

Review

Pyrometallurgical Processing of Iron Manganese Ores: A Review with Emphasis on Kazakhstan's Mineral Resources and Technological Prospects

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Abstract

The depletion of high-grade manganese ore reserves, accompanied by the progressive decline in ore quality, has intensified concerns regarding the supply of suitable manganese raw materials for Kazakhstan's ferroalloy industry. Under these conditions, the development of efficient processing technologies for iron manganese ores characterized by low Mn/Fe ratios and complex mineralogical compositions has become increasingly important. This review examines current pyrometallurgical approaches for the processing of iron manganese ores, including carbothermic reduction roasting followed by magnetic separation, reduction smelting for the production of rich manganese slag, and hydrogen-based selective reduction followed by magnetic separation. Particular attention is given to the mineralogical and chemical characteristics of Kazakhstan's iron manganese ores, which significantly limit their direct utilization in conventional ferromanganese production processes. The advantages and limitations of these technologies are critically evaluated in terms of metal recovery, Mn/Fe upgrading efficiency, energy requirements, environmental performance, and industrial applicability. The comparative analysis identifies reduction smelting as the most suitable route for Kazakhstan's iron manganese ores under current technological conditions. This conclusion is primarily supported by the low Mn/Fe ratios, elevated iron contents, and complex mineralogical associations characteristic of the major Kazakhstan deposits, which limit the efficiency of solid-state reduction followed by magnetic separation. During smelting, the original mineral structure is destroyed, and iron and manganese are separated directly between the liquid metal and slag phases. Published studies report iron recoveries exceeding 95%, MnO recovery to the slag of approximately 94.6%, and Mn/Fe ratios above 15 in the resulting rich manganese slag. In addition, the process produces two potentially marketable products—cast iron and rich manganese slag—and can be integrated more readily into Kazakhstan's existing ferroalloy production infrastructure. Therefore, reduction smelting currently represents the most technologically mature and practically feasible route for the comprehensive utilization of Kazakhstan's iron manganese resources.



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Keywords: selective reduction; smelting; rich manganese slag; ferroalloy; Mn/Fe ratio; carbothermic reduction roasting; hydrogen-based reduction

1. Introduction

Manganese is a critical raw material for the production of high-quality steels and remains an essential component of the global metallurgical industry. The growing demand for steel products, particularly in developing economies, has led to a steady increase in manganese ore consumption.

Manganese alloys play a crucial role in steelmaking, with approximately 90% of global manganese production being consumed by the iron and steel industry [1–4]. Manganese improves key steel properties, including strength, hardness, wear resistance, impact toughness, and weldability, making it indispensable for construction, transportation, automotive manufacturing, and infrastructure development [5–8]. In addition, manganese-containing alloys are widely used as deoxidizing and desulfurizing agents during steel production, contributing to improved steel quality and process efficiency [9–11].

In recent years, manganese has gained increasing importance in advanced technologies, particularly in rechargeable batteries, permanent magnets, electronic devices, next-generation memory systems, and energy-storage materials, where it contributes to improved energy density, thermal stability, and service life [12–19].

Manganese compounds are used in medicine for their antiseptic and antimicrobial properties, while manganese itself is essential for neurological development, metabolism, glucose regulation, and bone formation [20–24].

Industrially, manganese ferroalloys are produced almost exclusively by carbothermic reduction of manganese ore, in which manganese ore, flux (limestone or dolomite), and a carbonaceous reductant (coke, coal, or charcoal) are continuously charged and melted at high temperature to yield a liquid alloy together with a co-produced slag. Three principal groups of manganese ferroalloys are obtained by this route: standard, or high-carbon, ferromanganese, typically containing 74–82% Mn and 6–7.5% C; silicomanganese, containing approximately 65–70% Mn and 14–20% Si; and refined, low- and medium-carbon ferromanganese, produced by subsequent silicothermic or oxidative refining of high-carbon ferromanganese to lower its carbon content [25]. The dominant industrial unit for all three products is the electric submerged arc furnace (SAF), in which the charge descends through a coke bed while three electrodes submerged in the burden supply the heat required for reduction [1,25]. High-carbon ferromanganese was historically also produced in blast furnaces, and this route remains in limited use in China, Russia, and several other countries; however, blast-furnace smelting is progressively being displaced by submerged arc furnace technology because of its lower tolerance for fine and variable-quality burden and its higher specific coke consumption [26].

Regardless of furnace type, the charge materials used in ferromanganese production must satisfy strict compositional and physical requirements. Metallurgical-grade manganese ore typically contains 38–55% Mn [27]. Because the iron oxides present in the charge are reduced together with the manganese oxides and report almost quantitatively to the metal, the Mn/Fe ratio of the ore or ore blend largely determines the manganese content of the resulting alloy: producing standard ferromanganese with approximately 78% Mn generally requires a charge Mn/Fe ratio of at least 7–7.5, and comparable or higher ratios are required for silicomanganese and for the ferromanganese subsequently used as feed for refining [25,28]. Phosphorus and sulfur are likewise critical, because virtually all of the phosphorus contained in the charge is reduced together with manganese and reports

to the alloy; because standard ferroalloy production includes no refining stage capable of selectively rejecting phosphorus without also rejecting manganese, this phosphorus cannot be removed by any subsequent metallurgical treatment integral to the process [29] (see Section 6.4), while sulfur influences slag-metal partitioning and the alloy's suitability for steelmaking; commercial ore specifications therefore commonly restrict the phosphorus content to a few hundredths of a percent and constrain the P/Mn ratio of the charge accordingly [25,28]. Particle size is a further critical parameter: submerged arc furnaces require a lump or sized burden, typically several millimeters to several tens of millimeters, to preserve gas permeability within the coke bed and stable electrode operation, whereas the substantial fines fraction generated during mining and crushing of many manganese ores must first be agglomerated by sintering, pelletizing, or briquetting before it can be charged [25,26].

As shown in the following sections, Kazakhstan's iron manganese ores depart substantially from this specification, primarily because of their low Mn/Fe ratio, which is below 3 for the majority of reserves, and their complex, finely intergrown mineralogy, which together explain why these ores cannot be charged directly into existing submerged arc furnaces without prior beneficiation or a change of processing route.

The Republic of Kazakhstan possesses substantial reserves of manganese-containing mineral resources. Most of the country's manganese ore reserves are concentrated in Central Kazakhstan and are associated with deposits of the Atasu ore district. The largest deposits include West Karazhal, Zhomart, Ushkatyn-I, Ushkatyn-III, Big Ktai, Tur, and Kamys [30–32]. At present, mining activities are primarily focused on oxidized manganese ores occurring in the upper horizons of these deposits, as their extraction and beneficiation require relatively lower capital and operating costs. However, such ores account for only a small proportion of the total explored reserves, representing approximately 4% of Kazakhstan's manganese resource base [33].

The majority of Kazakhstan's manganese deposits belong to the primary sedimentary type. The principal ore-forming minerals include braunite, pyrolusite, psilomelane, vernadite, and hausmannite. Low- and medium-grade ores predominate within the explored reserves: approximately 60% contain 10–20% Mn, about 32% contain 20–30% Mn, and only around 11% of the reserves contain more than 30% Mn. In addition, Kazakhstan's manganese ores are generally characterized by relatively low concentrations of deleterious impurities, particularly phosphorus (0.02–0.08%) and sulfur (0.1–0.3%), a feature that is favorable for subsequent metallurgical processing [34].

A significant portion of manganese resources does not meet the requirements for the production of standard grades of manganese ferroalloys. This is because the majority of these ores are represented by iron manganese ores. Within the total reserves of manganese-containing ores, approximately 70% are iron manganese ores, while the remaining 30% consists of oxidized and refractory primary manganese ores [35–37]. Traditional ferromanganese smelting processes are designed primarily for the processing of high-grade manganese ores with an Mn/Fe ratio greater than 5. $\text{Mn/Fe} > 5$ is a commonly cited minimum threshold for standard-grade manganese ferroalloy feed; however, higher ratios reported in the literature up to 7–9 or more may be required for low-carbon or high-purity ferromanganese and silicomanganese grades [25,27], so this threshold should be understood as indicative rather than a fixed, universal industry specification.

However, for the majority of Kazakhstan's iron manganese ores, this ratio is below 3, which significantly complicates their utilization in conventional metallurgical processes [38,39].

The direct metallurgical processing of iron manganese ores is complicated by the difficulty of producing marketable manganese alloys, which limits their industrial utilization. As a result, a significant proportion of iron manganese ores mined together with

high-grade manganese ores is stockpiled and not subject to further processing. At the same time, Kazakhstan's iron manganese ores should be considered a complex mineral resource containing valuable components, including manganese, iron, and silicon, which creates opportunities for their integrated utilization.

Various beneficiation and processing methods are used in global metallurgical practice to improve the quality of manganese raw materials, including gravity, magnetic, and flotation separation, as well as thermal treatment based on oxidation-reduction reactions [40–45]. However, the effectiveness of these methods depends strongly on the chemical and mineralogical composition of the ore, the degree of intergrowth between iron- and manganese-containing minerals, particle size, and the selected process conditions.

Physical beneficiation methods may be less effective for finely intergrown or complex iron–manganese mineral phases, whereas thermal treatment generally requires high-temperature processing and may involve additional stages such as grinding and magnetic separation. Carbonaceous reduction and roasting can also generate CO, CO₂, and dust-containing off-gases, although the reviewed studies do not provide standardized emission values per tonne of processed ore. Reported manganese recoveries and Mn/Fe upgrading efficiencies vary considerably among studies because of differences in feed composition and experimental conditions [46,47]. Therefore, the suitability of each processing route should be evaluated individually for a specific ore rather than described using a single generalized efficiency value.

In addition to the pyrometallurgical routes that form the focus of this review, hydrometallurgical processing of iron manganese ores has also been reported, typically based on reductive or SO₂-assisted acid leaching that selectively dissolves manganese as MnSO₄ while leaving most of the iron in the leach residue [42,48,49]. Kallam et al. [49] demonstrated SO₂ leaching of iron manganese ore with Mn recoveries of 94–98% and limited iron co-dissolution. However, hydrometallurgical routes generally require fine grinding, generate acidic or sulfate-containing effluents requiring treatment or recycling, and are oriented mainly toward manganese sulfate or electrolytic/chemical manganese dioxide products rather than a metallurgical-grade feed for existing submerged arc furnaces. For this reason, and because Kazakhstan's ferroalloy industry is built around pyrometallurgical smelting infrastructure, hydrometallurgical processing is noted here for completeness but is not analyzed further in this review.

In addition to hydro and pyrometallurgical methods, there are several additional combined pyro-hydrometallurgical options. Sulfation roasting followed by water leaching converts manganese oxides to soluble MnSO₄ under an SO₂-containing atmosphere while iron remains largely as insoluble oxide, and has been demonstrated specifically for iron-rich manganese ores [48,49]. Gas-based reduction using CO/CO₂ mixtures or natural gas (methane) has been investigated as an alternative to solid-carbon reduction in the pre-reduction stage of ferromanganese production, including integrated schemes that couple natural-gas reforming with manganese-ore prereduction and iron-ore direct reduction to lower coke consumption and CO₂ emissions [50,51]. Microwave-assisted reduction, in which microwave heating accelerates carbothermic or pyrite-assisted reduction of manganese ore prior to leaching, has also been reported to shorten reaction times and lower reduction temperatures at laboratory scale [52]. These approaches remain largely at the laboratory or early pilot stage; they are noted here as complementary developments rather than reviewed in detail, since the present study focuses on the three pyrometallurgical routes most relevant to Kazakhstan's existing ferroalloy infrastructure.

Given the growing demand for manganese raw materials in the ferroalloy and steel industries, research aimed at developing effective technological approaches for the process-

ing of iron manganese ores and their broader utilization in metallurgical production is of particular importance.

Therefore, the objective of this study is to analyze existing pyrometallurgical technologies for the processing of iron manganese ores and to assess their potential application to the development of iron manganese ore deposits in Kazakhstan.

2. Review Methodology

This study was conducted as a structured review of scientific and technical literature on the processing of iron manganese ores. The literature search was focused on pyrometallurgical methods aimed at the selective separation of iron and manganese and the production of manganese-rich products suitable for subsequent ferroalloy production. Relevant publications were identified using the Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar databases. In addition, official reports and statistical data published by the U.S. Geological Survey and available scientific and technical sources concerning Manganese deposits in Kazakhstan were examined.

The following keywords and their combinations were used: «iron manganese ore», «manganese ore benefit», «pyrometallurgical processing of manganese ore», «carbothermic reduction roasting», «magnetic separation of manganese ore», «selective reduction of iron manganese ore», «rich manganese slag», «manganese slag smelting», «hydrogen reduction of manganese ore», «Mn/Fe separation», «Kazakhstan manganese deposits».

Priority was given to peer-reviewed journal articles, review papers, conference proceedings, monographs, official geological reports, and industrial or pilot-scale studies published mainly between 2002 and 2026.

Publications were included if they provided information on at least one of the following aspects:

- the chemical or mineralogical composition of iron manganese ores;
- the separation of iron and manganese during reduction or smelting;
- operating parameters, including temperature, residence time, reducing-agent consumption, and magnetic-field intensity;
- manganese and iron recoveries and the composition of the resulting products; laboratory-, pilot-, or industrial-scale implementation;
- energy consumption, environmental performance, or technological limitations;
- the applicability of the technology to ores characterized by low Mn/Fe ratios and complex mineralogical compositions.

Publications were excluded when they addressed only high-grade manganese ores without considering iron-manganese separation, provided insufficient information on process conditions or products, duplicated previously reported results, or were not directly relevant to pyrometallurgical processing.

The selected studies were grouped into three principal technological categories: carbothermic reduction roasting followed by magnetic separation, reduction smelting for the production of cast iron and rich manganese slag, and hydrogen-based selective reduction. The technologies were comparatively evaluated according to manganese and iron recovery, improvement of the Mn/Fe ratio, product quality, process temperature, energy and reducing-agent requirements, environmental impact, technological maturity, need for additional separation stages, and potential compatibility with Kazakhstan's existing ferroalloy production infrastructure.

The available results were synthesized to identify the advantages, limitations, and industrial applicability of each technological route, with particular emphasis on the characteristics of Kazakhstan's iron manganese ores.

3. World Manganese Reserves

According to the U.S. Geological Survey (USGS) [53], the global market is currently experiencing a shortage of manganese raw materials. Although manganese is a relatively abundant element in the Earth's crust, ranking fourteenth among all metals and second only to iron among heavy metals, economically viable extraction is possible from only a limited number of large deposits.

The distribution of manganese reserves is highly uneven (Figure 1). The largest shares are concentrated in South Africa (31.4%), Australia (26.2%), China (14.7%), Brazil (14.2%), Ukraine (7.3%), Gabon (3.2%), India (1.8%), Ghana (0.7%), Mexico (0.3%), and Kazakhstan (0.3%).

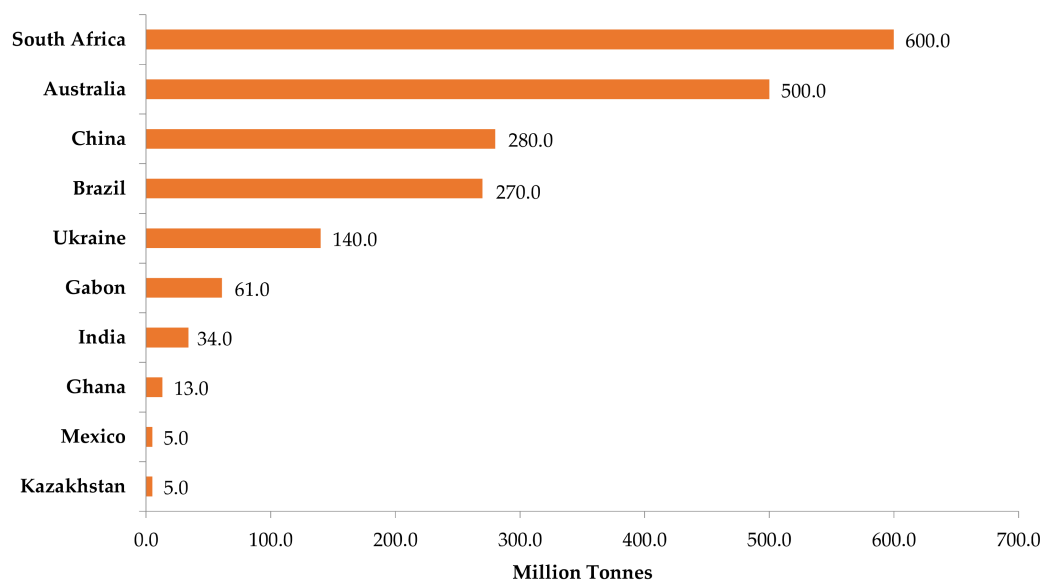


Figure 1. World manganese reserves in 2024 according to USGS data.

Global manganese ore production currently amounts to approximately 19–20 million tonnes per year in terms of manganese content (Figure 2) [53]. The leading producing countries are South Africa (7.2 million tonnes), Gabon (4.6 million tonnes), and Australia (3.0 million tonnes), which together account for more than 70% of global manganese production. Significant production volumes are also reported in Ghana, China, India, and Brazil, indicating a high geographic concentration of manganese ore reserves and production.

The global production structure is dominated by medium-grade ores containing 30–44% Mn, which account for approximately 50% of total output. High-grade ores (Mn > 44%) account for approximately 40% of total production, whereas low-grade ores containing less than 30% Mn represent approximately 10%.

An analysis of the global manganese mineral resource base reveals considerable diversity among manganese deposits in terms of both their genesis and the chemical and mineralogical composition of their ores. Depending on their formation conditions, these deposits are classified as sedimentary, volcanogenic-sedimentary, hydrothermal, metamorphic, and supergene types, each characterized by specific mineral assemblages, manganese contents, and processing characteristics.

As shown in Table 1, the largest and highest-grade manganese ore deposits are concentrated in South Africa, Australia, Gabon, Ghana, and Brazil. The formation of these deposits is associated with long-term sedimentary processes and subsequent supergene enrichment, resulting in the development of high-grade ores with manganese contents typically ranging from 40% to 47%. These ores are characterized by relatively low concentrations of

deleterious impurities and high metallurgical value, enabling their efficient utilization in metallurgical production, particularly in the smelting of manganese ferroalloys.

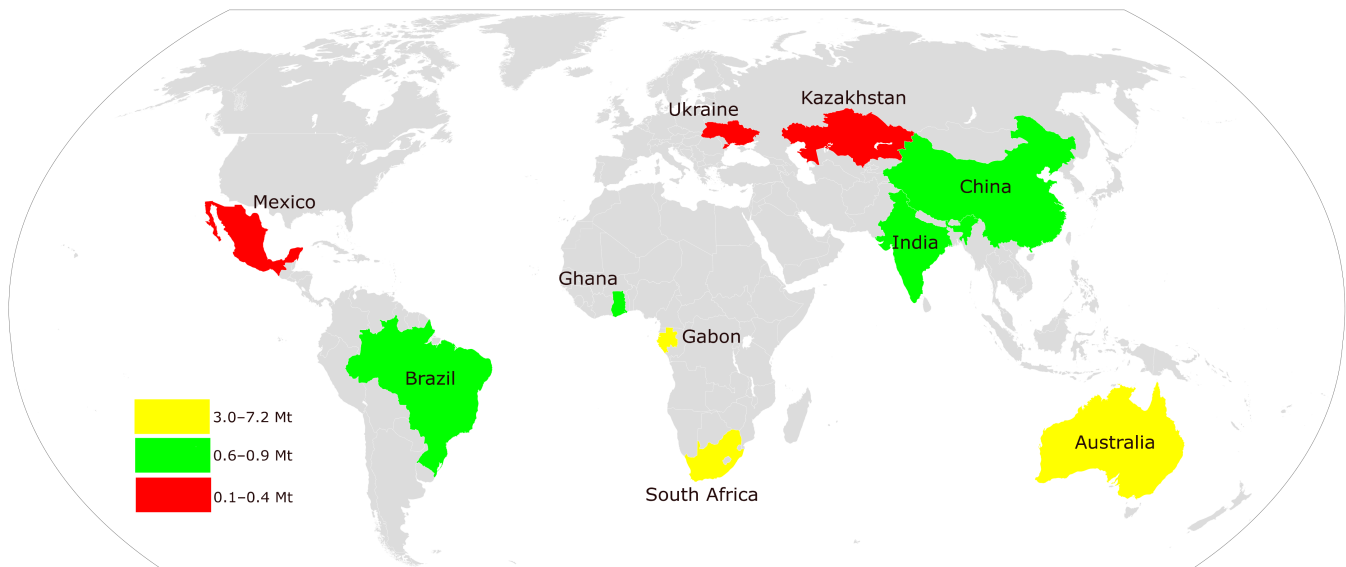


Figure 2. Top Manganese Mining Countries in the World in 2024 According to USGS.

At the same time, a significant portion of the world's manganese raw material reserves is represented by low- and medium-grade ores, which are typical of China, India, Ukraine, Kazakhstan, and several other countries. In India, nearly half of the manganese ore resources are of iron origin [54,55]. In China, more than 73% of manganese ores are iron manganese ores with a low Mn/Fe mass ratio (<3) [56]. These ores are characterized by high iron and silica contents, complex mineralogical compositions, fine intergrowths of ore and non-metallic minerals, and heterogeneous material compositions. Such characteristics significantly complicate beneficiation and subsequent metallurgical processing, particularly when conventional manganese ferroalloy production technologies designed for high-quality raw materials with high Mn/Fe ratios are employed.

Table 1. Manganese content in ores of different countries.

Country	Content Mn, %	Minerals
South Africa ¹	~48	braunite (Mn_2O_3), hausmannite (Mn_3O_4), jacobsonite (MnFe_2O_4)
Australia ²	~55	pyrolusite (MnO_2), cryptomelane ($\text{K}(\text{Mn}^{4+}, \text{Mn}^{3+})_8\text{O}_{16}$)
China ³	20–30	rhodochrosite (MnCO_3), pyrolusite, psilomelane ($\text{Ba}(\text{Mn}^{2+})(\text{Mn}^{4+})_8\text{O}_{16}(\text{OH})_4$), vernadite ($\text{H}_2\text{MnO}_3 \cdot \text{H}_2\text{O}$)
Brazil ⁴	28–50	braunite, hausmannite, pyrolusite, cryptomelane, pyrolusite, todorokite
Ukraine ⁵	11–35	$((\text{Na}, \text{Ca}, \text{K}, \text{Ba}, \text{Sr})_{1-x}(\text{Mn}, \text{Mg}, \text{Al})_6\text{O}_{12} \cdot 3\text{--}4\text{H}_2\text{O})$, cryptomelane, birnessite ($((\text{Na}_{0.3}\text{Ca}_{0.1}\text{K}_{0.1})(\text{Mn}^{4+}, \text{Mn}^{3+})_2\text{O}_4 \cdot 1.5\text{H}_2\text{O})$)
Gabon ⁶	45–49	psilomelane, manganite ($\text{MnO}(\text{OH})$), grutite ($\text{Mn}^{3+}\text{O}(\text{OH})$), pyrolusite
India ⁷	<35	pyrolusite, psilomelane, manganite, braunite
Ghana ⁸	~40	rhodochrosite
Mexico ⁹	~27.5	rhodochrosite, braunite
Kazakhstan ¹⁰	20–25	braunite, pyrolusite, psilomelane, vernadite, hausmannite

Note: The formulas presented for cryptomelane, psilomelane, vernadite, birnessite, and todorokite are generalized. These minerals may have variable and non-stoichiometric compositions owing to differences in the $\text{Mn}^{3+}/\text{Mn}^{4+}$ ratio, the contents of tunnel or interlayer cations, and the amount of structural water. Psilomelane is used here as a collective mineralogical term for hard, hydrous manganese oxides rather than as a single mineral species. Data taken from the following sources: ¹ Beukes, N.J. et al. [57], ² Sorensen, B.E. et al. [58], ³ Peng, E. et al. [59], ⁴ Afonso, J.C. [60] and da Costa et al. [61], ⁵ Sasmaz, A. et al. [62] and Nikopol Manganese Basin [63], ⁶ Beukes, N.J. et al. [57] and Guo, X. et al. [64], ⁷ Indian Bureau of Mines [65], ⁸ Guo, X. et al. [64] and Nyame, F.K. [66], ⁹ Madondo, J. et al. [67] and Zhunusov, A.K. et al. [68], ¹⁰ Sirgetaeva [32] and Yessengaliyev [34].

4. Manganese Deposits of Kazakhstan

Kazakhstan possesses strategically important reserves of manganese raw materials, which belong to a group of mineral resources that form the foundation of the country's economic security. More than 100 manganese deposits and ore occurrences have been identified in Kazakhstan [69,70]. The national mineral reserve inventory includes 38 manganese ore deposits suitable for industrial development, of which 16 are currently in operation, while the remaining 22 deposits have been explored and are held in reserve [71].

The principal reserves of manganese-containing raw materials in the Republic of Kazakhstan are concentrated in Central Kazakhstan and are represented by three groups of deposits: Atasu, Zhezdy, and Ushkatyn. The largest deposits are West Karazhal and Ushkatyn-III, which contain approximately 90% of the country's manganese reserves. These deposits are primarily mined for oxidized manganese ores occurring in the upper horizons of the ore bodies, which require relatively low beneficiation and development costs [67].

Oxidized, partially oxidized manganese, iron manganese, iron, and barium-containing lead ores have been identified at the Ushkatyn-III deposit. The principal ore-forming mineral in the oxidized ores is psilomelane, while braunite, vernadite, hausmannite, and pyrolusite occur in subordinate amounts. Owing to their high manganese content and low phosphorus concentration, the oxidized manganese ores from this deposit are widely used in ferroalloy production [72–76].

The Karazhal deposit, which contains silicate-type iron manganese ores, is the largest of its kind in Kazakhstan. Most of the manganese is concentrated in the oxidized ores, where the manganese-containing mineral assemblage is represented predominantly by pyrolusite formed through the replacement of braunite and hausmannite [77]. The distinctive mineralogical and material composition of iron manganese ores significantly limits the applicability of conventional beneficiation methods, necessitating the development and implementation of more efficient processing technologies. Research is currently focused on improving beneficiation techniques and enhancing the comprehensive utilization of these raw materials. The principal manganese ore deposits of Kazakhstan are presented in Table 2.

Table 2. The main manganese deposits of Kazakhstan.

№	Deposit	Content, %			Minerals
		Mn	Fe	SiO ₂	
1	Ushkatyn-III	2.32–44.26	1.74–42.79	11.76–23.92	psilomelane, braunite, vernadite, hausmannite, pyrolusite
2	West Karazhal	20.37	9.45	21.52	pyrolusite, braunite, hausmannite
3	Ushkatyn-I	8.20–18.80	28.60–40.70	11.70	hausmannite, psilomelane
4	Big Ktai	9.78–23.31	12.38–31.58	17.87–22.34	braunite, vernadite, pyrolusite, psilomelane
5	Zhomart	21.0–26.0	5.47–9.11	13.95–26.32	braunite, hausmannite, rhodochrosite
6	Bogach	26.6–31.8	1.9–8.9	12.02–19.80	braunite, pyrolusite, psilomelane, vernadite
7	West Kamys	17.81–26.23	1.88–5.16	38.59–41.3	braunite, pyrolusite
8	Tur	15.0–17.0	11.0–14.0	22.80	vernadite, pyrolusite, psilomelane
9	Yesimzhal	36.0–42.13	4.3–7.8	6.95–9.95	braunite, pyrolusite

As shown in Table 2, most of the deposits under consideration are characterized by elevated iron contents in their ores. The presence of significant amounts of iron-containing minerals complicates the processing of manganese raw materials using conventional methods and requires the application of specialized technological solutions aimed at the selective extraction of manganese and the reduction of iron content in the final product.

Prospects for expanding Kazakhstan's manganese mineral resource base are primarily associated with the development of deposits in the Karaganda, Mangystau, and Zhambyl regions. Of particular interest are the reserves of high-grade manganese peroxide ores, with estimated resources of approximately 1 billion tons [77].

5. Pyrometallurgical Methods for Processing Iron Manganese Ores

Processing iron manganese ores is one of the most challenging tasks in the metallurgical industry due to their complex mineralogical composition, the fine intergrowth of iron- and manganese-containing minerals, and the widespread isomorphic substitution of iron and manganese within mineral crystal structures. The primary objective of the processing methods employed is to increase the Mn/Fe ratio to levels that enable the use of these raw materials for manganese ferroalloy production ($\text{Mn/Fe} > 5$).

Pyrometallurgical methods for the separation of iron and manganese from iron manganese ores can be broadly classified into several categories: carbothermic reduction roasting followed by magnetic separation, smelting to produce manganese slag, and hydrogen reduction followed by magnetic separation.

Before pyrometallurgical treatment, the feed material must be prepared according to its particle-size distribution, mechanical strength, moisture content, mineralogical composition, and the requirements of the selected reactor. Lump iron manganese ore with sufficient thermal and mechanical strength may be charged directly after crushing, screening, and size classification. In contrast, fine ores and concentrates generally require agglomeration by sintering, pelletization, or briquetting to reduce dust losses, improve burden permeability, ensure more uniform gas-solid contact, and stabilize furnace operation. Agglomeration is particularly important for shaft, fixed-bed, and submerged-arc furnace processes, whereas fine particles may be processed without prior agglomeration in reactors specifically designed for fine feeds, such as fluidized beds. The selection of the preparation method should therefore be considered an ore- and process-specific stage rather than a universal requirement.

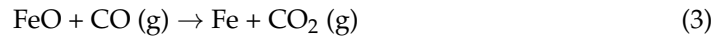
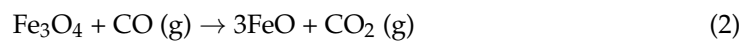
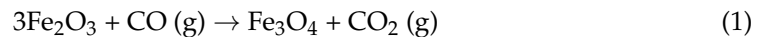
5.1. Carbothermic Reduction Roasting

Carbothermic reduction roasting followed by magnetic separation is one of the most extensively studied methods for the selective separation of iron and manganese from iron manganese ores. The process involves the reduction of iron manganese ores using carbonaceous reducing agents (coke or coal) at elevated temperatures to selectively reduce iron and subsequently increase the Mn/Fe ratio.

The method is based on heating the ore in a reducing atmosphere, resulting in the selective transformation of iron oxides into strongly magnetic magnetite and/or metallic iron, while wüstite, when formed as an intermediate reduction product, exhibits only weak magnetic properties. Most manganese remains in weakly magnetic or nonmagnetic oxide and silicate phases, enabling subsequent separation of the iron-rich magnetic fraction from the manganese-rich nonmagnetic fraction.

This enables the separation of the iron-containing magnetic fraction from the manganese-containing nonmagnetic fraction after grinding the roasted product, thereby increasing the Mn/Fe ratio in the manganese concentrate.

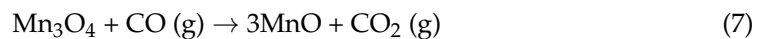
At elevated temperatures CO becomes the principal gaseous reducing agent within the ore-carbon mixture. Iron oxides are reduced stepwise according to the following simplified reactions:



Direct reduction by solid carbon may also occur at the points of contact between the oxide and reducing agent:



Higher manganese oxides are also reduced stepwise; however, under the conditions used for selective roasting, the reduction generally terminates at MnO:



Iron reduction becomes thermodynamically feasible at approximately 650 °C, whereas the reduction of manganese oxide to metallic manganese requires a considerably higher temperature of about 920 °C [78]. Within the intermediate temperature range, iron oxides can be reduced preferentially while manganese remains predominantly in the oxide phase. From a thermodynamic perspective, iron reduction therefore begins earlier than manganese reduction, resulting in the preferential transfer of iron into the metallic phase. This difference in reduction temperatures provides the fundamental basis for the selective separation of iron and manganese.

In the study by Yi et al. [79], anthracite was used as the reducing agent, and reduction roasting was carried out in a laboratory furnace followed by magnetic separation. The optimal conditions included a temperature of approximately 1100 °C and a holding time of approximately 100 min. Under these conditions, an iron-containing product containing 62.3% Fe and 23.3% Mn was obtained, along with a manganese product containing 63.7% Mn, 3.74% Fe, 8.23% SiO₂, 4.16% CaO, 1.03% MgO, 0.25% Al₂O₃, and 0.015% P. The recovery of iron to the magnetic product was 88.2%, while the recovery of manganese to the manganese product reached 70.4%.

In the study by Gao et al. [80] on iron manganese ore, the optimal process parameters included a roasting temperature of 1050 °C, a roasting time of 6 h, an ore particle size of 8–13 mm, and a fixed carbon-to-oxygen ratio of 2.5. After roasting, the product consisted primarily of MnO, metallic iron, and gangue minerals. Magnetic separation at a magnetic field strength of 100 mT produced a manganese product containing 56.20% Mn, with a manganese recovery of 71.00%, an iron recovery to the magnetic fraction of 93.60%, and an Mn/Fe ratio of up to 10.85.

Coal, coke, graphite, anthracite, and other carbon-containing materials are commonly used as reducing agents. Upon heating, carbon reacts with the oxygen contained in iron and manganese oxides to form CO, which subsequently participates in the reduction process. Initially, the higher oxides of manganese and iron are reduced; subsequently, iron is reduced more readily than manganese, providing the basis for their selective separation. However, at excessively high temperatures or under conditions of excess reducing agent, complex Mn-Fe oxides, spinels, and solid solutions may form, adversely affecting subsequent magnetic separation [80,81].

Laboratory studies are typically conducted in tube, muffle, or chamber furnaces with controlled temperature and atmospheric conditions. The ore is pre-crushed, ground, mixed with a reducing agent, and, in some cases, combined with fluxing additives before being loaded into crucibles. In industrial applications, the most promising equipment includes rotary kilns, shaft furnaces, fluidized-bed reactors, and reduction roasting units used in direct reduction technologies [82].

Temperature is a key factor affecting the process. According to various studies, reduction roasting of iron manganese ores is most commonly carried out within the temperature range of approximately 650–1100 °C, with the specific temperature depending on the mineralogical composition of the ore, the contents of iron, manganese, silica, and alumina, the particle size of the material, the type of reducing agent, and the required degree of reduction. In the study by Nurjaman et al. [83], the dependence of the Mn/Fe ratio in the non-magnetic product on the reduction-roasting temperature was demonstrated. For the selected particle-size fractions, the Mn/Fe ratio increased as the temperature rose from 500 to 700 °C. Specifically, it increased from 1.28 to 1.96 for the Lampung ore (−60 + 80 mesh) and from 1.92 to 3.99 for the East Java ore (−40 + 60 mesh). However, a further increase in temperature to 900 °C reduced the corresponding ratios to 0.68 and 1.98, respectively, as illustrated in Figure 3.

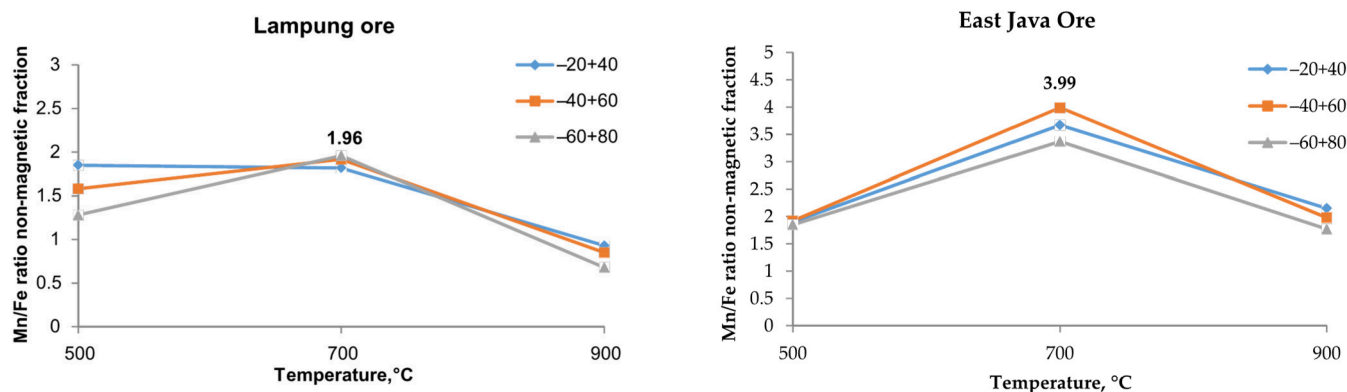


Figure 3. The dependence of the Mn/Fe ratio in the non-magnetic product on the reduction-roasting temperature.

The maximum Mn/Fe ratio observed at 700 °C was attributed to the transformation of hematite into magnetic magnetite, while manganese oxides were converted predominantly into weakly magnetic or paramagnetic phases. At 900 °C, part of the magnetite reacted with silica to form non-magnetic fayalite, resulting in the transfer of additional iron to the non-magnetic fraction and a decrease in the Mn/Fe ratio [83]. These results indicate that increasing the roasting temperature does not necessarily lead to a continuous improvement in separation efficiency and that the optimum temperature strongly depends on the mineralogical composition and particle size of the ore.

Research by Gao et al. [81] shows that, in carbothermic reduction roasting, not only temperature but also holding time, reducing agent consumption, and subsequent grinding of the roasted product prior to magnetic separation are important process parameters.

After roasting, the material is cooled, crushed, and ground to liberate the newly formed phases. Magnetic separation is then performed. At this stage, metallic iron, magnetite, and other ferromagnetic iron-containing phases are recovered in the magnetic product, whereas manganese is predominantly concentrated in the nonmagnetic or weakly magnetic fraction. Dry or wet magnetic separators are used for separation, and the selection of magnetic field strength depends on the composition of the roasted product and the degree of iron reduction. If iron is reduced to the metallic state or to magnetite, low-intensity magnetic

separation can be applied; however, in the presence of weakly magnetic Mn-Fe phases, higher magnetic field strengths may be required. The process flowsheet for carbothermic reduction roasting is presented in Figure 4.

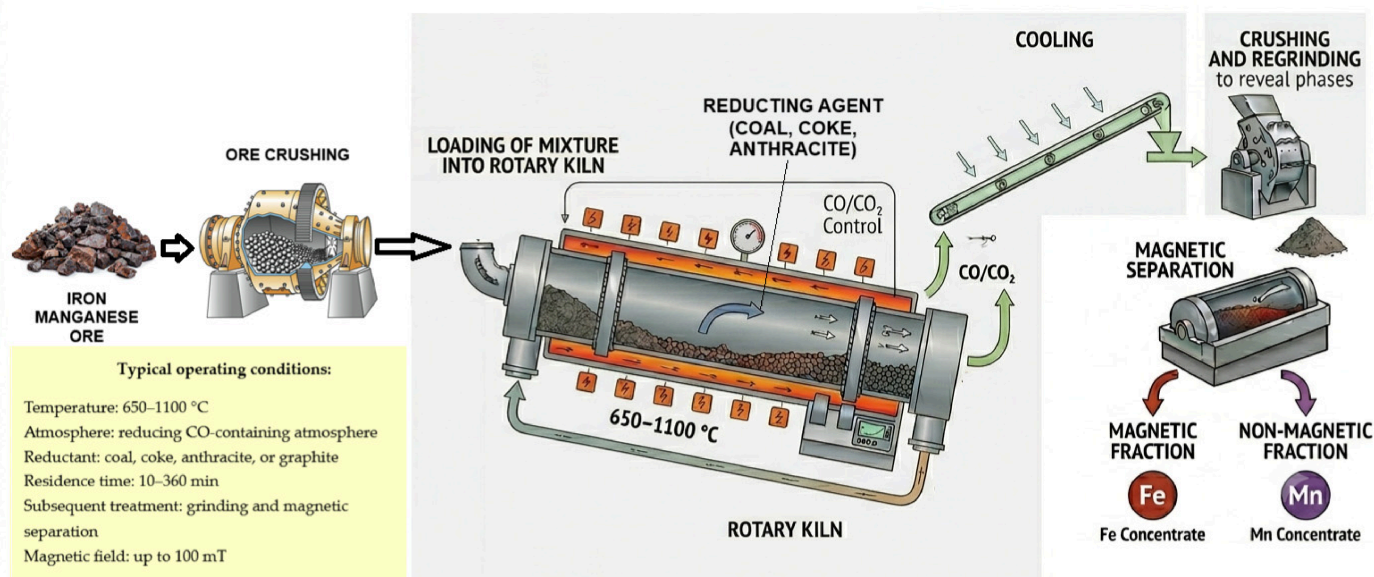


Figure 4. Flowsheet of Carbothermic Reduction Roasting of Iron Manganese Ores.

All experimental data discussed in this subsection (Yi et al. [79]; Gao et al. [80,81]; Nurjaman et al. [83]) were obtained at laboratory scale, using bench-top tube, muffle, or rotary furnaces with sample masses ranging from several grams to a few kilograms. To date, no industrial-scale application of carbothermic reduction roasting specifically for iron manganese ore beneficiation has been reported in the literature; the rotary kilns, shaft furnaces, and fluidized-bed units referred to in [82] are industrially proven for iron-ore direct reduction but have not yet been demonstrated at full industrial scale for this particular ore type.

5.2. Smelting to Produce Manganese Slag

Smelting of iron manganese ores for the production of cast iron and rich manganese slag is a pyrometallurgical method for the selective separation of iron and manganese based on differences in the thermodynamic reducibility of their oxides. The process is based on reduction smelting, during which iron oxides are preferentially reduced to metallic iron and transferred to the metallic phase, whereas most of the manganese remains in oxide form and is concentrated in the slag phase. As a result, two products are obtained: an iron-containing metal similar in composition to cast iron and a rich manganese slag that can be used as a raw material for the subsequent production of manganese ferroalloys [84,85].

This method is particularly relevant for the processing of iron manganese ores characterized by high iron contents and low Mn/Fe ratios. For example, Singh et al. [86] used iron manganese ores containing 25–30% Mn and having an Mn/Fe ratio of approximately 1. During smelting, rich manganese slags containing 52.59–58.24% MnO and exhibiting an Mn/Fe ratio greater than 15 were produced, together with manganese-containing cast iron containing 8.5–24.0% Mn. The efficiency of manganese and iron separation exceeded 95%.

A similar approach was applied to the processing of Egyptian manganese ore in a smelting furnace. Eissa et al. [87] demonstrated that the process produced low-manganese cast iron and rich manganese slag. Under optimal operating conditions, the metal yield reached 98%, iron recovery to cast iron was 95.82%, and MnO recovery to the rich manganese slag reached 94.59%. The process was successfully tested in a 100 kVA pilot-scale

smelting furnace. The general process flowsheet for the production of rich manganese slag is presented in Figure 5.

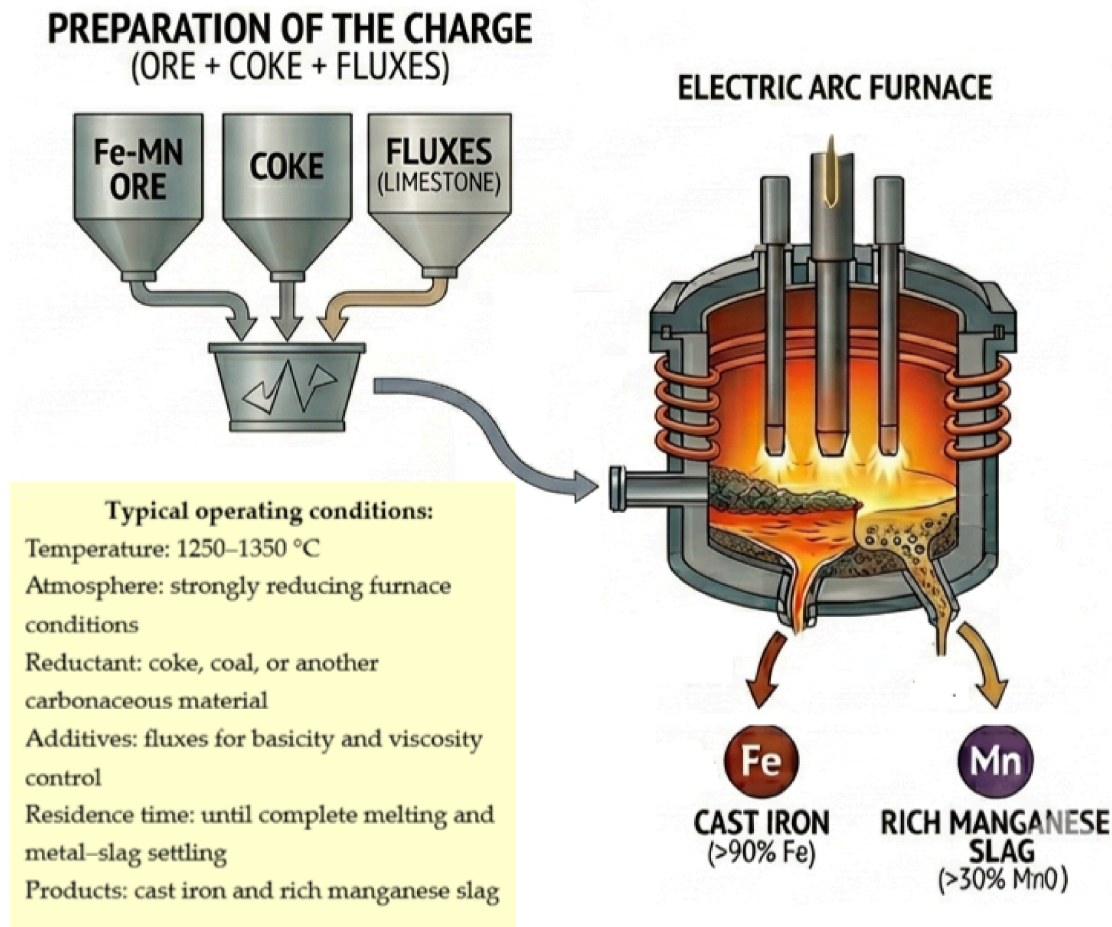


Figure 5. Flowsheet for the Production of Rich Manganese Slag from Iron Manganese Ores by Smelting.

Among the studies reviewed in this subsection, Singh et al. [86] operated at pilot scale (a 50 kVA electric arc furnace processing 10 kg ore batches), and Eissa et al. [87] likewise used a 100 kVA pilot-scale smelting furnace. Submerged arc furnace smelting itself is a mature, industrially implemented technology for manganese ferroalloy production worldwide (e.g., Eramet Norway’s Sauda plant, and TNK Kazchrome’s Aksu and Aktobe ferroalloy plants in Kazakhstan); however, industrial-scale smelting configured specifically to produce rich manganese slag and cast iron from low-grade, high-iron ores of the type discussed here has not yet been reported.

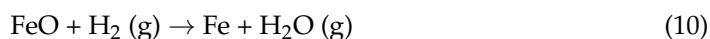
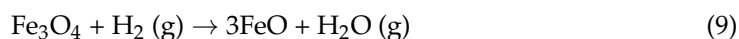
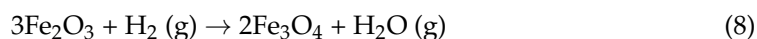
5.3. Hydrogen Reduction Followed by Magnetic Separation

Hydrogen-based reduction is considered a promising approach for the selective separation of iron and manganese from iron-manganese ores. The method is based on the preferential reduction of iron oxides to metallic iron, while manganese is retained predominantly in the oxide or silicate phase. The resulting difference in the magnetic properties of the phases creates favorable conditions for the subsequent separation of an iron-rich magnetic product from a manganese-rich nonmagnetic product.

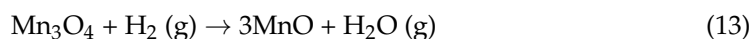
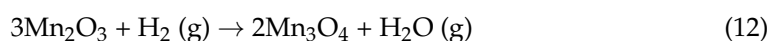
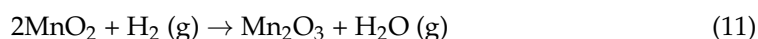
Compared with conventional carbothermic processes, hydrogen reduction does not require a solid carbonaceous reducing agent. Water vapor is formed as the principal gaseous reaction product instead of CO and CO₂. Therefore, the technology has significant potential

for reducing direct carbon emissions, particularly when hydrogen is produced using low-carbon or renewable energy sources. However, its practical implementation depends on reduction kinetics, phase transformations, gas consumption, hydrogen production costs, and the efficiency of subsequent separation.

The selective reduction of iron-manganese ores by hydrogen is governed by differences in the thermodynamic stability of iron and manganese oxides. Under reducing conditions, iron oxides are subsequently transformed according to the following pathway:



Higher manganese oxides are also reduced by hydrogen, but the process generally terminates at the stable MnO stage:



The reduction of iron oxides becomes thermodynamically favorable at lower temperatures than the reduction of MnO to metallic manganese. Depending on the mineralogical composition of the ore and the hydrogen partial pressure, the formation of metallic iron generally becomes significant above approximately 600–700 °C and proceeds more intensively at 700–900 °C.

Higher manganese oxides, including MnO₂ and Mn₂O₃, may also be reduced during heating; however, manganese is predominantly stabilized as MnO. Further reduction of MnO to metallic manganese is thermodynamically unfavorable under the temperature and hydrogen-pressure conditions generally used for selective iron reduction. Consequently, manganese remains mainly in the oxide phase or becomes incorporated into stable silicate and aluminosilicate compounds, such as Mn₂SiO₄ and Mn-containing aluminosilicates [88,89].

The presence of iron–manganese spinels and complex solid solutions significantly affects reduction selectivity. During intermediate reduction stages, phases such as Fe₂MnO₄ may form. Their subsequent decomposition promotes the formation of metallic iron; however, incomplete decomposition may retain iron in the manganese-rich residue. Silica and alumina can additionally stabilize mixed Mn-Fe silicate and spinel phases, thereby reducing the completeness of iron–manganese separation.

Thus, the thermodynamic basis of the method is favorable for the selective reduction of iron. Nevertheless, the actual phase distribution depends on temperature, hydrogen partial pressure, ore composition, and the stability of intermediate mixed oxide phases.

The kinetics of hydrogen reduction are controlled by several interacting factors, including temperature, particle size, ore porosity, mineralogical composition, hydrogen flow rate, gas-solid contact conditions, and reduction time. Increasing the temperature generally accelerates the reduction of iron oxides and promotes the formation of metallic iron. Similarly, decreasing the particle size shortens the diffusion path and increases the specific reaction surface.

The reduction process commonly begins at the external surface of ore particles and progressively advances toward their interior. In the initial stages, oxygen is removed from higher iron and manganese oxides, resulting in the formation of lower oxides. Metallic iron

subsequently nucleates and grows within the reduced particles. With increasing reduction time, isolated iron particles may coalesce and form a more continuous metallic phase.

At the same time, manganese is retained mainly in an oxide or silicate matrix. The formation of a distinct metallic iron phase and a manganese-rich oxide phase facilitates their subsequent liberation by grinding and magnetic separation. However, the effectiveness of this separation strongly depends on the resulting microstructure.

Fine metallic iron particles enclosed within the oxide matrix may not be completely recovered by magnetic separation. Conversely, residual iron oxides, mixed Mn-Fe spinels, and complex silicates may remain associated with the manganese-containing phase. These effects explain why a high degree of iron reduction does not always result in complete physical separation of iron and manganese.

The reduction rate increases with decreasing particle size and increasing temperature, as confirmed by fixed-bed and laboratory furnace studies [88–90]. However, excessively high temperatures may cause particle sintering, reduce pore accessibility, and promote the formation of dense reaction layers. These structural changes can restrict hydrogen diffusion and slow the later stages of reduction. Therefore, the reduction regime must ensure both sufficient iron metallization and the formation of a microstructure suitable for subsequent phase liberation.

Kosdauletov et al. [88] investigated the selective hydrogen reduction of iron–manganese ore containing 5.0% Mn_2O_3 , 44.88% MnO_2 , 23.34% Fe_2O_3 , 17.57% SiO_2 , 4.87% CaO , 3.57% Al_2O_3 , and 0.42% MgO . The ore was ground to a particle size below 1 mm, moistened, pelletized, and dried at 150 °C for 1 h. Reduction was conducted in a laboratory vertical furnace at 800–900 °C for 60 min using a hydrogen flow rate of 0.5 L/min.

The thermodynamic calculations and experimental results showed that iron oxides were reduced to metallic iron, whereas manganese remained predominantly in the form of MnO and manganese-containing silicate and aluminosilicate phases. The metallic phase contained approximately 93.6–99.5% total iron, while the oxide phase contained approximately 52.1–57.9% manganese and only 2.2–6.1% residual iron. These results demonstrate the potential of hydrogen for selective iron removal from iron–manganese ores.

El-Gawad et al. [89] studied the hydrogen reduction of Egyptian manganese ore containing 28.6% Mn, 23.2% Fe, 15.3% SiO_2 , 2.3% Al_2O_3 , 2.4% CaO , and 0.95% MgO . The ore was ground to below 75 μm and briquetted using molasses as a binder. Reduction was carried out in a hydrogen atmosphere at temperatures between 650 and 950 °C.

X-ray diffraction analysis showed that iron was almost completely reduced to the metallic state, whereas manganese remained mainly as MnO. The study confirmed that differences in the thermodynamic stability of iron and manganese oxides can be used to produce a metallic iron phase and a manganese-containing oxide phase suitable for subsequent magnetic separation.

Hydrogen reduction of South African Nichwaning manganese ore was investigated in a fixed-bed reactor [90]. The initial ore contained approximately 45.4% manganese and 9.9% iron. The reduction degree increased with increasing temperature and decreasing particle size. At approximately 800–900 °C, Fe_2O_3 was effectively reduced toward metallic iron, whereas higher manganese oxides were mainly converted to MnO. The reduced material contained approximately 50.5–52.2% manganese and 10.5–12.4% iron.

The kinetic analysis indicated that the reduction rate was largely controlled by the chemical reaction at the gas–solid interface. The results also demonstrated that hydrogen-based pre-reduction can decrease the amount of fossil carbon required during the subsequent production of manganese ferroalloys.

All hydrogen-reduction studies discussed above (Kosdauletov et al. [88]; El-Gawad et al. [89]; Schanche et al. [90]) were performed at laboratory scale, using vertical tube or

fixed-bed furnaces with sample masses of a few tens of grams. No pilot- or industrial-scale implementation of hydrogen reduction specifically for iron-manganese ores has yet been reported in the literature.

Although these studies provide promising results, most experiments were performed using relatively small samples and controlled laboratory conditions. Differences in ore mineralogy, particle size, sample preparation, hydrogen flow, and analytical procedures limit direct comparison of the reported results. In addition, high iron metallization does not automatically guarantee efficient magnetic separation unless adequate liberation of the metallic phase is achieved.

Modern approaches to hydrogen reduction focus on improving gas-solid contact, hydrogen utilization, heat recovery, process continuity, and the integration of reduction with downstream separation or smelting operations. The choice of reactor configuration depends primarily on the particle size and physical form of the feed material.

Fixed-bed and moving-bed reactors are more suitable for lump ores, pellets, and briquettes because they provide stable gas flow through a mechanically resistant burden. Fluidized-bed reactors are more appropriate for fine ores because they offer intensive gas-solid contact, uniform temperature distribution, and high heat- and mass-transfer rates. However, the use of fine particles may create difficulties associated with entrainment, agglomeration, and pressure control.

Hydrogen recycling is another important direction for the development process. After water vapor is removed from the reactor off-gas, the unreacted hydrogen may be returned to the reduction unit. Such recycling can decrease hydrogen consumption and improve process economics. Heat recovery from the hot reduced product and off-gas may also reduce the external energy demand.

The use of hydrogen as a preliminary reduction stage before electric smelting represents a particularly promising hybrid approach. Selective removal of iron before smelting may reduce the furnace burden, carbon consumption, and the quantity of iron entering the manganese alloy. However, the technical advantages of such integrated schemes must be confirmed by complete mass and energy balances.

Green hydrogen produced through electrolysis using renewable electricity offers the greatest potential for reducing the carbon footprint of the process. However, hydrogen reduction cannot be regarded as automatically carbon-free because its overall environmental performance depends on hydrogen production, compression, heating, circulation, and recycling. Cheraghi et al. [91] identified gaseous reduction as a promising direction for the decarbonization of manganese processing but also emphasized the need for further development of reaction models, reactor technologies, and industrial-scale validation.

At present, hydrogen reduction of iron-manganese ores remains mainly at the laboratory and early pilot stages. Its wider industrial application is constrained by hydrogen cost, infrastructure requirements, process-safety considerations, and the need for subsequent grinding and magnetic separation.

The general flowsheet for hydrogen reduction of iron-manganese ores is presented in Figure 6. The process begins with ore preparation, including crushing and grinding to obtain the particle size required for effective gas-solid interaction. Fine material may be pelletized or briquetted to improve gas permeability and mechanical stability during reduction.

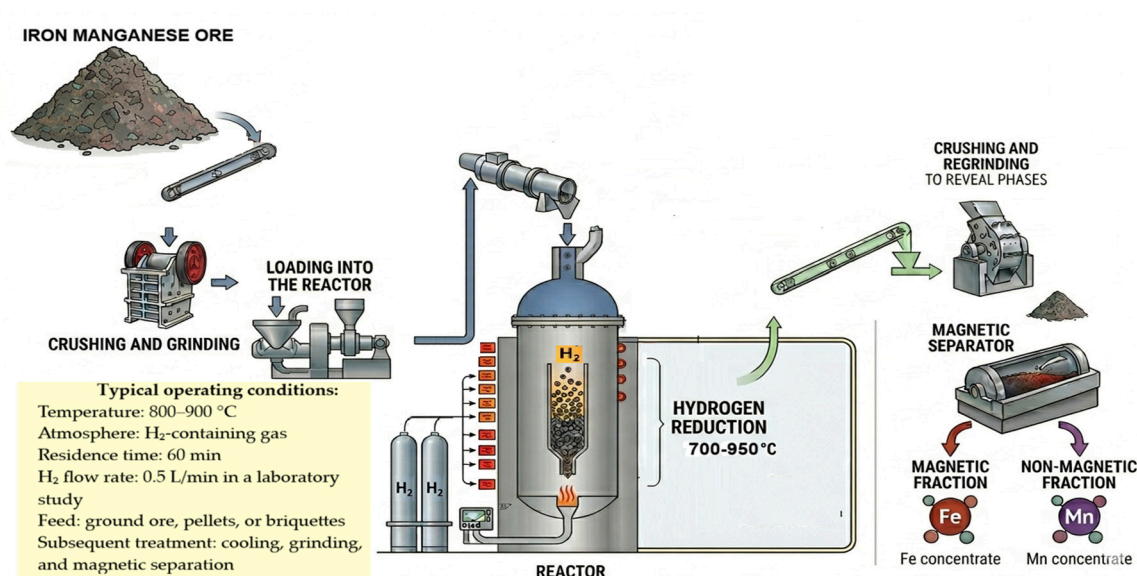


Figure 6. Flowsheet for Hydrogen Reduction of Iron Manganese Ores.

The prepared material is introduced into the reduction reactor and heated in a hydrogen-containing atmosphere. During this stage, iron oxides are selectively reduced to metallic iron, while manganese remains mainly in the oxide or silicate phase. The reduced product is subsequently cooled under conditions that minimize the reoxidation of metallic iron.

After cooling, the material is ground to liberate the newly formed metallic iron particles from the manganese-containing oxide matrix. Magnetic separation is then used to divide the material into an iron-rich magnetic fraction and a manganese-rich weakly magnetic or nonmagnetic fraction. The iron-rich product may be used as a metallurgical raw material, whereas the manganese-rich product may be subject to further beneficiation or used in subsequent manganese ferroalloy production.

The efficiency of the overall flowsheet depends not only on the degree of iron reduction but also on the liberation of the metallic phase, the magnetic separation conditions, hydrogen utilization, and the chemical quality of both final products.

6. Discussion

The available literature confirms that carbothermic reduction roasting, hydrogen-based selective reduction, and reduction smelting can all improve the utilization of iron manganese ores. However, direct comparison of the reported results is difficult because the studies differ substantially in ore composition, mineralogy, particle size, reducing-agent dosage, temperature, residence time, equipment, and the methods used to calculate metal recovery. Consequently, the highest recoveries or Mn/Fe ratios reported in individual studies should not be interpreted as universally achievable process indicators.

6.1. Carbothermic Reduction Roasting Followed by Magnetic Separation

Carbothermic reduction roasting is the most extensively investigated route for upgrading iron manganese ores. The published results demonstrate that selective iron reduction can produce a manganese-rich nonmagnetic fraction. For example, manganese products containing approximately 53.6–63.7% Mn have been reported, with manganese recoveries ranging from approximately 70.4% to 89.38% and Mn/Fe ratios reaching 5.43–10.85 [79–81]. These results indicate that the method can substantially improve the quality of iron manganese ores.

However, the wide variation in the reported indicators reveals the strong dependence of the process on the mineralogical and chemical characteristics of the feed material. High manganese recovery does not necessarily coincide with the highest Mn/Fe ratio or the most

complete iron removal. This trade-off is caused by the simultaneous reduction of iron- and manganese-containing phases and by the formation of complex spinels, silicates, and solid solutions, including (Fe,Mn) oxides and Mn-Fe-Si phases. These phases retain manganese in the magnetic product or iron in the nonmagnetic fraction and therefore reduce separation selectivity [80,81,92].

The process also requires several successful operations, including fine grinding, mixing with a reducing agent, roasting, cooling, regrinding, and magnetic separation. Each additional operation increases energy consumption, equipment requirements, dust generation, and material losses. Although industrial-scale trials reported by Singh et al. [82] demonstrated the technical possibility of processing large quantities of low-grade ore, the authors also identified roasting costs, reducing-agent consumption, magnetic-separation requirements, and unstable concentrate quality as important constraints.

These limitations are particularly relevant to Kazakhstan's iron manganese ores. Their relatively high silica and aluminum contents and the close intergrowth of manganese- and iron-containing minerals may promote the formation of difficult-to-separate silicate and spinel phases. Therefore, laboratory results obtained for more favorable ores cannot be transferred directly to deposits such as West Karazhal, Ushkatyn-I, and Big Ktai without deposit-specific testing. Carbothermic roasting may be suitable for selected ores, but its industrial applicability depends on achieving sufficient mineral liberation without excessive grinding and energy consumption.

6.2. Hydrogen-Based Selective Reduction

Hydrogen reduction offers an important environmental advantage because water vapor, rather than CO or CO₂, is the principal gaseous reaction product. Cheraghi et al. [91] noted that gas-phase reduction is one of the most promising approaches for the decarbonization of manganese ferroalloy production. The literature demonstrates that iron oxides can be selectively reduced to metallic iron at approximately 800–950 °C, while manganese remains predominantly in the form of MnO or manganese-containing silicates. In some laboratory studies, the metallic phase contained 93.6–99.5% Fe, whereas manganese was concentrated in the oxide phase [88,89].

However, the reported selectivity should be evaluated cautiously. Most studies were conducted using small samples, finely ground ores, pellets or briquettes, pure hydrogen, and controlled laboratory furnaces. These conditions differ considerably from industrial operation. In addition, the formation of Mn-Fe spinels and manganese silicates may prevent complete liberation of the metallic iron phase. The reduced product therefore still requires grinding and magnetic separation, and residual iron contents may remain relatively high in the manganese-rich fraction.

The environmental advantage of this technology also depends on the origin of the hydrogen. If hydrogen is produced from fossil fuels without carbon capture, the reduction in total greenhouse-gas emissions may be substantially lower than expected. At present, the literature contains insufficient comparative life-cycle assessments, energy balances, and economic evaluations for hydrogen reduction of iron manganese ores.

For Kazakhstan, hydrogen reduction should therefore be considered a strategically promising long-term technology rather than an immediately available industrial solution. Its implementation is currently limited by hydrogen cost, the absence of large-scale low-carbon hydrogen infrastructure, gas-handling and safety requirements, and the lack of pilot-scale data for Kazakhstan ores. Further studies should focus on reaction kinetics, hydrogen utilization efficiency, gas recycling, and magnetic separation of products obtained from representative domestic ores.

Quantitative cost data support this assessment. According to the International Energy Agency's Global Hydrogen Review 2025, the levelized cost of renewable («green») hydrogen produced by electrolysis currently ranges from approximately USD 3.5 to 6 per kilogram outside China, where lower electrolyser and electricity costs allow production 40–45% cheaper than in Europe or the United States [93]. By comparison, metallurgical coke and coking coal, the principal carbon-based reducing agents used in conventional reduction roasting and smelting, have traded at approximately USD 230–250 per tonne through 2025–2026, equivalent to roughly USD 0.23–0.25 per kilogram [94]. On a simple mass basis, green hydrogen therefore remains more than an order of magnitude more expensive than the carbonaceous reductants currently used in Kazakhstan's ferroalloy industry. This cost gap, together with the absence of large-scale low-carbon hydrogen production, transport, and storage infrastructure in Kazakhstan, is the principal reason why hydrogen-based reduction is considered less practical than carbothermic routes under current conditions.

6.3. Reduction Smelting for the Production of Rich Manganese Slag

Reduction smelting has produced the most consistent separation indicators among the technologies considered. Published studies report rich manganese slags containing approximately 52.59–58.24% MnO, Mn/Fe ratios greater than 15, iron recoveries exceeding 95%, and MnO recovery to the slag of approximately 94.59% [82,86,87]. The principal advantage of this route is that iron and manganese are separated directly between two liquid phases: iron is transferred to the metal, whereas manganese is retained mainly in the slag.

Unlike reduction roasting, smelting destroys the original mineralogical structure of the ore. Therefore, the process is less sensitive to fine intergrowths of manganese- and iron-containing minerals and does not require subsequent magnetic separation. It also enables the simultaneous production of two potentially marketable products: cast iron and rich manganese slag suitable for subsequent ferromanganese or silicomanganese production. Tangstad et al. [95] noted that manganese slag plays a key role in modern manganese ferroalloy production because of its favorable slag chemistry and improved reduction conditions during smelting in submerged arc furnaces.

European metallurgical research groups, most notably at the Norwegian University of Science and Technology and SINTEF in Trondheim, Norway, have generated an extensive body of fundamental and pilot-scale work on the behavior of manganese ores and slags, and several of these studies already underpin the analysis presented above [1,58,90,91,95]. Beyond ore pretreatment and gas-phase reduction, Norwegian groups have specifically addressed the slag-side chemistry that governs manganese retention during reduction smelting. Kudyba and Safarian [96] demonstrated that manganese and aluminum can be recovered from spent ferromanganese slag and aluminum white dross through a high-temperature smelting-reduction route, showing that rich manganese slag of the type considered in this review can itself be revalorized once its primary metallurgical function has been fulfilled. More recently, Rimal and Tangstad [97] established that carbothermic reduction of MnO in ferromanganese slags proceeds through three kinetically distinct stages that are closely linked to the transition of the slag from a multiphase to a single-phase liquid as basicity and temperature change. This mechanism helps explain why the reduction and recovery indicators reported for rich manganese slag in Section 6.3 are so sensitive to basicity, and it reinforces the conclusion that slag chemistry, and not ore mineralogy alone, becomes the dominant lever for process optimization once smelting is adopted.

Japanese research has approached manganese metallurgy from a complementary, systems-level perspective, focusing on the industrial-scale flow and reuse of manganese-containing slags within integrated steelworks. Nakajima et al. [98] carried out a national

substance-flow analysis of manganese in the Japanese iron and steel industry and showed that a substantial share of manganese input is retained in steelmaking slag rather than reporting to the final steel product, identifying slag-based recovery as an important route for improving overall manganese utilization. Building on this systems-level view, Kim et al. [99], working at Tohoku University, developed a kinetic model of the slag-matte reaction used to recover ferromanganese alloy directly from steelmaking slag, providing quantitative rate parameters for industrial-scale manganese recovery from slag. Although these Japanese studies concern steelmaking slag rather than iron manganese ore smelting directly, they provide independent confirmation, obtained under industrial reaction conditions, that rich manganese slag is a technically recoverable and economically meaningful metallurgical product rather than an inert waste stream. This conclusion supports the broader argument of the present review that the rich manganese slag produced from Kazakhstan's iron manganese ores should be regarded as a genuine co-product of smelting rather than a byproduct of secondary importance.

However, the superiority of smelting should not be overstated. The process requires high temperatures, electrical energy, carbonaceous reducing agents, fluxes, and refractory materials. Its technical and economic performance depends strongly on slag basicity, viscosity, melting temperature, manganese activity, and the degree of iron reduction. An increase in iron reduction may improve cast-iron recovery but may also increase manganese losses to the metallic phase. Conversely, insufficient iron reduction may lower the Mn/Fe ratio of the slag. Thus, process optimization requires a controlled balance between iron metallization and manganese retention.

Despite these limitations, reduction smelting appears to be the most technically realistic route for Kazakhstan under current conditions. This is not merely a general expectation but reflects an already operating industrial base: the country's manganese and chromium ferroalloy industry has for decades relied on submerged-arc and enclosed ore-reduction electric furnaces of the type required for reduction smelting [69,72]. The Aksu Ferroalloy Plant of JSC TNC Kazchrome, one of the world's largest ferroalloy producers, operates 26 electric furnaces across four smelting shops with a combined output exceeding 1 million tons of ferroalloys per year, including ferrosilicomanganese; its Smelting Shop 1 alone comprises six 33-MW enclosed ore-reduction (RKZ-type) furnaces used, among other duties, for manganese-ore smelting [100]. A second facility, the Taraz Metallurgical Plant LLP, has produced ferrosilicomanganese from Kazakhstan manganese ores for many years and remains the subject of ongoing research on the electrothermal treatment of manganese-ferroalloy smelting dusts [101]. This existing base of furnace capacity, operating experience, and qualified personnel means that industrial implementation of reduction smelting for iron manganese ores would primarily require adaptation of existing furnace practice, burden preparation, and slag handling, rather than construction of an entirely new technological base, which substantially reduces the barriers to implementation compared with hydrogen-based processes, for which no comparable domestic infrastructure currently exists. Moreover, the high iron content and low Mn/Fe ratios of many Kazakhstan ores, which are disadvantages for conventional beneficiation, may be advantageous for the production of cast iron and rich manganese slag.

The suitability of reduction smelting for Kazakhstan's iron manganese ores can be illustrated using the West Karazhal and Ushkatyn-III deposits. West Karazhal ore contains approximately 20.37% Mn, 9.45% Fe, and 21.52% SiO₂, corresponding to an Mn/Fe ratio of about 2.2. Its mineral composition is represented mainly by pyrolusite, braunite, and hausmannite, and the ore is characterized by a complex silicate-type structure. These features limit direct ferroalloy production and may reduce the efficiency of solid-state reduction followed by magnetic separation because manganese and iron can remain associated in

silicate and spinel phases. During reduction smelting, the original mineral structure is destroyed, iron is preferentially transferred to the metallic phase, and manganese is concentrated in the slag. Therefore, smelting is more suitable for overcoming the mineralogical intergrowth characteristic of West Karazhal ore. However, its relatively high silica content may increase slag volume and viscosity; consequently, the process requires optimization of slag basicity, flux addition, and melting temperature.

The Ushkatyn-III deposit is more heterogeneous, with Mn contents ranging from 2.32 to 44.26%, Fe contents from 1.74 to 42.79%, and SiO₂ contents from 11.76 to 23.92%. The ore contains psilomelane, braunite, vernadite, hausmannite, and pyrolusite. High-grade oxidized portions of the deposit may be suitable for conventional beneficiation or direct ferroalloy use, whereas iron-rich portions with low Mn/Fe ratios are more appropriate for reduction smelting. In these ore varieties, iron can be recovered as a metallic product, while manganese is retained in a rich slag suitable for subsequent ferroalloy production. Thus, the applicability of smelting to Ushkatyn-III should be based on selective mining, mineralogical classification, and blending of different ore types rather than on treating the entire deposit as a uniform raw material.

This deposit-specific analysis supports the conclusion that reduction smelting is particularly appropriate for iron manganese ore varieties in Kazakhstan. At the same time, it shows that smelting should not be applied indiscriminately to all manganese ores and that the final selection process must account for ore heterogeneity, silica content, mineralogical associations, and the quality requirements for both the metallic and slag products.

Table 3 shows the main indicators of the three methods.

Table 3. Main indicators of the methods.

Parameter	Carbothermic Reduction Roasting + Magnetic Separation	Reduction Smelting	Hydrogen Reduction + Magnetic Separation
Representative feed ore	Iron manganese ore, ~25–32% Mn, Mn/Fe ~1–3 [79–83]	Iron manganese ore, ~25–30% Mn, Mn/Fe 0.68–1 [86,87]	Iron manganese ore, e.g., 5% Mn ₂ O ₃ , 44.9% MnO ₂ , 23.3% Fe ₂ O ₃ [88]; 28.6% Mn, 23.2% Fe [89]
Reductant	Coal, coke, anthracite, or graphite	Coke, coal, or another carbonaceous material	Hydrogen gas
Typical temperature range	650–1100 °C	1250–1350 °C	700–950 °C
Initial particle size	<5 mm [79]; 8–13 mm [80]; fine ore, –20/–80 mesh [83]	Not explicitly reported	<1 mm [88]; <75 µm [89]
Final particle size (before separation)	<0.074 mm [79]	Not applicable (liquid metal/slag separation)	Not explicitly reported
Holding time	100 min [79]; 6 h [80]; 10–120 min [81]	Not explicitly reported	60 min [88] 0–60 min [89]
Reactor/furnace type	Rotary kiln, shaft furnace, fluidized-bed (industrial); tube/muffle furnace (lab) [82]	Submerged arc furnace (pilot: 50 kVA [86]; 100 kVA [87])	Fixed-bed/vertical tube furnace (lab) [88–90]
Separation method	Magnetic separation	Direct liquid metal-slag phase separation	Magnetic separation
Magnetic field intensity	140 A/m [79]; 100 mT [80]	Not applicable (no magnetic separation)	Not explicitly reported
Main products	Iron-containing metal concentrate and manganese-containing non-magnetic fraction	Cast iron and rich manganese slag	Iron-containing metal concentrate and manganese-containing non-magnetic fraction
Reported manganese product quality	53.6–63.7% Mn in the manganese-containing fraction	38.57–58.24% MnO in rich manganese slag	52.1–57.9% Mn in the manganese-containing fraction
Mn/Fe ratio	3.99–10.85	>15	>8
Manganese recovery	70.4–89.38%	90–95%	90–97%
Iron recovery	88.2–93.6%	93–95%	93–99%
By-products	Fine dust	Furnace off-gas and dust	Off-gas (H ₂ O)

6.4. Comparative Assessment and Research Gaps

A critical limitation of the existing literature is the absence of direct comparative studies in which all three technologies are tested using the same ore, particle-size distribution, system boundaries, and evaluation criteria. Reported recovery values cannot therefore be compared solely on a numerical basis. A process showing a high manganese recovery may require greater energy consumption, finer grinding, more reducing agent, or additional separation stages than a process with a slightly lower recovery.

Most publications emphasize metallurgical indicators, such as manganese content, Mn/Fe ratio, and metal recovery, while providing limited information on:

- specific energy and reducing-agent consumption;
- capital and operating costs;
- carbon dioxide emissions and full life-cycle environmental performance;
- water consumption and dust generation;
- refractory wear and equipment durability;
- product quality stability under variable feed compositions;
- scale-up from laboratory to pilot and industrial operation;
- economic value and marketability of all process products.

These gaps prevent a definitive ranking of the technologies on economic and environmental grounds. Therefore, the conclusion that reduction smelting is the most promising option for Kazakhstan should be understood as a conditional assessment based on current technological readiness, ore characteristics, reported separation efficiency, and compatibility with existing industrial infrastructure, rather than as proof of universal economic superiority.

The applicability of the technologies reviewed differs among Kazakhstan's manganese deposits because of substantial variations in Mn/Fe ratio, iron content, silica concentration, and mineralogical composition. Reduction smelting appears to be the most suitable route for the strongly iron ores of Ushkatyn-I, Big Ktai, Tur, and the iron-rich portions of Ushkatyn-III, where the low Mn/Fe ratio limits direct ferroalloy production. In these cases, iron can be recovered into the metallic phase, while manganese is concentrated in rich slag. Reduction smelting may also be appropriate for West Karazhal; however, its relatively high silica content and silicate mineralogy require careful control of slag basicity, viscosity, flux consumption, and manganese losses.

Carbothermic reduction roasting followed by magnetic separation may be more applicable to Zhomart and selected intermediate-grade portions of Ushkatyn-III, where the iron content is moderate and selective iron removal could increase the Mn/Fe ratio. However, its effectiveness must be confirmed experimentally because silica-rich ores may form complex Mn-Fe silicates and spinels that reduce magnetic-separation selectivity. High-grade ores from Yesimzhal, Bogach, and selected oxidized zones of Ushkatyn-III may be suitable for conventional beneficiation, direct ferroalloy production, or blending and therefore may not require energy-intensive pyrometallurgical upgrading.

Future investigations should include parallel experimental testing of representative ores from the principal Kazakhstan deposits. Particular attention should be paid to the influence of Mn/Fe ratio, silica and aluminum contents, phosphorus distribution, mineralogical associations, and particle size. Pilot-scale studies should establish complete mass and energy balances and compare specific energy consumption, reducing-agent requirements, emissions, product quality, and economic performance.

A combined or hybrid flowsheet may also be more effective than the application of a single processing method. Preliminary beneficiation or selective reduction could remove part of the iron before smelting, thereby reducing furnace energy consumption and slag volume. Alternatively, hydrogen could be used for partial pre-reduction when low-carbon

hydrogen becomes economically available, followed by smelting for final phase separation. Such integrated approaches deserve further investigation.

The utilization of process by-products is rarely discussed in the reviewed literature. The iron-containing metal concentrate obtained from carbothermic reduction roasting and hydrogen reduction is, in principle, a potential feed for ironmaking or steelmaking, though its acceptance depends on residual manganese, phosphorus, and gangue contents, which are rarely reported. Fine roasting or reduction dust generated during these routes is generally treated as metallurgical waste requiring agglomeration (pelletizing/briquetting) or disposal. For reduction smelting, cast iron is a marketable product, though a phosphorus-rich variant may be restricted to specific foundry applications or require further processing; rich manganese slag is the ferroalloy feedstock; and furnace off-gas dust requires separate collection and handling.

Phosphorus behavior requires separate consideration because it is one of the most restrictive impurities affecting the quality and marketability of manganese ferroalloys and iron-containing co-products. In conventional manganese ferroalloy smelting, phosphorus-containing compounds may be reduced under strongly reducing conditions, after which phosphorus is preferentially transferred to the metallic phase. Once dissolved in manganese- or iron-rich metal, phosphorus is considerably more difficult to remove than sulfur and may require a separate oxidizing dephosphorization stage involving a highly basic slag. None of the three processing routes considered in this review inherently includes such a refining stage. Moreover, selective removal of phosphorus from a manganese-rich alloy is thermodynamically and practically difficult, because the oxidizing, high-basicity slag conditions required to reject phosphorus also promote the oxidation and loss of manganese, the alloy's primary value component; experimental dephosphorization trials on commercial ferromanganese alloys have achieved only limited and inconsistent phosphorus removal, generally accompanied by measurable manganese losses [29]. Consequently, once phosphorus has reported to a manganese ferroalloy, it cannot, in practice, be economically removed by subsequent metallurgical treatment, consistent with the statement in the Introduction; dedicated dephosphorization is instead an established industrial practice for iron and steel, where the co-rejection of manganese together with phosphorus and silicon during hot-metal pretreatment is acceptable or even intended [102]. This distinction is the reason why dephosphorization is discussed below only for the iron-rich cast-iron co-product of reduction smelting, rather than for the manganese ferroalloy or rich manganese slag themselves. Therefore, phosphorus content and the phosphorus-to-manganese ratio of the feed should be evaluated together with the Mn/Fe ratio when assessing the suitability of upgraded products for downstream ferroalloy production.

During carbothermic reduction roasting followed by magnetic separation, phosphorus behavior depends on its mineralogical occurrence. Phosphorus associated with apatite, phosphates, gangue minerals, or finely intergrown manganese-containing phases may remain predominantly in the weakly magnetic or nonmagnetic manganese-rich fraction. Consequently, magnetic separation alone cannot be assumed to provide effective phosphorus rejection. If phosphorus-containing minerals are sufficiently liberated, partial removal may be possible through prior physical beneficiation; however, this requires mineralogical characterization and direct experimental verification. The phosphorus content of both the iron-containing metal concentrate (magnetic product) and the manganese-containing non-magnetic product should therefore be determined before their metallurgical utilization.

In reduction smelting, the high temperature and low oxygen potential promote the reduction of phosphorus-containing compounds and the transfer of phosphorus into the metallic phase. This partitioning may be advantageous for producing a rich manganese slag with a comparatively low phosphorus content, but it can restrict the use of the resulting

cast iron in foundry and steelmaking operations. A phosphorus-rich metallic product may require blending with low-phosphorus iron, controlled use in applications with less stringent specifications, or a separate hot-metal dephosphorization treatment [102]. However, the effectiveness and economic feasibility of such treatment depends on the carbon, silicon, manganese, and phosphorus contents of the metal and should be evaluated experimentally.

Under hydrogen-reduction conditions, typically approximately 800–950 °C, iron oxides can be reduced selectively while manganese remains mainly as MnO. At these comparatively lower temperatures, the reduction of stable phosphate phases is expected to be less extensive than during high-temperature smelting. Phosphorus may therefore remain in the unreduced oxide or manganese-rich residue. Nevertheless, its distribution between the metallic iron phase and the oxide fraction has not been systematically investigated for iron manganese ores, and direct conclusions cannot yet be drawn. Future hydrogen-reduction studies should include phosphorus mass balances and phase-specific chemical analyses.

The relatively low phosphorus contents reported for Kazakhstan's principal manganese deposits, approximately 0.02–0.08%, reduce but do not eliminate this concern. Even at low bulk concentrations, phosphorus may become concentrated in one product during iron-manganese separation. Accordingly, future laboratory and pilot-scale studies should determine phosphorus distribution coefficients, phosphorus recovery to the metal and slag phases, and the P/Mn ratio of the final manganese-containing product. Such data are necessary to confirm whether the rich manganese slag, manganese concentrate, and iron-containing co-products meet the requirements of downstream ferroalloy, foundry, and steelmaking operations.

Overall, the literature indicates that no processing method is universally optimal for all iron manganese ores. Carbothermic reduction roasting is technically established but highly sensitive to mineralogy and requires several downstream operations. Hydrogen reduction offers the greatest potential for decarbonization but remains limited by cost, infrastructure, and technological maturity. Reduction smelting provides the most robust phase separation and the best compatibility with Kazakhstan's existing ferroalloy industry, but its energy consumption, carbon footprint, impurity distribution, and economic performance must be verified through pilot-scale studies using domestic raw materials.

7. Limitations

This review has several limitations that should be considered when interpreting its conclusions. First, although the literature search was conducted using several major scientific databases and clearly defined thematic keywords, the study was designed as a structured narrative review rather than a systematic review or meta-analysis. Consequently, some relevant publications may not have been identified because of differences in database coverage, indexing, terminology, language, or accessibility.

Second, direct quantitative comparison of the reviewed technologies is limited by the substantial heterogeneity of the available studies. The ores investigated in these studies differ considerably in manganese and iron contents, Mn/Fe ratios, silica and aluminum concentrations, mineralogical associations, particle-size distributions, and sample-preparation procedures. Experimental conditions also vary in terms of temperature, residence time, reducing-agent dosage, atmosphere, furnace or reactor configuration, magnetic-field strength, and the methods used to calculate recovery and product yield. Therefore, the reported metallurgical indicators cannot be compared as if they were obtained under identical conditions.

Third, most published studies emphasize manganese content, Mn/Fe upgrading, phase transformations, and metal recovery, while providing limited information on specific electricity consumption, reducing-agent and flux requirements, gaseous and dust emissions,

refractory wear, water consumption, product-quality stability, and capital and operating costs. Industrial-scale evidence is particularly limited for hydrogen-based reduction, which has primarily been investigated under laboratory or early pilot-scale conditions. These gaps prevent a definitive economic and environmental ranking of the three processing routes.

Fourth, the amount of peer-reviewed experimental evidence specifically addressing Kazakhstan's iron manganese ores remains limited. Some deposit-specific information is derived from geological reports, dissertations, and regional scientific publications because detailed mineralogical and technological data for the West Karazhal, Ushkatyn, Big Ktai, Tur, and other deposits are not consistently available in international journals. In addition, the wide compositional variability within individual deposits means that conclusions obtained for one ore sample cannot necessarily be extended to the entire deposit.

Finally, this review does not present new experimental smelting, roasting, or hydrogen-reduction results. The proposed application of reduction smelting and other processing routes to Kazakhstan's ores is therefore based on a critical synthesis of published evidence, ore-composition data, technological maturity, and compatibility with the existing metallurgical infrastructure. The conclusions should consequently be regarded as a basis for selecting future research priorities rather than as a substitute for deposit-specific laboratory, pilot-scale, techno-economic, and environmental validation.

8. Conclusions

The comparative assessment shows that the selection of a processing technology for Kazakhstan's iron manganese ores should be based on deposit-specific mineralogical and chemical characteristics rather than on a single universal flowsheet. In particular, the Mn/Fe ratio, iron and silica contents, distribution of manganese among oxide and silicate minerals, particle-size characteristics, and softening and melting behavior should be determined before selecting the processing route.

For the iron manganese ores of Ushkatyn-I, Big Ktai, Tur, Ushkatyn-III reduction smelting should be prioritized for pilot-scale evaluation. West Karazhal ore may also be considered for this route, although its relatively high silica content requires careful control of slag basicity, viscosity, melting temperature, flux consumption, and manganese distribution between the metal and slag phases. Carbothermic reduction roasting followed by magnetic separation may remain appropriate for selected intermediate-grade ores where sufficient liberation of iron- and manganese-containing phases can be achieved. High-grade oxidized ores should first be evaluated for direct use, conventional beneficiation, or blending to avoid unnecessary thermal treatment.

The next stage of research should move beyond laboratory recovery indicators and establish complete process data for representative Kazakhstan ores. Pilot-scale investigations should determine specific electricity and reductant consumption, manganese and iron mass balances, slag and metal yields, refractory wear, dust formation, direct and indirect greenhouse-gas emissions, and the stability of product quality under variable feed compositions. Particular attention should be paid to feed preparation, including crushing, screening, sintering, pelletization, or briquetting, because agglomerate strength, reducibility, and softening behavior may significantly affect furnace performance.

The marketability of both products must also be demonstrated. The composition of the cast-iron phase should be evaluated against the requirements of iron and steel production, while the rich manganese slag should be tested as a feedstock for ferromanganese and silicomanganese smelting. Such testing should include the effects of residual iron, silica, alumina, phosphorus, slag basicity, and manganese oxidation state on downstream ferroalloy production. Economic assessment should therefore consider the value of both products rather than evaluating manganese recovery alone.

A staged implementation strategy is recommended. The first stage should include mineralogical classification and bench-scale smelting of representative ores from the principal deposits. The second stage should involve pilot-scale trials with complete material, energy, environmental, and economic balances. The third stage should assess integration with existing ferroalloy furnaces and supporting infrastructure in Kazakhstan. Hybrid flowsheets, including preliminary beneficiation or selective reduction followed by smelting, should also be investigated where they can reduce furnace load, carbon consumption, or slag volume.

Hydrogen-based reduction should be regarded as a longer-term option for low-carbon manganese metallurgy. Its future application will depend on the availability and cost of hydrogen, efficient gas recycling, reactor scale-up, and successful separation of the resulting metallic and oxide phases. In the near term, hydrogen may be more realistically evaluated as a partial pre-reduction stage integrated with smelting rather than as a complete replacement for established pyrometallurgical processes.

Accordingly, reduction smelting represents the most practical starting point for the industrial development of Kazakhstan's iron manganese resources, but its adoption should remain conditional on deposit-specific pilot testing, verification of energy and environmental performance, and confirmation that both the metallic product and rich manganese slag satisfy downstream industrial requirements.

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