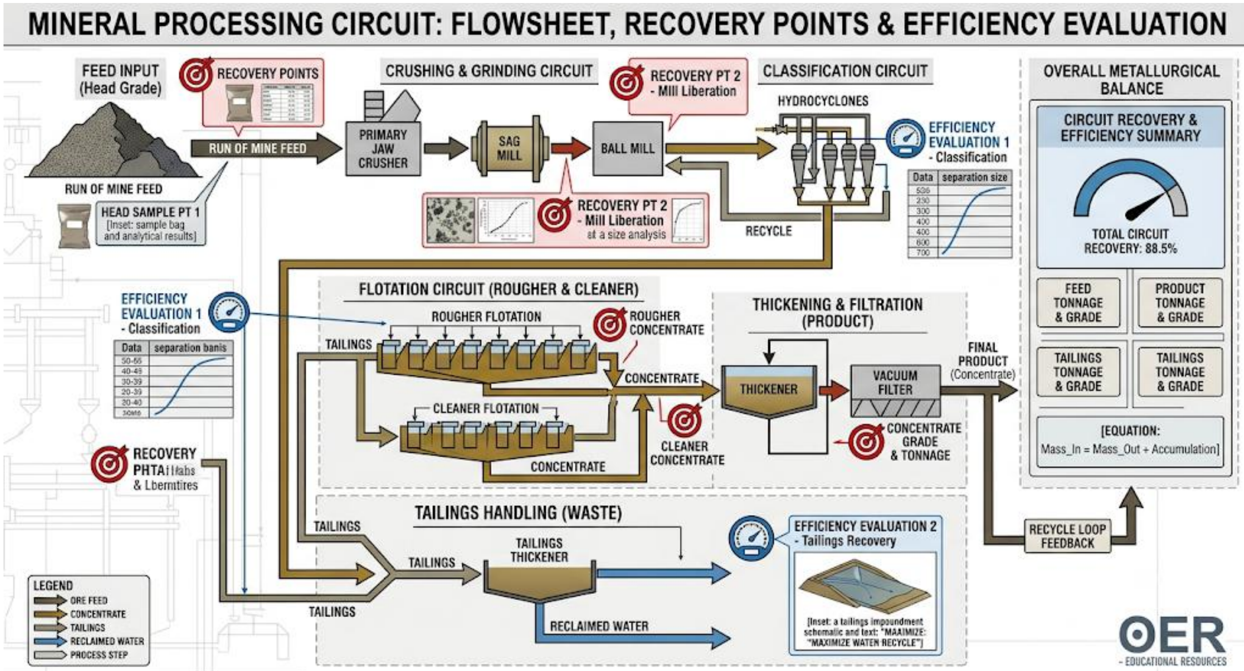
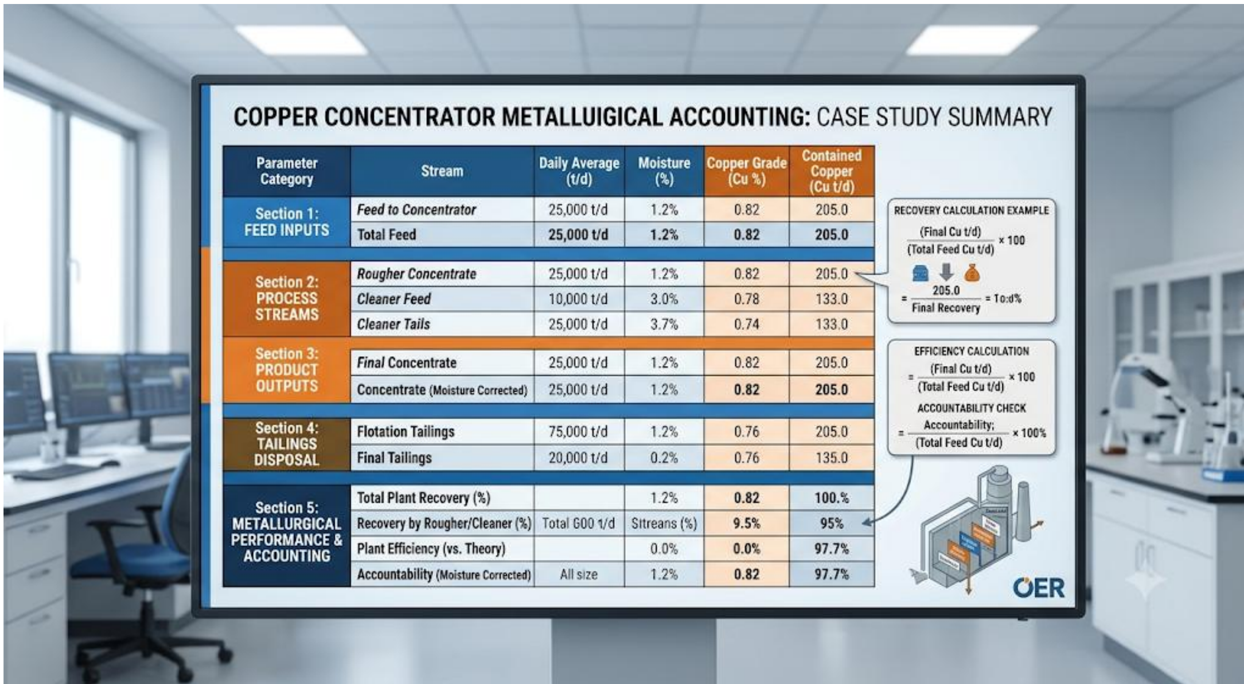



Diagram showing flowsheet with recovery points and efficiency evaluation *Figure 5.4: Evaluating circuit efficiency using metallurgical balances*

### 5.4.3 Case studies in metallurgical accounting

Case studies illustrate how metallurgical balances are applied in real-world operations. For example, a copper concentrator may use balances to track recovery across grinding, flotation, and dewatering stages. By analysing discrepancies between expected and actual recoveries, engineers can identify bottlenecks and improve plant performance.

Fill in the blank: Case studies in metallurgical accounting help identify ______ and improve plant performance.




Box 5.4: Example case study – Copper concentrator recovery analysis

**Pilot questions 5.4**

1. Define recovery, grade, and yield in mineral processing.
2. Why are these parameters important for process evaluation?
3. How is circuit efficiency assessed?
4. State one cause of inefficiency in a mineral processing circuit.
5. What is the purpose of case studies in metallurgical accounting?

**Series Summary**

This Series focused on **Metallurgical Balances and Laboratory Practice**, which are essential for ensuring accuracy and efficiency in mineral processing. We began with the principles of metallurgical balances, covering mass balance fundamentals, metal accounting, and recovery calculations. Next, we explored sampling and assay methods, highlighting representative sampling, assay techniques, and sources of error. We then examined laboratory practice, including equipment, safety protocols, experimental procedures, and data interpretation. Finally, we applied balances in process evaluation, calculating recovery, grade, and yield, assessing circuit efficiency, and reviewing case studies.

By completing this Series, you should now be able to explain metallurgical balances, apply sampling and assay methods, demonstrate laboratory practice, and evaluate process performance using balances.

**Glossary of Terms**

- **Assay**: Analytical technique used to determine the concentration of metals in a sample.
- **Grade**: The concentration of valuable metal in a product stream.
- **Laboratory practice**: Controlled experiments and procedures conducted to simulate industrial mineral processing.
- **Mass balance**: Accounting of material entering and leaving a process.
- **Metal accounting**: Quantification of valuable metal recovered compared to feed.
- **Recovery**: Percentage of valuable metal recovered from feed.
- **Representative sampling**: Collecting samples that accurately reflect the whole material.
- **Yield**: Mass of product obtained relative to feed.

**Concept Check Questions [Series 5]**

**Objective questions**

1. A mass balance ensures that total input equals total ______ plus accumulation. (Linked to SLO 5.1)
2. Fire assay is commonly used to determine the concentration of ______ metals. (Linked to SLO 5.2)
3. Laboratory safety protocols require the use of personal ______ equipment (PPE). (Linked to SLO 5.3)

**Short-answer questions**

4. Define recovery in mineral processing. (Linked to SLO 5.1)
5. State one source of sampling error. (Linked to SLO 5.2)
6. Why is systematic data recording important in laboratory practice? (Linked to SLO 5.3)

**Long-answer questions**

7. Explain the importance of metallurgical balances in plant performance. (Linked to SLO 5.1)
8. Evaluate how recovery, grade, and yield are used to assess circuit efficiency. (Linked to SLO 5.4)

**Answers to Concept Check Questions [Series 5]**

**Objective questions**

1. Output.
2. Precious.
3. Protective.

**Short-answer questions**

4. Recovery is the percentage of valuable metal recovered from feed into concentrate.
5. Segregation, size bias, or contamination.
6. It ensures reliability, minimises bias, and supports accurate interpretation of results.

**Long-answer questions**

7. Metallurgical balances are important because they monitor plant performance, identify losses, optimise operations, and ensure accountability in production reporting.
8. Recovery, grade, and yield together provide a comprehensive measure of circuit efficiency. Recovery shows how much metal is captured, grade indicates product quality, and yield reflects production volume. Comparing these values against expected results helps identify inefficiencies and guide improvements.

**Answers to Pilot Questions [Series 5]**

1. A mass balance accounts for material entering and leaving a process.
2. It ensures input equals output plus accumulation.
3. Recovery (%) = (Metal in concentrate ÷ Metal in feed) × 100.
4. They monitor performance and identify inefficiencies.
5. Applications include accountability and optimisation.
6. Representative sampling ensures accuracy.
7. Fire assay and AAS are common techniques.
8. Fire assay is used for precious metals.
9. Segregation is a source of sampling error.
10. Errors are minimised with strict protocols and quality control.
11. Crushers and flotation cells are common equipment.
12. Safety protocols protect personnel from hazards.
13. Flotation tests are common separation experiments.

14. Recovery, grade, and yield are measured.
15. Systematic recording ensures reliability.
16. Recovery, grade, and yield are key parameters.
17. Circuit efficiency is compared against theoretical values.
18. Inefficiencies may arise from poor liberation or reagent use.
19. Case studies identify bottlenecks.
20. They improve plant performance.

**References and Attributions [Series 5]**

- Figure 5.1: Mass balance principle. Suggested AI prompt: "Create a labelled diagram showing mass balance with input, output, and accumulation streams." Search string: "mass balance mineral processing diagram OER."
- Table 5.1: Recovery calculation example. Suggested AI prompt: "Create a table showing feed grade, concentrate grade, and recovery calculation." Search string: "metal recovery calculation example table OER."
- Box 5.1: Applications of metallurgical balances. Suggested AI prompt: "Create a table listing applications of metallurgical balances." Search string: "applications metallurgical balances mineral processing table OER."
- Figure 5.2: Representative sampling principle. Suggested AI prompt: "Create a labelled diagram showing representative sampling points." Search string: "representative sampling mineral processing diagram OER."
- Plate 5.2: Assay techniques. Suggested AI prompt: "Generate image of laboratory assay equipment." Search string: "assay techniques mineral processing laboratory equipment OER."
- Box 5.2: Sources of error. Suggested AI prompt: "Create a table listing sampling and assay errors." Search string: "errors in sampling and assays mineral processing table OER."
- Plate 5.3: Laboratory equipment and safety. Suggested AI prompt: "Generate image of mineral processing laboratory with flotation cells and PPE." Search string: "mineral processing laboratory equipment safety OER."
- Figure 5.3: Laboratory flotation experiment. Suggested AI prompt: "Create a labelled diagram showing flotation test procedure." Search string: "laboratory flotation experiment diagram OER."

- Box 5.3: Best practices in data recording. Suggested AI prompt: “Create a table listing best practices in laboratory data recording.” Search string: “laboratory data recording interpretation best practices table OER.”
- Table 5.4: Recovery, grade, yield calculation. Suggested AI prompt: “Create a table showing feed, concentrate, tailings data with recovery, grade, yield.” Search string: “recovery grade yield calculation mineral processing table OER.”
- Figure 5.4: Circuit efficiency evaluation. Suggested AI prompt: “Create a labelled diagram showing mineral processing circuit efficiency evaluation.” Search string: “circuit efficiency metallurgical balances diagram OER.”
- Box 5.4: Case study example. Suggested AI prompt: “Create a table summarising copper concentrator case study.” Search string: “copper concentrator metallurgical accounting case study table OER.”