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Mining and Processing of Mineral Resources: A Comparative Study of Simulated and Operational Processes

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Abstract

The aim of this study is to analyze the representation of geological, mining, processing, and environmental processes in platform Minecraft. Based on a methodological comparison of in-platform mechanics with technological and geoscientific procedures, the article assesses the degree of accuracy, simplification, and didactic applicability of individual processes related to the extraction and use of mineral resources. The analysis is structured into seven main thematic areas covering the entire resource value chain—from geological exploration through mining, ore beneficiation and processing, to quantitative indicators (e.g., waste-to-ore ratio), fluid resources, and environmental impacts. Special attention is given to the potential of modifications that significantly enhance the complexity and accuracy of simulated processes. The results show that Minecraft, enriched with thematic mods, can serve as an accessible and flexible tool for the popularization and education of industrial and geoscientific processes, while engaging a wide range of audiences.

Keywords: Minecraft; mineral resources; mining; processing engineering; resource value chain; environmental impact

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Academic Editors: Feng Du, Leilei Si, Chaojun Fan and Qiming Zhuo

Received: 17 July 2025
Revised: 14 August 2025
Accepted: 18 August 2025
Published: 3 September 2025

Citation: Rybár, R.; Beer, M.; Bednárová, L. Mining and Processing of Mineral Resources: A Comparative Study of Simulated and Operational Processes. *Processes* **2025**, *13*, 2823. https://doi.org/10.3390/pr13092823

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1. Introduction

Today's world faces challenges that are closely tied to the ways in which we extract and utilize mineral resources. As noted by [1], mineral resource extraction has been one of the key activities shaping the development of human society from prehistory to the present day. Climate change, geopolitical instability, and the growing demand for critical raw materials—such as lithium, copper, cobalt, and rare earth elements—highlight the urgent need for greater awareness of the processes involved in geological exploration, mining, and resource processing [2]. Nevertheless, this topic remains complex, poorly understood by the general public, and often controversial. The communication gap between the expert community and the wider society can result in misunderstandings, oversimplifications, or even rejection of the scientific and technological aspects of mineral resource utilization.

As noted in [3], there is a growing importance of informal education and popularization tools that can convey scientific knowledge in an engaging and accessible manner. One of the most prominent digital phenomena proving to be a suitable platform for developing scientific thinking and acquiring geoscientific concepts is the platform Minecraft. This platform, developed by Mojang Studios, is based on a system of interaction with an environment composed of unit-based blocks representing various materials and objects [4]. With more than 140 million active players per month and a vast community of users, educators,

and content creators, Minecraft represents a unique space for bridging gameplay with scientific education [5–9].

One of the key mechanics in Minecraft is the extraction of mineral resources. The player explores a procedurally generated world, searches for and mines various types of ores—from coal and iron to copper, gold, diamonds, and emeralds. These ores appear in the game based on depth, rock type, and environment. In newer versions of Minecraft (particularly since version 1.18), the ore distribution system partially reflects geological principles such as stratigraphic layering, localized occurrences, and large ore veins. Examples of raw material blocks, the distribution of raw material blocks within the rock environment, and the approach to designing a mining excavation for surface mineral extraction in Minecraft are shown in Figure 1. While these processes are simplified in the base version of the Minecraft, various community-developed modifications (e.g., BetterGeo, Immersive Geology, Geoimmersion) greatly enhance the level of geological realism, allowing players to simulate complex processes related to exploration, mining, and mineral processing [2]. These mods introduce advanced features such as chemical separation, gravity-based sorting, oil extraction, fuel refining, and realistic mining technologies involving appropriate equipment and tools.

Gamified learning is an approach in which game elements—such as points, levels, challenges, or storylines—are integrated into educational activities to increase participant engagement and motivation. In the context of geoscience disciplines, this approach has proven particularly effective, as it enables the combination of visually appealing and interactive environments with solving real-world problems and modeling natural processes [10]. Studies confirm that gamification supports deeper cognitive engagement, experimentation, and collaboration, while enhancing the ability to transfer acquired knowledge into practical situations [11]. The latest systematic review of gamification in geoscience education highlights that this approach has high potential for developing spatial thinking, understanding complex processes, and ensuring long-term knowledge retention, especially when specialized digital tools and simulations are utilized [12].

Numerous scientific studies and projects over the past decade have confirmed that Minecraft holds significant potential for education and the popularization of scientific topics, including geoscientific disciplines [13–21]. A systematic review of research published in [22] demonstrated that Minecraft is utilized in educational contexts across a wide range of fields—from mathematics and physics to biology and technology—while emphasizing that the application of the game in geology and mineral resource sciences remains relatively uncommon. Similarly, the study in [13] identified three primary areas of educational use: integration into formal instruction, enhancement of student engagement, and development of practical skills. Although these studies highlight a high degree of motivation and interactivity, they rarely address content accuracy or analogies with real-world geological processes.

In the Minecraft environment, there is a concept of modifications (mods), which are external software extensions that alter or expand the original game content. These add-ons, most often created by the gaming community or independent developers, can change existing game mechanics, add new objects, blocks, tools, game modes, or entire technological systems. The scope of modifications ranges from simple add-ons (e.g., new decorative elements or changes to the user interface) to complex expansions that simulate realistic geological processes, mining techniques, raw material processing, and energy systems that are absent in the base game. For instance, the BetterGeoEdu project, supported by the EIT RawMaterials initiative, developed the BetterGeo extension, which enriches the world of Minecraft with realistic geological layers, new minerals, rocks, and processing techniques [23]. The aim of the project was to introduce students to basic

geological principles, responsible resource management, and the environmental aspects of mining. Similarly, the British Geological Survey (BGS) used Minecraft to visualize the geological structure of the United Kingdom, allowing the public to perceive rock layers that would otherwise remain inaccessible. Several case studies also demonstrate that Minecraft can serve as an effective tool for conveying concepts such as stratigraphy, the rock cycle, or geochemical phenomena through simulations of layering, precipitation, deformation, and player interaction with the environment [24–26]. Research published in [27] shows how students modeled cave systems, planetary structures, or landscape evolution, highlighting the platform's strong potential for developing spatial imagination and fundamental geoscience concepts.

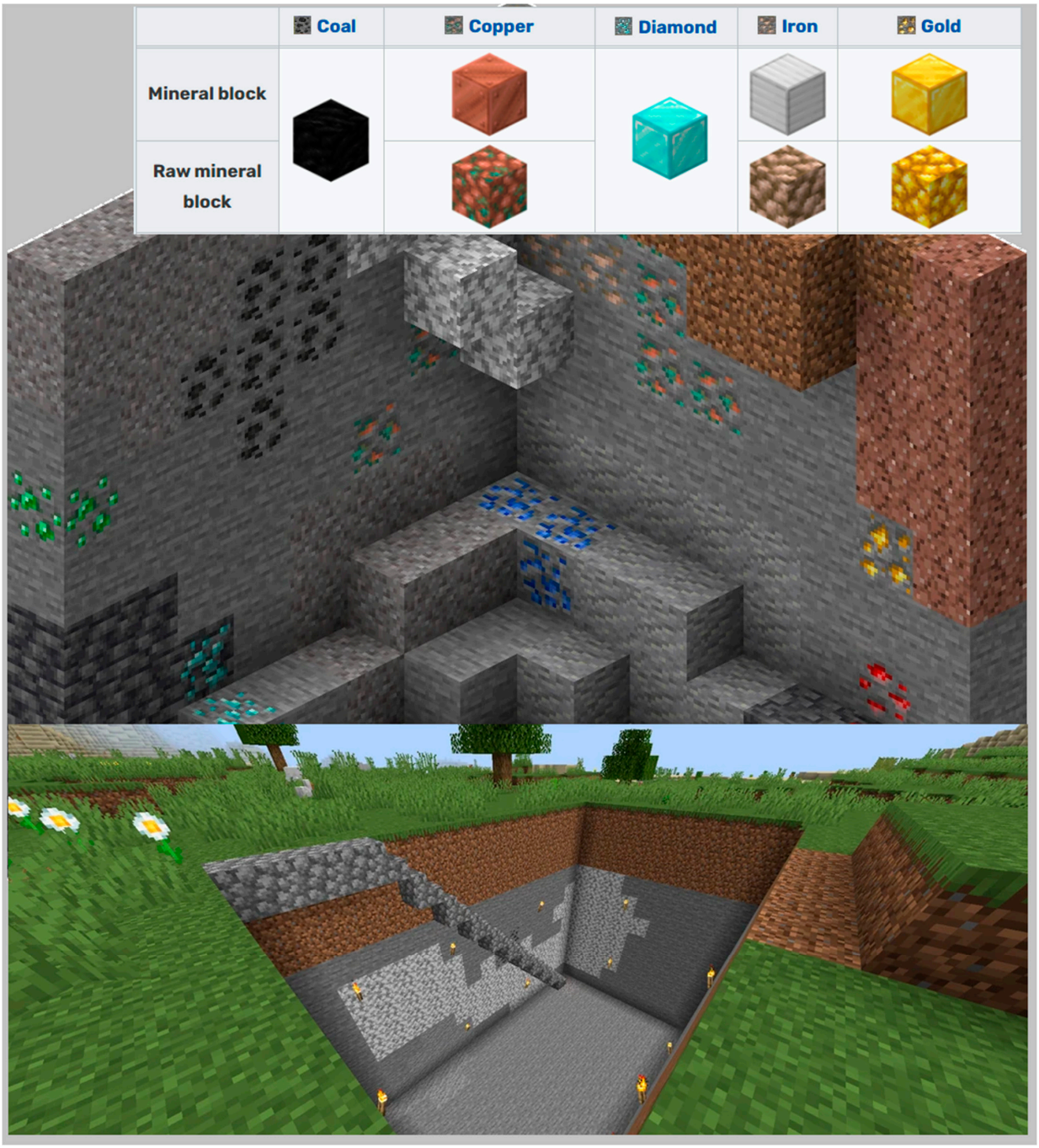


Figure 1. A composite image showing examples of raw material blocks, the distribution of raw material blocks within the rock environment, and the design of a mining excavation for surface mineral extraction in Minecraft.

Despite these positive examples, the academic literature has so far only marginally addressed deeper process-level analysis—that is, the extent to which Minecraft's mechanisms correspond to real-world processes of exploration, extraction, beneficiation, and processing of mineral resources. Most existing studies focus on qualitative aspects of learning, player motivation, or specific classroom applications. What remains largely absent is a systematic comparison of concrete process steps in the platform versus those in industry—such as deposit formation, geological prospecting, rock fragmentation, sorting, flotation, or chemical treatment of ores. This gap provides the impetus for our research, which focuses precisely on these aspects.

In this study, we concentrate on a detailed analysis of how specific processes are represented in Minecraft, how closely they align with actual geoscientific and engineering practices, and what their educational potential and limitations are. In doing so, we aim to expand current knowledge about the use of digital gaming platforms in education and scientific communication, with special attention given to the complex nature of the raw material cycle as a system of interconnected natural and technological processes.

This study aims to systematically examine how accurately Minecraft represents individual aspects of the real-world mineral resource acquisition processes. It focuses on the following key research questions:

(1) To what extent are the game mechanics of mining, ore distribution, and processing aligned with geological and technological realities?
(2) What analogies can be drawn between mining techniques in the game and real-world extraction methods (e.g., underground vs. surface mining)?
(3) What is the educational potential of the base Minecraft game and its modifications in the context of teaching geoscientific and engineering disciplines?
(4) Where are the limits of simplification in the game's model, and what risks may arise from its uncritical use in educational contexts?

A specific contribution of this work lies in the comparison of quantitative parameters—such as the waste-to-ore ratio, depth-based ore distribution, or separation processes—with real geological data and industrial practices. Such comparisons make it possible to identify both the strengths and limitations of the game model, while also creating opportunities to propose potential modifications or expansions aimed at increasing its scientific accuracy and didactic value.

2. Materials and Methods

This study focuses on the analysis of selected processes within the environment of Minecraft—including its educational and modified versions—that resemble real-world geological, mining, and mineral processing operations. The objective was to systematically examine the extent to which in-game mechanisms represent the fundamental stages of the real raw material cycle and to assess their didactic potential for use in education and the popularization of mineral resource acquisition processes. In this context, Minecraft was approached as a simplified, model-representational system that enables the simulation of complex natural and technological phenomena in an accessible and interactive digital form.

The methodological framework of the study was based on a multi-level comparison between virtual game processes and their real industrial or geoscientific counterparts. The analysis combined qualitative and comparative approaches, with the primary aim not to evaluate the completeness or accuracy of individual models, but rather their ability to faithfully reflect the structure and logic of actual raw material processes.

Data collection was conducted in parallel from multiple sources [28–32]. The first group consisted of official documentation and community wiki platforms focused on Minecraft (e.g., Minecraft Wiki, BetterGeo Wiki, and the Modrinth and CurseForge mod-

ding sites), which describe game mechanics such as ore distribution, crafting recipes, generation of geological structures, and tool usage. These sources provided essential information on the functionality of individual game elements in the context of resource acquisition. The second group included monographs [33–35], as well as scientific and technical articles dealing with real-world processes of geological exploration, mining, separation, and mineral processing [36–48]. These materials were crucial for establishing a reference framework through which the degree of analogy and fidelity of in-game processes could be assessed.

An important component of the study involved practical observation of game mechanics. This included the use of gameplay videos—particularly "mod showcases" on the YouTube platform—as well as direct observation of the game environment in both the base version of Minecraft (version 1.18 and above) and modified versions incorporating mods such as BetterGeo, BuildCraft, Immersive Engineering, Immersive Petroleum, Geoimmersion, TerraFirmaCraft, and Rocks Done Right. These modifications were selected based on their thematic focus on geological and mining elements and analyzed in terms of implemented processes, levels of simulation, structure of input–output operations, and visualization capabilities [49]. The selection of mods was guided by two main criteria: (1) the mod had to expand or more realistically simulate a specific phase of the mineral resource value chain, and (2) it had to be technically stable and compatible with the current version of the game. Only publicly available and well-documented mods were included.

Supplementary sources included discussion forums and player communities on platforms such as Reddit and Discord, which provided feedback and insights on the practical use of mods, including their advantages and limitations from the players' perspective—an important consideration when evaluating their didactic application.

Numerical data on ore occurrence and generation parameters were obtained through a combination of direct observation in three independently generated worlds (default seed, ver. 1.18+) and verified by comparison with results from community measurements available on the Minecraft Wiki and player forums. Each world was explored for approximately 6–8 h, with vertical profiles, ore counts per chunk, and average W:O ratios being mapped.

For the purposes of analysis, in-game processes were classified into thematic categories reflecting the real-world raw material value chain:

(1) Geological formation and distribution of resources,
(2) Geological exploration processes,
(3) Mining techniques and resource extraction,
(4) Beneficiation and processing of raw materials,
(5) Waste-to-ore ratio,
(6) Fluid-phase resources,
(7) Environmental and systemic processes.

Within each category, specific game elements (blocks, structures, tools, machines) that represent a given process or operation were identified. These elements were subsequently compared with real-world industrial technologies and standards applied in mining and mineral processing practices.

The comparison was conducted according to several criteria. The first was technological accuracy, meaning the extent to which game mechanics correspond to real-world processes (e.g., deposit formation, stratigraphic structure, extraction techniques, separation principles). The second criterion was processual consistency, the coherence of individual operations and their logical arrangement into a functional sequence. The third was quantitative realism, which involved examining factors such as the waste-to-ore ratio, ore yield, vertical distribution, rarity of elements, and related parameters. Additional criteria

included the degree of simplification (abstraction from real-world models) and didactic potential (accessibility, clarity, memorability, and the ability to convey core principles).

The analysis was carried out in iterative steps: identification of an in-game process → determination of its real-world equivalent → qualitative and quantitative comparison → evaluation of similarities, discrepancies, and educational applicability. This methodological approach enabled not only a descriptive but also an evaluative assessment of how effectively and realistically Minecraft, as a digital model, can convey the complex domain of geological and technological processes. From the perspective of result validation and reproducibility verification, it is essential to note that the primary information base relied on the most reputable platforms in the field, such as Reddit (e.g., subreddits r/Minecraft or r/feedthebeast) and Discord servers, which contain empirical insights not explicitly stated in official descriptions and obtained directly by users. From a formalized perspective, this study has several methodological limitations, as full data triangulation was not applied—the results are based primarily on observations and the analysis of available in-game and community sources, without direct verification through experimental testing or surveys among players and educators. The scope of examined game worlds, modifications, and versions was also limited, although this was intended to eliminate marginal forms. However, given the nature of the examined processes and environment, these factors should not affect the broader interpretation of the results or their application in educational or research contexts. The authors believe that implementing some of the steps listed here as methodological limitations could, in fact, lead to a narrowing of validity or possible distortion of results, due to the increased influence of subjective inputs from a limited group of users. The results of this analysis are presented in the following sections of the article.

3. Results and Discussion

The results of this study are based on a systematic analysis aimed at comparing the individual processes related to the exploration, extraction, beneficiation, and processing of mineral resources within the Minecraft game environment with their real-world industrial and geological counterparts. Drawing from observations and examinations of both the base game mechanics and selected technical modifications, the study explored the degree of process accuracy, complexity, and didactic potential of specific activities. Attention was given not only to technical aspects—such as mining techniques, raw material processing, or the treatment of fluid resources—but also to broader systemic connections, including the waste-to-ore ratio, environmental impacts, and the game's ability to convey complex technological chains.

Each of the following subsections focuses on a specific type of process and its representation within the game, with the objective of evaluating the extent to which Minecraft can be utilized as a tool for illustrative, publicly accessible, and scientifically informed education on the acquisition and processing of mineral resources.

3.1. Geological Formation and Resource Distribution

One of the key aspects of realistically simulating mining processes is how geological conditions—particularly the formation of the rock environment and the distribution of mineral resources—are represented in the model. In the base version of Minecraft, rocks and ores are generated through procedural generation algorithms that create a three-dimensional environment composed of voxels (blocks). Each world is generated randomly, with primary block types including stone, deepslate, and various rocks such as granite, diorite, and andesite. These rock types are distributed along a vertical profile, with a significant breakthrough in geological accuracy introduced in version 1.18. This update

implemented a new ore distribution algorithm based on uneven probability patterns and the principle of Reduced Air Exposure (RAE), which limits the visibility of certain ores in air-exposed environments.

In the Minecraft coordinate system, the height or depth of a block in the game world is represented by the Y coordinate, with Y = 0 corresponding approximately to sea level. Positive values represent features with positive elevation above sea level, while negative values indicate elevations below sea level. The game's vertical space in current versions (1.18 and above) extends from Y = −64 (the deepest possible layer) to Y = +320 (the maximum build height). There is no direct conversion between in-game Y-levels and real-world depths; however, it is commonly assumed that 1 Y unit roughly corresponds to 1 m. This represents a simplified analogy to real geological depth.

The distribution of individual ores in the game (e.g., coal, iron, copper, gold, diamonds, redstone, emeralds) is defined in newer versions through depth-dependent distribution curves that form so-called triangular occurrence patterns. For example, iron ore is most commonly found in subsurface layers between levels Y = −24 and Y = 54, peaking around Y = 16. Diamonds occur below Y = −16, with their frequency increasing with depth down to bedrock. This pattern reflects a fundamental principle of vertical stratification of ore deposits and introduces a degree of analogy to real geological processes such as magmatic differentiation, hydrothermal mineralization, or metamorphic zoning. The vertical distribution of ores in Minecraft (version 1.18+) by Y-level is illustrated in Figure 2, showing a clear correlation with specific rock environment horizons and a recognizable analogy to the vertical stratification seen in the distribution of mineral resources, depending on the formation mechanisms of their deposits.

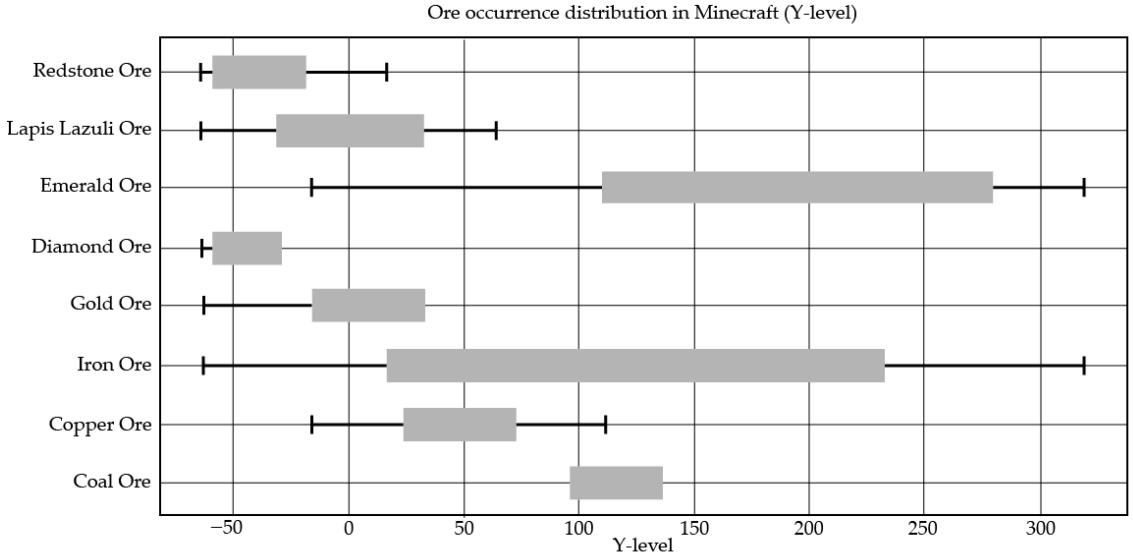


Figure 2. Vertical distribution of ores in Minecraft (Version 1.18+) by Y-level occurrence.

Despite this analogy, the in-game distribution does not account for broader geotectonic relationships, typological classification of ore deposits (e.g., magmatic, sedimentary, or metamorphic), or their association with structures such as fault zones, intrusions, or geochemical anomalies. All ores are dispersed as relatively homogeneous clusters (so-called ore veins), which are generated independently of the genetic type or lithological characteristics of the surrounding rock. In reality, ore deposits exhibit complex geometries, structures, and connections to specific rock complexes and tectonic settings.

From a didactic perspective, however, this represents a significant advancement over earlier versions of the game. The updated algorithm allows players to recognize the basic

principle of stratigraphic variability and depth-dependent resource occurrence. Moreover, the Minecraft environment enables straightforward visualization of the vertical profile of a rock mass and allows for the systematic observation of compositional changes—making it particularly suitable for explaining fundamental geological concepts such as layers, horizons, overburden/bedrock, and zonality.

Mods such as BetterGeo (developed by the Geological Survey of Sweden (SGU) with the support of the BetterGeoEdu project funded by the EIT RawMaterials initiative) and Geolosys are significantly more complex in terms of geology and the mineral resource chain. On the other hand, without accompanying explanations or teacher guidance, they are difficult to grasp and complicated for laypersons or the main target group of Minecraft users. In an educational environment (with a teacher or a worksheet), however, they can be very beneficial and understandable. The application of these mods is thus more suited to guided instruction or as part of project-based learning. An important factor in resource acquisition is the abundance of individual minerals that serve as sources of chemical elements or compounds, or more specifically, the relative concentration of these elements within the rock environment. In geochemistry, this aspect is quantified using the Clarke value (or clarke), which represents the average concentration (or relative abundance) of a chemical element in a given geological entity [50].

Since Minecraft does not provide precise values for ore occurrence or elemental content (e.g., in ppm), a simplified approach can be adopted by introducing a quantifier called the Game Occurrence Index (GOI). This index represents the relative abundance of ores as defined by the game's generation algorithms. The GOI can be based on the average number of blocks of a given ore generated in a standard Minecraft world (version 1.18+) per unit of volume, such as a chunk, derived from community-reported world generation data. A higher value indicates greater abundance.

To express relative proportions, both the GOI and real-world Clarke values (in ppm) are normalized to a base value of 1. This allows proportional comparison between the abundance of elements in the Earth's crust, according to Clarke values [51], and their modeled abundance in the game environment. The results are presented in Table 1, taking into account values valid for the main game world, the Overworld, excluding the Badlands biome. Including this biome could distort the results due to the anomalously high occurrence of gold in this specific biome.

Table 1. Quantitative comparison of Clarke values (ppm) for the Earth's crust, with the GOI for selected elements.

Element (Ore)	Real World: Clarke Number [ppm]	Minecraft: Game Occurrence Index [Number of Blocks Per Chunk]	Real World: Relative Abundance (vs. Iron)	Minecraft: Relative Abundance (vs. Iron)	Consistency in Occurrence Rate
Iron (Fe)	56,300	200–300	1	1	Yes (most abundant)
Copper (Cu)	60	150–250	~0.001 (1/938)	~0.7 (1/1.4)	No (significantly higher in Minecraft)
Carbon/Diamond (C)	~200 (total C)	1–5 (max value at Y = −58)	~0.0035 (1/281)	~0.005 (1/200–1/400)	Yes (very low)
Gold (Au)	0.004	5–15 (Overworld, without Badlands)	~0.00000007 (1/14,075,000)	~0.04 (1/10–1/5)	No (significantly higher in Minecraft)

From the perspective of identifying analogies, the values of the GOI indicate that, relatively speaking, iron ranks highest in abundance both in Minecraft and in the real world. Copper is represented by a lower Clarke value in nature (approximately 0.001 relative to

iron), yet in Minecraft, its GOI approaches that of iron (0.7), suggesting a prioritization of gameplay mechanics over geochemical realism.

For carbon—represented in the game primarily as diamond—this methodology is more problematic. If we consider total carbon, which corresponds to the Clarke value, a major discrepancy arises due to the relatively low abundance of carbon in nature versus the high abundance of coal in the game. On the other hand, if we consider only diamond, the Clarke value for carbon does not reflect the rarity of this specific allotrope. This example highlights the limitations and nuances involved in mapping natural phenomena and real-world processes into simplified game environments.

Although it is not possible to directly compare the Clarke value of total carbon with the abundance of diamonds in Minecraft, the game successfully simulates the extreme rarity of diamonds, consistent with their exceptional status in nature. The difference in abundance between iron and diamonds in the game (200–300 vs. 1–5 blocks per chunk) serves as a simplified representation of the large disparity between common metals and rare elements or resources in natural settings.

Gold is the rarest of the elements compared in the Earth's crust, with a Clarke value of approximately 0.00000007 relative to iron. While gold is relatively rare in Minecraft, it is still considerably more abundant than in nature (GOI $\approx$ 0.04). This represents the most pronounced deviation from Clarke values in favor of game design balance.

If we express these values in terms of block abundance, we can state the average occurrence of selected ores per chunk. This is visually represented in Figure 3, which also includes error bars illustrating the minimum and maximum number of blocks.

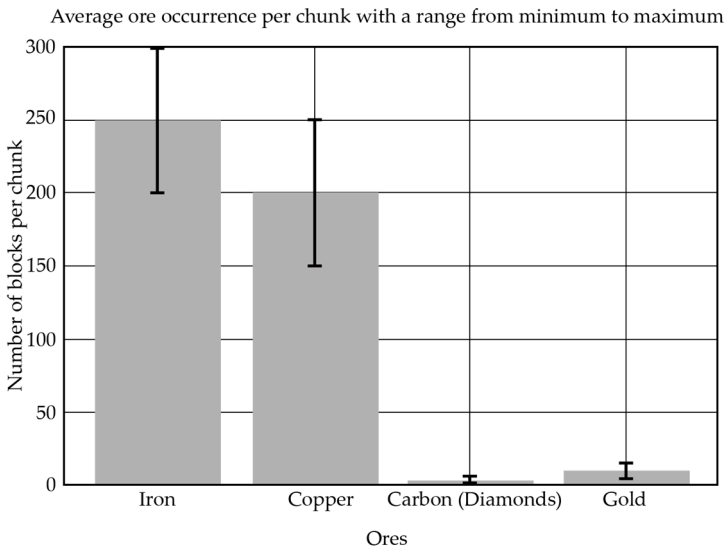


Figure 3. Average occurrence of selected ores/elements per chunk.

Overall, it can be concluded that the in-game representation of geological formation and resource distribution constitutes a simplified yet didactically effective model. It successfully conveys the vertical organization of geological phenomena and the importance of depth for the occurrence of mineral resources. From the perspective of process fidelity, it is a partially accurate model that, however, omits most genetic, structural, and geochemical aspects of real-world geology. The relative abundance of iron and the extreme rarity of diamonds in Minecraft reflect their actual distribution in nature. Nevertheless, the game significantly compresses the abundance range of other ores, particularly copper and gold. This "compression" serves gameplay purposes, as the extreme differences present in real-world geochemistry would otherwise make it excessively difficult for players to access various materials within a reasonable timeframe. Both approaches—realistic and

in-game—demonstrate that Minecraft incorporates principles of mineral and elemental distribution from the real world, albeit with highly adjusted values to support playability.

While the base version of Minecraft offers only highly simplified models of the occurrence and distribution of mineral resources, specialized modifications such as BetterGeo, GeoImmersion, or TerraFirmaCraft already introduce more realistic geological layers, genetic deposit types, and their relationships to specific rock complexes or tectonic environments into the game world. In some cases, they even simulate processes such as metamorphism, hydrothermal mineralization, or sedimentary deposition. These approaches approximate scientific geological simulations and can be used for teaching economic geology and ore deposit models. Our study, however, focused primarily on mainstream game mechanics and easily accessible modifications suitable for developing geoscience awareness among the general population and younger players. Detailed integration of complex geological models into Minecraft would require dedicated research and targeted methodological development. Nevertheless, given increasingly complex technologies that rely on a wide spectrum of materials and resources, even non-specialized mods would benefit from gradually incorporating critical elements such as molybdenum, nickel, lithium, lead and zinc, silver, and some others. The importance of this is also highlighted by the findings published in sources [52–59]. A simplified representation of tectonic features could be integrated into the base version of Minecraft to provide players with a basic understanding of the relationship between geological processes and the distribution of mineral resources. Potential implementations include the following:

Tectonic Map Layers: A simple color-coded overlay indicating different tectonic settings (convergent, divergent, and transform boundaries), which would influence the types and abundances of ores generated.

Fault Lines: Distinctive rock bands visually representing fault zones, signaling potential concentrations of certain minerals or the presence of hydrothermal veins.

Volcanic Zones: Areas with increased volcanic activity (e.g., lava outflows, already partially represented in the game), suggesting the occurrence of ores such as copper, gold, or rare minerals.

Sedimentary Basins: Lowland areas with layered rock formations where deposits of coal and similar resources could be concentrated.

These features would not require complex graphics or advanced simulations, yet they would provide intuitive cues for players, linking ore locations and geological contexts with tectonic processes.

From the perspective of incorporating the perception of geological time, it could be proposed that the distribution of geological formations over time be reflected in the game through phased world generation and the use of special maps simulating ancient geological periods, thereby providing the player with information on the geological evolution of the entire represented environment.

3.2. Geological Exploration Processes

In the real world, geological exploration represents a key phase in the mineral resource acquisition chain, during which geological conditions are systematically mapped, deposits identified, and their economic potential evaluated. This process includes a range of methods, from field observation and geophysical and geochemical analyses to exploratory drilling and deposit modeling. In the base version of Minecraft, however, exploration is not conceived as a distinct phase, but rather as an intuitive activity tied to world discovery—that is, as an integral part of gameplay itself. The player gains knowledge of the environment primarily through visual inspection of the surface and underground, or indirectly

through trial-and-error detection of ores while mining. This approach more closely resembles a pre-industrial, "manual" data-gathering technique, lacking systematic tools.

Some player strategies, such as branch mining or strip mining, do represent optimized exploration techniques based on statistical coverage of rock volume and maximizing the chance of ore discovery. However, these are not formal processes, but rather emergent gameplay behaviors shaped by the mechanics of the game. The base game lacks tools for remote ore detection, geophysical measurement, or geological unit mapping. Consequently, it does not provide a realistic representation of geological exploration as a technical-scientific process. This absence limits the understanding of the importance of pre-mining preparation and makes it difficult to communicate essential aspects such as economic feasibility, geological uncertainty, or resource and reserve classification.

A significant advancement is observed with the use of thematic modifications (mods), which explicitly introduce mechanics corresponding to geological exploration. A prime example is the Immersive Engineering mod, which includes a Core Sample Drill that allows players to determine the type of resources located beneath the surface in a given region. This simulates real-world core drilling and deposit modeling and introduces elements of planning, decision-making, and dealing with uncertainty. Similarly, the BetterGeo mod expands the game with basic geological mapping and rock classification, enabling players to predict typical ore associations based on the geological environment.

Other mods such as GeoImmersion or TerraFirmaCraft enrich the game with geochemical parameters of the environment, allowing players to locate deposits based on rock type, depth, or geological domain. These elements significantly enhance the processual realism of the game and allow players to experience geological exploration as a structured phase of the mining cycle. Furthermore, by enabling players to make decisions based on exploration data, the didactic potential of the model increases, creating opportunities to explain principles such as geological prediction, economic efficiency, and mine planning.

From a process-oriented perspective, Minecraft in its base version represents exploration only in a very simplified manner—as random discovery. It is only through specific modifications that this phase may be transformed into a meaningful, structured process analogous to real-world geoscientific and industrial activities. These modifications therefore serve as important tools for education in geology, mineral prospecting, and mining planning.

These statements align well with the findings presented in [52], which indicate that in the field of geology, most teachers are still aware of the potential of games to motivate, enhance, and reinforce the learning of geological content, with digital games being the preferred option. They emphasize the importance of teacher training in this area and the inclusion of game-based applications in school curricula to address various geology-related topics. The presented results suggest a certain lack of consistency in teachers' views on the impact of games on student learning, which creates room for improvement. In the study presented in [60], the authors implemented a virtual course based on Minecraft that achieved both curricular and extracurricular objectives, with its development being relatively simple. They recommend using Minecraft in the future specifically for virtual courses focused on aspects of geological exploration.

To strengthen the geological exploration aspect within the base version of Minecraft, several concepts are proposed:

Observation of Surface Indicators: Implementation of simple "indicator blocks" or rock discolorations on the surface (e.g., small random mineral grains embedded in stone) to suggest the possible presence of ore deposits underground.

Educational effect: Introduces the concept of geological indicators and their role in identifying target exploration sites.

Basic Geological Map: Development of a map displaying rock types in the surrounding area down to a specific depth.

Educational effect: Explains that different minerals are associated with specific geological environments.

Test Pits: Inclusion of small, rapidly deployable exploratory pits revealing surrounding rock layers, with an optional extension to exploratory drilling combined with schematic core analysis.

Educational effect: Demonstrates that exploration activities can include small-scale sampling and subsurface investigation techniques.

Basic Rock Classification: Provision of simplified information about a rock block after mining or examination, linked to the occurrence of specific valuable minerals.

Educational effect: Connects rock types with the typical occurrence of certain ores.

Simple Deposit Potential Assessment: After the discovery of a defined quantity of ore, display an estimate of the deposit's potential (e.g., "rich deposit" vs. "small occurrence").

Educational effect: Introduces the concept of economic viability in mineral resource extraction.

The integration of these elements would enable players to intuitively explore geological concepts such as indicator recognition, geological mapping, sampling, identification of lithological environments, and preliminary economic assessment, while preserving both the entertainment value and the educational potential of the game.

3.3. Mining Techniques and Resource Extraction

The extraction of mineral resources in the real world represents a complex system of technical operations aimed at efficiently, safely, and economically retrieving valuable minerals from the geological environment. These processes involve selecting appropriate mining methods, employing specialized equipment, excavating mine workings, ventilation, dewatering, implementing safety measures, and conducting environmental monitoring. In Minecraft, the mining process is significantly simplified but still exhibits several elements that can be interpreted as abstract models of real-world mining techniques.

In the base version of the game, players extract mineral resources manually using handheld tools—pickaxes—whose efficiency, speed, and durability depend on the material from which they are crafted (wood, stone, iron, diamond, netherite). Netherite is a fictional material that, while occupying the position of the strongest material in the game, has no analog in the real world and is therefore not the subject of our study; it is mentioned here for completeness only. The hierarchy of tools clearly reflects an analogy with the progressive enhancement of material quality and tool design in real mining practices. However, the use of certain materials (e.g., gold) should be interpreted more of a symbolic representation of value rather than a reflection of actual physical and technological properties.

The varying breakability (hardness) of blocks, which determines how long it takes to break them in Minecraft, is represented by the Mining Speed/Time parameter. Each block has an internal hardness value assigned (stone: 1.5, iron ore: 3, diamond ore: 3, obsidian: 50), and each pickaxe type has a base speed modifier (e.g., wooden: 2×, stone: 4×, iron: 6×, diamond: 8×, netherite: 9×). Minecraft also implements the concept of enchantments, which enhance tool performance. The Efficiency enchantment significantly reduces mining time, with each level increasing the mining speed by 25% compared to the tool's base speed (Efficiency I: +25%; Efficiency V: +125%). The Fortune enchantment increases the average quantity of ore dropped as follows: Fortune I: 1–2× (average 1.5×); Fortune II: 1–3× (average 2×); Fortune III: 1–4× (average 2.5×). The Silk Touch enchantment allows for the retrieval of the block itself rather than its fragmented form. This can be understood

as a mining process without separation or transformation, representing an analogous equivalent to the extraction of raw material without beneficiation.

The enchantment system can be viewed as analogous to real-world factors that influence the efficiency and yield of mining operations. It reflects an optimization process aimed at maximizing resource gain (material per unit time) relative to investment in tools and upgrades. Figure 4 illustrates the mining time curves for selected blocks (stone, obsidian, diamond ore) depending on tool type and Efficiency enchantment level. It is evident that for harder blocks such as obsidian, the differences in required mining time are more pronounced across tool types, whereas for softer blocks, the differences are less significant. This serves as a meaningful analogy to the impact of tool type relative to mineral hardness or ease of fragmentation in real-world extraction processes.

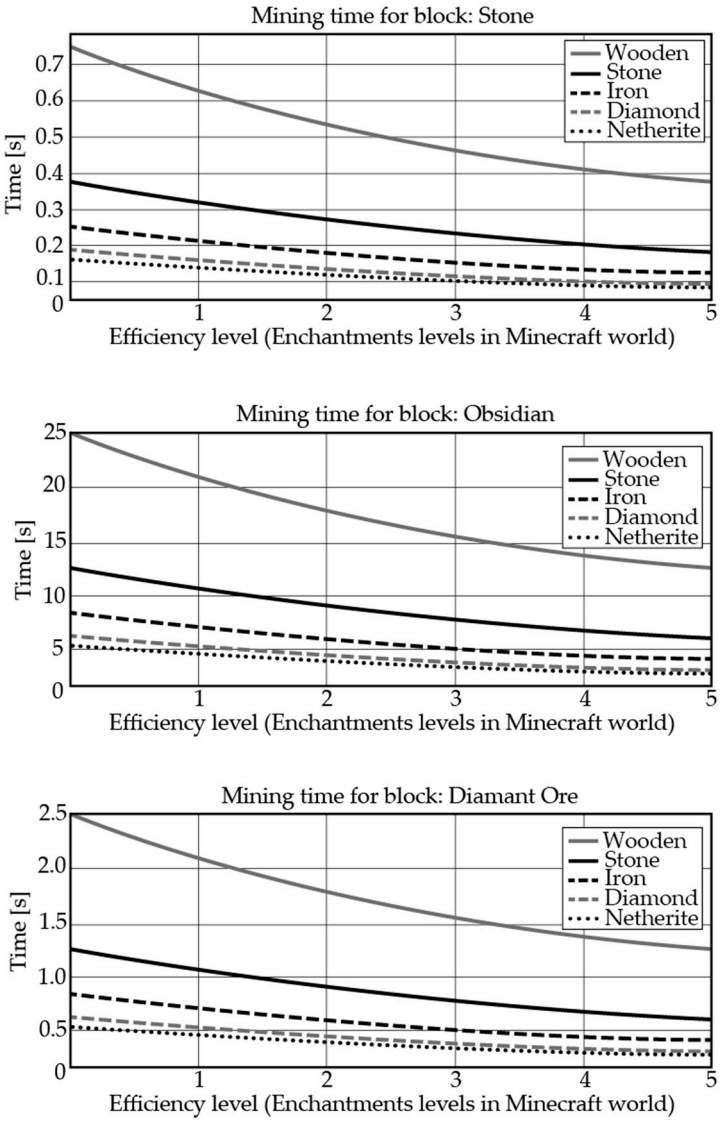


Figure 4. Block mining time (stone, obsidian, diamond ore) depending on tool type and enchantment level.

This system indirectly represents the principle of tool suitability for the hardness of the rock, although it lacks the quantitative accuracy of the Mohs scale or other mechanical parameters of rocks. The player does not have access to mechanized mining or advanced mining technologies (such as continuous miners, drilling rigs, or blasting techniques), and the rock fragmentation process is simplified to repeated clicks simulating the time needed to break a block.

In practice, however, players adopt optimized mining schemes that have emerged as a result of community-driven analysis—most notably branch mining, strip mining, quarry mining, and cave mining. These strategies aim to maximize the volume of explored rock while minimizing tool wear and time consumption. Their existence demonstrates how the game community intuitively replicates the principles of efficient planning of mining panels, space optimization, and the use of natural geological structures.

An important aspect, particularly in underground mining but also in surface excavation and waste dumps, is the stability of mining structures [34,42]. In the base version of Minecraft, apart from specific blocks such as sand, gravel, or red sand—which are affected by gravity and fall if unsupported—most blocks (such as stone, ores, deepslate, etc.) are unaffected by gravity. As a result, when a supporting block is removed beneath them, the blocks above remain suspended regardless of their height or number. Consequently, Minecraft does not simulate natural cave-ins or roof collapses due to structural instability or lack of support.

However, the game does include user-triggered collapses. These occur when a player removes a gravity-affected block (e.g., sand or gravel), which then falls. This mechanic can even be used as a mining technique for such loose materials, presenting an analogy to real-world gravity mining methods. Since blocks (except for sand and gravel) do not obey gravity, Minecraft lacks game mechanics requiring structural reinforcement to prevent collapses. While players may construct walls, ceilings, pillars, or use wooden beams (e.g., spruce/oak logs) as esthetic "supports" in their mines, this is implemented for visual or logistical reasons (e.g., railway support) rather than for functional structural stability.

More advanced tools and techniques are introduced into the game through modifications. For example, the BuildCraft mod adds mining robots (quarry machines) that autonomously excavate large volumes of rock and deposit the extracted materials into containers. This type of automated mining can be considered an analogy to large-scale surface mining operations using conveyor systems and high-capacity excavation machinery. The Immersive Engineering mod, in turn, introduces drills and elevators that improve the efficiency of deep mining and add new technical elements such as power limits, energy requirements, and logistics of extracted resources.

A major limitation of the base version of Minecraft, however, remains the absence of many key aspects of real-world mining processes: there is no ventilation of underground spaces, no monitoring of roof and wall stability, and the player is not exposed to the risks of gas accumulation, collapse, or spontaneous combustion. Basic engineering and environmental measures—such as structural supports, groundwater regulation, or reclamation planning—are also missing. These deficiencies limit the game's capacity to realistically simulate complex mining engineering planning, although it does provide a sufficiently illustrative model of basic excavation and ore sorting concepts.

From an educational perspective, Minecraft can be considered an effective tool for conveying the basic logic of resource extraction—such as the hierarchy of tools, the importance of planning mining routes, the ratio of waste to ore, and the significance of repetitive operations and logistical supply. However, a deeper understanding of these processes requires expansion through specialized modifications capable of integrating advanced technological and safety features into the game. In summary, the game offers a simplified yet comprehensible model of mining, which—especially when enhanced with mods—can be extended into a relatively complex simulation of industrial extraction processes.

3.4. Ore Processing and Refinement

Ore processing and refinement represent the intermediate stage in the process chain between extraction and final utilization of raw materials. Under real-world conditions, this

phase comprises a set of technological operations aimed at increasing the concentration of the target element, removing undesirable impurities, and preparing the raw material for further processing—whether metallurgical, chemical, or direct technological applications [36]. This includes processes such as sorting, crushing, grinding, flotation, gravity separation, magnetic separation, smelting, and refining [41]. In Minecraft, these processes are represented only in a very limited and highly simplified form.

In the base version of the game, the entire ore refinement process is reduced to a single step—smelting. After mining ore (e.g., iron ore), the player places the raw block into a furnace or a more advanced device (blast furnace) along with a fuel source to obtain a metal ingot (e.g., iron ingot). This linear and instantaneous conversion of "ore → metal" does not reflect the actual mineralogical or technological reality, where iron ore requires preprocessing (e.g., removal of gangue, drying, calcination), the reduction of iron oxide, and precise control over furnace temperatures and chemical reactions. Furthermore, in the game, each ore block is considered homogeneous and 100% composed of the target element, which is inconsistent with real-world yields, which typically range from several tens to just a few percent.

This shortcoming is partially addressed by thematic modifications that introduce more complex process chains into the game. For example, in the Immersive Engineering mod, players are required to first crush the ore (crusher), then sieve it (screening), and finally separate the gangue from the concentrate (e.g., via magnetic separation), before obtaining a pure material suitable for smelting. This process thus mirrors the basic scheme of physical-mechanical ore processing and reflects real technological steps applied in mineral processing plants. The Tech Reborn mod goes even further, introducing processes such as chemical leaching, electrolytic purification, and fractionation, thereby establishing a more robust and realistic model of industrial mineral processing.

An interesting addition is the inclusion of by-products and waste materials. While the base game uses a binary output system (either a metal is produced or nothing at all), the expansions can generate secondary fractions such as sand, dust, sludge, or secondary metals. These outputs create a more complex balance between input and output streams and offer opportunities to explain the environmental aspects of processing—such as waste production, recycling, or energy consumption.

Process flows in mods also introduce time delays and resource consumption (energy, water, chemicals), thereby enhancing the understanding of the energy demands and complexity of industrial processing. Players are required to plan sequential steps, build interconnected production lines, and optimize material flows, which facilitates an appreciation of the systemic nature of real-world processing industries.

Nevertheless, even the most complex mods rarely cover the entire technological chain, especially regarding the specificity of different metallurgical techniques (e.g., different reducing agents, furnace atmospheres). Mineralogical variability is also not considered—all ores of a given type (e.g., iron) are processed identically, regardless of their origin, structure, or associated minerals. Additionally, processes like quality control, certification, product purity monitoring, or economic feasibility assessments are missing.

From an educational perspective, however, even these simplified processes provide an excellent foundation for explaining linear and parallel processing, yield concepts, the significance of preprocessing, and material flow in technical environments. When supplemented with real-world examples and quantitative data in pedagogical settings, they can greatly enhance the understanding of industrial mineral processing principles. Ultimately, the game's representation of processing can be viewed as a flexible platform that offers a schematic introduction to resource flows and, when combined with mods, serves as a functional simulation tool for teaching technological processes.

3.5. Waste-to-Ore Ratio

One of the key quantitative indicators in the process of mining and mineral processing is the waste-to-ore ratio (W:O). This ratio expresses the amount of accompanying, technologically unutilizable rock (waste) that must be mined, moved, or processed together with the target mineral in order to obtain an economically usable quantity of raw material. In real-world mining, this is a crucial factor affecting costs, efficiency, logistics, and environmental impacts of extraction. Therefore, it is appropriate to analyze how and to what extent this ratio is implicitly or explicitly represented in the environment of Minecraft.

In the base version of the game, each ore block is embedded in a matrix composed predominantly of stone, deepslate, or other rocks, and ore occurrence is statistically rare. Based on the analysis of world generation algorithms in version 1.18 and above, it can be estimated that the occurrence of ores such as iron, copper, or coal ranges approximately from 0.5% to 1.5% of the total rock volume in certain elevation bands. This means that a player must mine approximately 66 to 200 blocks of waste for each block of ore—which aligns with the real-world range of waste-to-ore ratios in underground iron ore mining, where this indicator typically ranges between 10:1 and 100:1 depending on deposit conditions and the mining method.

More precise ratios vary depending on the ore type and the depth at which it occurs. Diamond ore is extremely rare, with an estimated occurrence of approximately 0.084% in regions below Y = −64, corresponding to a W:O ratio greater than 1100:1. In contrast, coal can occur in larger clusters and in some areas (e.g., mountain biomes) may comprise up to 2–3% of the rock volume. From a process-analytical perspective, the game environment is thus capable of reflecting the fundamental principle of low ore concentration and the necessity to handle a large volume of waste.

Figure 5 illustrates a comparison of waste-to-ore ratios (W:O) in Minecraft and in real-world mining, based on [44–48]. For comparison with the real world, the analogy was based on determining the waste-to-ore ratio (W:O) expressed as the ratio of waste blocks to useful mineral blocks. Based on data from actual world generation observations derived from [32,49] an effective minable chunk volume was set at approximately 65,000 blocks. Publicly available gameplay and community sources, such as player analyses and empirical tests reported in [32], yielded the following average ore block counts per chunk: diamonds: 1–5 blocks; gold: 5–15 blocks; copper: 150–250 blocks; iron: ~250 blocks; coal: ~500 blocks. These values apply to an unmodified game world generated in version 1.18+ under standard biome conditions. The presented values are given as the mean ± standard deviation, with the 95% confidence interval (CI) shown in parentheses. For example, the average occurrence frequency of iron ore was 247 ± 15 blocks/chunk (95% CI: 240–254). Diamond ore occurred at an average of 3.2 ± 1.1 blocks/chunk (95% CI: 2.9–3.5).

On the other hand, the in-game model does not account for the mass, volume, or logistical costs associated with handling waste material. All blocks are treated equally from the player's perspective—their extraction, transport, and storage are identical regardless of their actual density or volume. There is no incentive to separate waste, dispose of it, or manage it environmentally, which significantly simplifies the gameplay reality compared to the challenges faced in real-world mining operations. In reality, waste rock often represents a major burden, requiring the construction of tailings ponds, spoil heaps, dust control measures, and engineering structures to stabilize terrain.

Some modifications extend this issue. For example, in the Immersive Engineering mod, waste material appears as a byproduct of ore sorting, creating pressure to process or store it. In certain player scenarios, waste even becomes a limiting factor for construction, as it takes up space and complicates logistics. These mechanics enhance process fidelity and open up opportunities for discussing the environmental implications of mining.

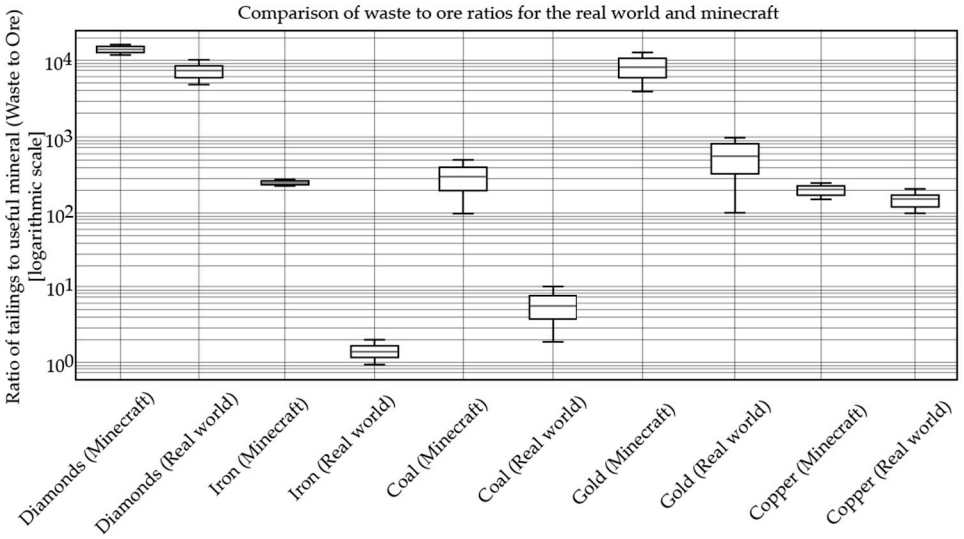


Figure 5. Waste-to-ore ratios (W:O) in Minecraft and in real-world mining.

From an educational standpoint, a quantitative analysis of the waste-to-ore ratio in Minecraft can serve as an excellent tool to introduce concepts such as recovery rate, material sorting, and mining efficiency. It offers a clear illustration that finding an ore is not the end of the task—rather, separating it from a low-concentration system is a technologically and energetically demanding process. The educational value of this analysis is further enhanced when combined with discussions on the environmental and economic impacts of waste disposal in the real world.

3.6. Fluid-Phase Resources

The extraction and processing of liquid resources such as crude oil, natural gas, and various types of liquid hydrocarbons represent a distinct industrial sector within the broader raw material chain in the real world. Unlike solid minerals, which are typically mined through mechanical means, liquid resources are primarily obtained via drilling, vacuum pumping, and subsequent processing in refineries. These operations are technologically complex, conducted under specific pressure and temperature conditions, and involve numerous chemical and separation processes. In terms of process representation, such resources and operations are practically absent in the core version of Minecraft.

The original game includes no form of crude oil or natural gas, and players cannot interact with hydrocarbon-based fluid energy sources. The only liquids present are water and lava, which, while enabling basic simulation of flow and physical properties (e.g., gravity, viscosity), serve no resource or technological function. This absence represents a significant limitation in any attempt to model comprehensive resource cycles—particularly when the aim is to support education in energy systems, refining processes, or petrochemical technologies.

However, this limitation is substantially mitigated through the use of thematic modifications. One of the most significant is the Immersive Petroleum mod, designed as an extension to Immersive Engineering and BuildCraft. This mod introduces a realistic simulation of oil extraction and processing into the game. Oil deposits are procedurally generated beneath the surface, and the player must locate them using a Core Sample Drill, which simulates geological exploration. Once a deposit is identified, the player can install a Pumpjack—a pumping apparatus that continuously extracts crude oil to the surface.

Crude oil in the game has no immediate use on its own. It must first be processed in a structure called the Distillation Tower, which realistically represents a fractional distillation column. Within this unit, crude oil is separated into various fractions—such as diesel,

gasoline, heavy oil, and asphalt—each with specific applications in other parts of the game. These fractions serve as fuels, lubricants, or inputs for further chemical processing. This represents an advanced model that captures not only the flow of processes but also the technological interdependence of production stages, the necessity of product storage, and the regulation of throughput.

Additional mods such as BuildCraft, Thermal Expansion, and PneumaticCraft introduce expanded capabilities for fluid handling, including pressure systems, pressurized tanks, pumps, and transport piping. These elements enable players to understand fundamental principles of fluid transport, storage, temperature control, and subsequent utilization. While these are not the exact replicas of real-world industrial technologies, they provide a sufficiently robust framework to explain the logic of fluid management, energy flows, and technological conversion.

From a process analysis perspective, these modifications represent a significant advancement toward a more realistic representation of liquid resources. They allow the player to progress through all key stages—from the discovery and evaluation of deposits, to extraction and transport, to separation and use of products. Furthermore, when incorporating energy requirements, fuel consumption, and output performance, players can create basic material and energy balances and assess operational efficiency—thereby significantly enhancing the game's potential for teaching process engineering.

The use of Minecraft with mods focused on fluid resources thus open up a new dimension in the education of raw material processing. In this case, it offers a more accessible and interactive introduction to the world of petroleum, refining, and liquid energy. These topics are often abstract and difficult to visualize in traditional education, and Minecraft provides a unique didactic bridge between gameplay, simulation, and real-world technological systems.

3.7. Environmental and Systemic Processes

Each real-world mining or processing operation is accompanied by environmental consequences and systemic effects that directly or indirectly impact the surrounding environment, biodiversity, water resources, and air quality. The responsible management of mineral resources therefore requires not only technological efficiency and economic viability but also the minimization of negative externalities and integration of processes into broader environmental and societal frameworks. In the case of Minecraft, environmental aspects are addressed only marginally, and in most gameplay scenarios, there is no ecological feedback or systemic evaluation of the consequences of mining and processing activities.

In the base version of the game, player activities such as mining, smelting, or burning fuels have no environmental repercussions. There is no modeled pollution of air, water, or soil; emissions, mining waste, or noise are not simulated. Players can create large waste piles, destroy vegetation, or drain water sources without any penalty or reaction from the environment. This represents a significant simplification of reality, which prevents players from perceiving resource-related processes as part of a larger ecological system. The game world lacks feedback mechanisms to warn players about overexploitation, the non-renewability of deposits, or landscape degradation.

Despite this absence, several community-driven modifications attempt to bridge this gap. For instance, the Pollution of the Realms mod introduces systems for air, water, and soil pollution. Activities such as metal smelting, coal combustion, or explosions lead to pollution that affects player health, crop productivity, and the appearance of the environment. Such systemic implementations provide a foundation for understanding the ecological consequences of human activity and can simulate the impacts of overmining and

unsustainable energy use. Similarly, mods like Better With Mods introduce mechanics for terrain degradation, water contamination, and the need for land reclamation after mining.

From a process-oriented perspective, these additions are significant because they allow the incorporation of concepts such as environmental balance, external costs, and the necessity of environmental management as an integral part of the production cycle. Players must consider not only yield and technical efficiency but also long-term consequences of their actions. This system-based approach reflects the reality of modern resource management, where environmental standards, emission limits, permits, and regulatory frameworks are essential to planning and operation.

Another critical aspect is recycling. While recycling is practically nonexistent in the base game (e.g., tools or weapons cannot be broken down into raw materials), some modifications—such as Tech Reborn or Industrial Foregoing—introduce systems for reprocessing used items, smelting metal tools, and recovering secondary materials. In this way, the game integrates the principle of a closed-loop material cycle, allowing players to optimize resource flows over the long term. Recycling mechanics also emphasize the importance of efficient material use and highlight the environmental advantages of recycling over primary extraction.

From an educational standpoint, the integration of environmental and systemic processes into Minecraft is highly beneficial. It allows learners to understand that technological processes are not isolated but are part of a broader system that impacts nature and society. By linking technical operations to their consequences, the game creates opportunities to discuss sustainability, mining ethics, environmental justice, and the rights of future generations to resources. While these elements are absent from the base game, the possibility of adding them through modifications makes Minecraft a flexible simulation space for exploring not only technical but also social dimensions of resource-related processes.

In Minecraft, it is possible to identify certain processes that reflect characteristics such as material degradation or corrosion. However, these are not implemented universally for all materials and are incorporated in a simplified and schematic form. The phenomenon of corrosion is specifically integrated into the behavior of copper blocks. Copper blocks and their variants (cut copper blocks, copper stairs, and copper slabs) gradually undergo a patination process when exposed to air. They pass through four stages of oxidation: pristine copper $\rightarrow$ lightly weathered $\rightarrow$ exposed $\rightarrow$ fully weathered (green patina). This progression serves as a direct analogy to copper corrosion in the real world.

Beyond copper oxidation, other forms of degradation or material transformation can also be interpreted as geological or environmental processes. Most notably, erosive processes caused by flowing water can transport and destroy certain blocks such as sand, gravel, farmland, or snow. This behavior presents a clear analogy to erosion and environmental degradation induced by natural forces.

The majority of blocks (e.g., stone, dirt, wood, iron, and gold blocks) in Minecraft do not change over time, nor do they disintegrate or corrode. The fact that gold is immune to corrosion in the game accurately reflects the real-world properties of this metal. However, the absence of iron corrosion—unlike copper—in both blocks and items—represents a significant discrepancy between material behavior in Minecraft and in reality. Iron and steel corrosion is a process with major negative implications for the global economy. According to data published in sources such as [52–64], direct global costs of corrosion are estimated to be 3–4% of the global GDP, while total costs, including indirect impacts, may reach 6–8% of GDP.

3.8. Impact of Modification Complexity on Accessibility and Educational Potential

The introduction of advanced modifications (mods) that expand the original game with new technological and geological features has a significant impact on the accessibility and playability of Minecraft, particularly in the context of its use in education. While these mods can substantially increase process accuracy, technological sophistication, and educational content, they can also create barriers for less experienced users or younger students.

From the player experience perspective, complex modifications may reduce the simplicity and intuitiveness that characterize the base version of Minecraft. Installing mods often requires knowledge of file management, the use of launchers (e.g., CurseForge), dependency configuration (e.g., Forge, Fabric), and navigation in an English-language interface. For primary school students or teachers without technical backgrounds, these requirements can be a considerable obstacle. Furthermore, some mods alter the game's economy, resource balance, and progression pace, which can diminish the sense of reward and flow.

An analysis of feedback from user forums (e.g., Reddit: r/feedthebeast, CurseForge discussion threads, Minecraft Forum) suggests that players appreciate advanced mods such as BetterGeo, Immersive Engineering, or GeoImmersion mainly for their realistic content and didactic potential. However, many point out that the complexity of these expansions requires accompanying guides, explanatory materials, or trained instructors. Some comments stress that without guidance, beginners can become "overwhelmed" with information and abandon the game before grasping its educational aim.

From a pedagogical standpoint, it is therefore important to balance the degree of complexity. Ideally, one should begin with simpler mods or specially prepared maps (so-called modpacks) with predefined objectives, simplified interfaces, and limited scope. In later stages, the difficulty can be gradually increased, new elements introduced, and thematic connections deepened. The target age group is also a critical factor—while advanced modifications can be beneficial for high school and university students, they may be counterproductive for younger learners.

Based on these findings, the following is recommended:

- Use thematic mods with regard to age, technical skills, and educational objectives;
- Provide support in the form of explanatory materials or an instructor;
- Combine modified and unmodified environments according to complexity levels;
- Ensure that even advanced game content remains fun, visually engaging, and motivating.

Such an approach will ensure that Minecraft remains not only accurate but also accessible and engaging as a tool for teaching mineral resource processes and environmental education.

Table 2 presents a diagram mapping game mechanics and recommended modifications to specific stages of the mineral resource value chain, taking into account specialized mods aimed at enhancing the educational enrichment potential of each process stage.

Table 2. Comparison of real and simulated processes by category.

Process Phase	Real-World Process	Minecraft Simulation	Level of Correspondence	Educational Potential
1. Geological Formation and Distribution of Resources	Geotectonic processes, deposit typology, association with rock complexes, geochemical anomalies.	Procedural world generation, simple vertical ore stratification, RAE algorithm (version 1.18+), no geotectonic associations.	Medium	Visualizes stratification and depth-dependent resource occurrence.

Table 2. *Cont.*

Process Phase	Real-World Process	Minecraft Simulation	Level of Correspondence	Educational Potential
2. Geological Exploration	Mapping, geophysics, geochemistry, drilling, deposit modeling.	Base game—random discovery; mods—Core Sample Drill (Immersive Engineering), geological mapping (BetterGeo).	Low to medium	Mods allow the simulation of exploration phases and planning.
3. Mining Techniques and Extraction	Surface/underground mining, machinery, ventilation, stability, occupational safety.	Manual mining with tools; hardness and speed parameters; mods—quarry machines, drilling rigs.	Medium	Teaches the principle of tool suitability, route optimization, and basic extraction models.
4. Mineral Processing and Treatment	Sorting, crushing, flotation, separation, smelting, refining.	Base game—direct smelting in a furnace; mods—crushing, magnetic separation, chemical processes (Tech Reborn).	Low to medium	Introduces the concept of yield and material separation.
5. Waste-to-Ore Ratio	Waste rock as accompanying material, handling, stockpiling, environmental measures.	Implicitly high W:O in game; no weight or logistics; mods—byproducts, storage requirements.	Medium	Introduces the concept of yield and material separation.
6. Fluid-State Resources	Oil, natural gas—exploration, pumping, refining, fraction processing.	Base game—absent; mods—Immersive Petroleum (pumping units, fractional distillation).	Medium to high (in mods)	Simulates fluid flow, energy, and technological linkages.
7. Environmental and System Processes	Monitoring, emission control, reclamation, recycling.	Base game—no environmental feedback; mods—Pollution of the Realms, recycling systems.	Low	Enables the explanation of broader mining impacts and sustainability concepts.

4. Conclusions

The analysis of individual processes has shown that Minecraft, while operating with a highly simplified model of mineral resource extraction and processing, is still capable of conveying the basic principles of various stages—from geological exploration, through mining and beneficiation, to technological processing and systemic impacts. Such a game environment offers a useful tool for modeling and understanding the fundamental processes of the mineral resource cycle—from geological exploration, through mining and beneficiation, to technological processing and environmental aspects. In the base game, intuitive, player-optimized approaches dominate without an explicit process structure; however, the inclusion of thematic modifications opens the possibility of simulating more realistic technological and environmental operations. Even with its simplifications, the base game provides a fundamental framework for understanding the logic of mineral resource acquisition and utilization. The included game mechanics support intuitive decision-making, workflow organization, mining planning, and the assessment of inputs and outputs, which are key elements of real-world technological chains. A major contribution to process analysis comes from thematic modifications that enrich the game world with new technological nodes, more realistic mineral processing, more detailed geological

exploration, and elements of environmental impact. These expansions enable a more precise tracking of the sequence of operations, illustrate multi-step mineral processing, and introduce feedback between production, consumption, and environmental consequences. This also reinforces the ability to consider sustainability, efficiency, and recycling within the entire resource cycle. Despite the absence of detailed parameters (e.g., yield, contamination, energy balances), the game—especially in targeted education—can convey an understanding of the basic interconnections between inputs, operations, and outputs in the process of resource acquisition. A particular value lies in its ability to link technical operations with their broader impacts, such as waste generation, environmental burden, or recycling. In combination with mods, Minecraft thus provides an effective model space for studying, visualizing, and explaining the individual components of a complex resource system from a process perspective.

From a historical perspective, the time frame reflected in Minecraft's representations of mining and resource needs most closely resembles an era of intensive yet predominantly manual mining—dependent on simple tools and basic processing techniques. The gradual progression of tool quality and the emergence of primitive automation (e.g., Redstone mechanisms) shifts this timeline towards the dawn of the industrial age. The game thus combines elements of mining practice from several centuries, while offering considerable potential for the future integration of contemporary, complex procedures, strategies, and technologies.

From an educational standpoint, the game environment fosters active learning through interaction, experimentation, and visual feedback. Working with game-based models can complement traditional teaching of geology, mining engineering, and environmental science by introducing an experiential dimension that facilitates the understanding of complex phenomena through hands-on simulation. The game also provides a platform for creative thinking, technological problem-solving, and discussions about the interrelations between technical, ecological, and societal aspects of mineral resource extraction.

In conclusion, while not a scientific simulation tool, the virtual environment offers a process-based framework that can be employed not only in science communication but also in formal education about the operations behind mining and processing raw materials. This flexibility and openness make Minecraft an innovative didactic platform with strong potential for further development and research in the domain of digital process modeling.

It is important to distinguish between approaches focused on educational modeling and those aimed at strict scientific simulation. Some of the Minecraft modifications mentioned come close to scientific simulation tools in terms of accuracy, complexity, and emphasis on realistic parameters, and could even be applied in research scenarios. However, our analysis primarily focused on so-called mainstream solutions, which are more accessible, technically less demanding to implement, and better suited for education or raising awareness of raw material processes among the widest possible group of users. This approach prioritizes interactivity, clarity, and player engagement over complete technical precision, thereby aligning with the goals of popularization and educational modeling.

Overall, Minecraft may be regarded as a flexible, modular, and scalable digital model that, with appropriate combinations of modifications, achieves the following:

(1) Covers the majority of key operations in the resource chain with sufficient detail for introductory university instruction;
(2) Provides quantifiable variables (e.g., mining volume, energy consumption, waste-to-ore ratio) suitable for coursework and laboratory exercises;
(3) Enables the integration of environmental and social impacts into technical decision-making.

We therefore recommend using Minecraft as a didactic extension of traditional lectures and lab work. On average, it requires 6–8 teaching hours to build and operate a simplified

mining and processing system. Future research should focus on expanding mineralogical variability, improving energy balance accuracy, and connecting the Minecraft platform to real-world deposit databases to enhance scientific validity and support decision-making in the context of sustainable resource management.

The future integration of scientific data sets and educational curricula could significantly enhance the usability and accuracy of models created in the Minecraft environment. Relevant data sources could include geological deposit databases (e.g., USGS Mineral Resources Data System or GeoSciML), environmental data from monitoring networks (e.g., air quality, hydrological parameters), or the results of 3D geological mapping. These data could be directly linked to world generators, allowing players to work within environments that reflect real geological conditions. Equally important is aligning in-game scenarios with official educational curricula, such as Science, Technology, Engineering, and Mathematics (STEM), to create comprehensive educational modules containing tasks, assessments, and feedback. Such integration would provide teachers and instructors with a ready-made framework, enabling them to effectively incorporate game-based simulation into both formal and informal education.

Finally, the authors believe that a thoughtful integration of certain identified concepts and a careful adaptation of game mechanics to real-world processes could deliver significant benefits that go beyond strict science or formal education. This approach has the potential to promote natural public outreach and contribute to a more objective perception of reality through a widely adopted game, thereby helping to shape rational and balanced public attitudes toward key issues concerning the present and future development of society.

Author Contributions: Conceptualization, R.R. and M.B.; methodology, R.R.; formal analysis, M.B.; investigation, M.B.; data curation, M.B.; writing—original draft preparation, R.R.; writing—review and editing, R.R. and M.B.; visualization, M.B.; supervision, L.B.; project administration, R.R.; funding acquisition, L.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by KEGA: 056TUKE-4/2024, a platform for the effective creation, evaluation, and transfer of innovations and the efficient management of university research outputs with a practical orientation.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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