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Value Addition Options for Sri Lankan Low-Grade Iron Ores: The Critical Role of Goethite-to-Magnetite Conversion

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Abstract
Sri Lanka possesses approximately 2.2 million tonnes of iron ore deposits, predominantly as hydrated iron oxides in regions like Dela and Pelpitigoda. This study investigates value addition pathways for these low-grade ores through strategic beneficiation. Four iron ore samples were characterized using XRD and ICP-MS, revealing goethite as the dominant phase in hydrated deposits with iron contents of 58.52% (Dela) and 31.23% (Pelpitigoda). Roasting of goethite samples at 450°C for 4 hours successfully transformed them into magnetite with 85-90% and 70-75% phase conversion efficiency, respectively. The converted magnetite showed iron enrichment to 64.83% (Dela) and 31.76% (Pelpitigoda) through structural water removal and exhibited strong ferromagnetic properties essential for downstream processing. As iron ore deposits in the country aren't utilized in the steel industry due to low grades or low resource content, the converted magnetite enables multiple value-added opportunities, including ferrosilicon production for import substitution, iron oxide pigment synthesis, cement manufacturing applications, ceramic tile production, and emerging nanotechnology applications. This pre-processing step transforms underutilized hydrated iron ores into versatile industrial feedstock. The study demonstrates that goethite-to-magnetite conversion is essential for unlocking the economic potential of Sri Lanka's low-grade iron ore resources, supporting sustainable industrial development.

Keywords: Beneficiation, Ferrosilicon, Hydrated iron ore, Iron oxide pigments, Thermal treatment, X-ray diffraction

1 Introduction

Iron constitutes the fourth most abundant element in Earth's crust, averaging 2-3% in sedimentary rocks and up to 8.5% in igneous rocks [1]. Despite possessing over 2.2 million tonnes of iron ore deposits, Sri Lanka's resources remain largely unexploited [2]. The country's iron ore deposits are categorized into three types: primary magnetite deposits (Buttala, Panirendawa), copper-magnetite deposits (Seruwila), and secondary hydrated iron oxide deposits predominantly in southwestern regions [3].

The hydrated iron oxide deposits, consisting primarily of goethite ($FeO(OH)$), present unique challenges due to their lower iron content (62.85% theoretical) compared to magnetite (72.4% theoretical) and the presence of structural water [4]. Direct utilization of goethite in high-temperature metallurgical processes is inefficient due to energy penalties from dehydration and poor magnetic properties that prevent beneficiation. Global trends emphasize value addition and beneficiation of low-grade resources rather than raw material export [5]. However, the hydrated nature of goethite necessitates pre-processing before most industrial applications become viable.

This study investigates value addition options for Sri Lankan low-grade iron ores, demonstrating that goethite-to-magnetite conversion is the critical enabling technology for resource utilization.

2 Materials and Methods

2.1 Iron Ore Deposits in Sri Lanka

Sri Lanka possesses several iron ore deposits with varying characteristics and economic potential. Table 1 summarizes the major deposits, providing context for sample selection in this study, and Figure 1 demarcates the respective locations.

Table 1 - Summary of major iron ore deposits in Sri Lanka

Deposit	Location	Main Characteristics	Ore Reserve	Mining Conditions	Reference
Seruwila	Trincomalee District, Eastern Province	Discovered in 1971. Copper-magnetite ore with chalcopyrite, pyrrhotite, and pyrite. Occurs at 100 m depth.	4 million tonnes (1-2% Cu, 40% Fe)	Open-cast limited; underground suggested	[6]
Panirendawa	Chilaw, Puttalam District, North Western Province	Discovered in 1962. Magnetite deposit 30-120 m below ground. Four isolated deposits.	5.6 million tonnes	Uneconomical due to small tonnage, depth, and discontinuous nature	[7]
Buttala	Monaragala District, Uva Province	Discovered in 2001. Primary magnetite with serpentinite, gold, and corundum. Exposed as a 1 km² mountain dyke.	78.84 wt% Fe_2O_3 (55.14 wt% Fe)	High-grade deposit with economic extraction potential	[8]
Dela	Ratnapura District, Sabaragamuwa Province	Hydrated iron ore (goethite). Associated with quartz, feldspar, and sillimanite. Phanerozoic ironstone.	88 wt% Fe_2O_3 (61.5 wt% Fe)	High-grade ore: economic potential not evaluated	[9]
Panvila	Central Province, Highland Group	High crystalline magnetite bands parallel to the Knuckles Massif.	1 million tonnes (93-98% magnetite, 1.3-3.4% TiO_2)	Economic potential not evaluated	[10]
Wilagedara	Kurunegala District, North Western Province	First bedded magnetite deposit in Sri Lanka. Associated with baryte.	Not reported	Uneconomical due to small size	[11]
Pelpitigoda	Kalutara District, Western Province	Newly identified. Primarily goethite with magnetite and hematite. Lateritic formations.	38.47% Fe	Economic potential not evaluated	[12]

Figure 1 – Major iron ore deposits in Sri Lanka

2.2 Sample Collection and Characterization

Four iron ore samples were collected from major Sri Lankan deposits:

- Dela and Pelpitigoda: Hydrated iron oxide (goethite) deposits
- Buttala and Panirendawa: Primary magnetite deposits (for comparison)

Samples were crushed to <5 mm using a jaw crusher and ground to 75-150 μm using a disk mill. Phase identification was performed using X-ray diffraction (XRD) with Cu Kα radiation (λ=1.5406 Å) on a 2θ range of 5-80° with a step size of 0.01°. Chemical composition was determined using inductively coupled plasma mass spectrometry (ICP-MS) after aqua regia digestion (0.5 g sample with 3 mL HCl, 1 mL H_2O_2, and 2 mL HNO_3 at 120°C for 3 hours).

2.3 Goethite-to-Magnetite Conversion

Based on characterization results, goethite-rich samples (Dela and Pelpitigoda) underwent thermal conversion following these steps:

1. Ground samples were mixed with graphite as a reducing agent at a ratio of 100:5 (goethite: graphite) by weight.
2. Pelletization with 5% Chemifix bonding agent produced spherical pellets with diameters ranging from 8-20 mm.
3. Pellets were air-dried for 24 hours at ambient temperature to remove excess moisture.
4. Thermal treatment at 450°C for 4 hours in a laboratory-scale muffle furnace [13].
5. Magnetic separation of converted products using a strong neodymium magnet (>1.2 Tesla).

The mixing ratios were calculated according to the stoichiometry of the conversion equation. The conversion follows:

$$6FeO(OH) + C \rightarrow 2Fe_3O_4 + 3H_2O + CO \quad (1)$$

3 Results

3.1 Characterization of Raw Samples

XRD analysis of the four iron ore samples revealed distinct mineralogical compositions. Dela and Pelpitigoda samples showed characteristic goethite peaks at 2θ = 21.22°, 33.24°, 36.65°, and 53.23°, confirming α-FeO(OH) as the dominant phase, with additional peaks indicating quartz and clay minerals. Buttala exhibited well-crystallized magnetite peaks at 2θ = 35.64°, 43.25°, 57.40°, and 62.76°, typical of primary deposits. The Panirendawa sample showed magnetite as the primary phase with significant quartz gangue (Figures 2 to 5). Table 2 summarizes the characteristics of raw materials.

Table 2 - Mineralogical composition and iron content of raw samples

Sample	Primary Mineral	Secondary Phases	Fe (%)
DL-1	Goethite	Quartz, clay minerals	58.52
PPG-1	Goethite	Quartz, kaolinite	31.23
BT-1	Magnetite	Hematite	40.32
PD-1	Magnetite	Quartz	51.83

ICP-MS analysis confirmed iron contents consistent with the mineralogical composition. The lower Fe content in hydrated samples reflected the presence of structural water (approximately 10% by weight in goethite) and gangue minerals.

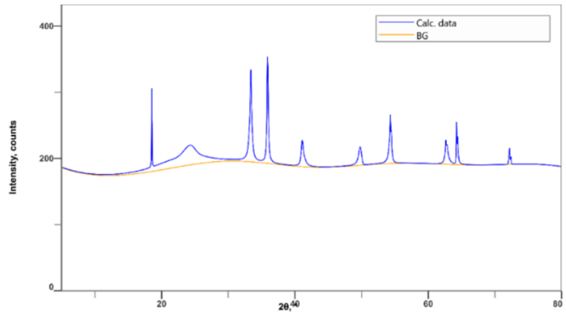

Figure 2 - DL-1 (Dela Sample)

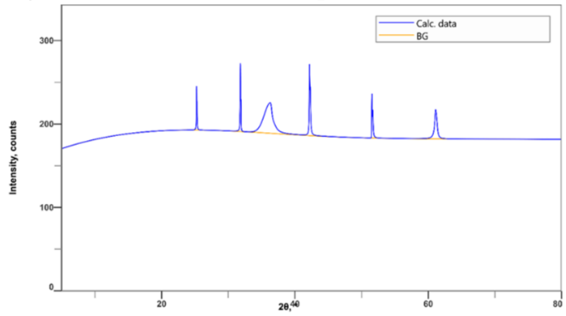

Figure 3 - PPG-1 (Pelpitigoda Sample)

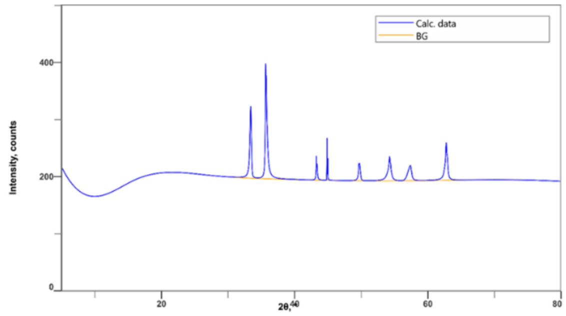

Figure 4 - BT-1 (Buttala Sample)

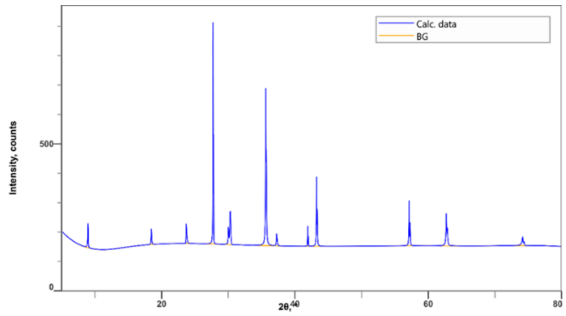

Figure 5 - PD-1 (Pandirendawa Sample)

3.2 Conversion Results

Post-roasting XRD patterns of Dela and Pelpitigoda samples demonstrated successful phase transformation. New peaks emerged at 2θ = 30.1° (220), 35.6° (311), 43.2° (400), 57.2° (511), and 62.8° (440), corresponding to magnetite (Fe_3O_4) crystal structure. Goethite peaks were significantly diminished or absent, indicating effective conversion (Figure 6 and Figure 7).

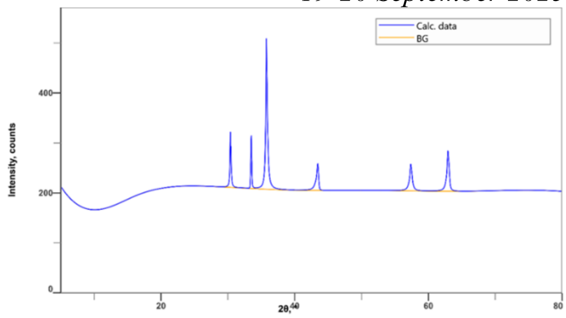

Figure 6 - XRD patterns comparing roasted samples (DL-M)

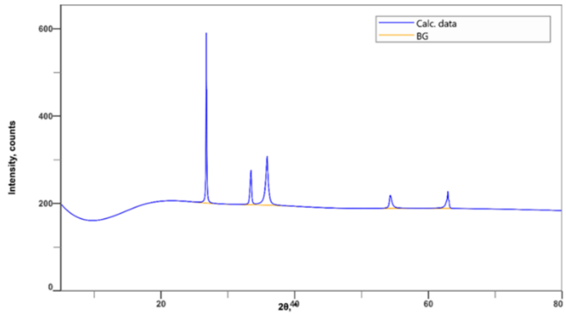

Figure 7 - XRD patterns comparing roasted samples (PPG-M)

Chemical analysis revealed iron content enhancement from 58.52% to 64.83% for Dela samples, representing a 10.8% relative increase. This enrichment results from the removal of structural water during goethite dehydration. Pelpitigoda samples showed minimal change (31.23% to 31.76%) due to high gangue mineral content that diluted the enrichment effect (Table 3 and Table 4).

Figure 8 - Roasted Samples (Pelpitigoda - Left, Dela - Right)

The converted samples exhibited strong ferromagnetic behavior, readily separating with the hand magnet, contrasting with the weakly magnetic or paramagnetic behavior of the original goethite samples. This magnetic enhancement is crucial for downstream beneficiation processes.

Table 3 - Comparison of properties before and after conversion (Dela sample)

Property	DL-1 (Before)	DL-M (After)
Dominant Phase	Goethite	Magnetite
Fe Content (%)	58.52	64.83
Magnetic Susceptibility	Weakly magnetic	Strongly magnetic
Conversion Efficiency (%)	-	85-90

Table 4 - Comparison of properties before and after conversion (Pelpitigoda sample)

Property	PPG-1 (Before)	PPG-M (After)
Dominant Phase	Goethite	Magnetite
Fe Content (%)	31.23	31.76
Magnetic Susceptibility	Weakly magnetic	Strongly magnetic
Conversion Efficiency (%)	-	70-75

4 Discussion

4.1 Significance of Conversion

The successful goethite-to-magnetite conversion addresses fundamental limitations of hydrated iron ores:

1. Enhanced iron content: Removal of structural water concentrates iron, particularly evident in relatively pure ores like Dela.
2. Improved magnetic properties: Transformation from paramagnetic goethite to ferromagnetic magnetite enables magnetic separation.
3. Thermal stability: Magnetite provides stability for high-temperature processing without dehydration penalties.
4. Reduced energy consumption: Pre-conversion eliminates in-situ dehydration energy requirements in downstream processes.

The conversion efficiencies of the two samples were calculated based on XRD peak intensity ratios and found to be 85-90% for Dela and 70-75% for Pelpitigoda samples. The differential Fe content results (ICPMS) between Dela (10.8% Fe increase) and Pelpitigoda (1.7% Fe increase) highlight the importance of gangue content in determining beneficiation effectiveness.

4.2 Value-Addition Pathways

4.2.1 Ferrosilicon Production

Sri Lanka imported 382,700 kg of ferrosilicon valued at $953,280 in 2021 [14]. Local production using converted magnetite combined with abundant quartz waste can substitute these imports. Ferrosilicon production requires:

- Iron source: Magnetite with >60% Fe (Dela converted material meets this specification)
- Silica source: >95% SiO_2 (available from gem mining waste)
- Carbon reductant at 1600-1700°C [15]

The converted magnetite offers advantages over direct goethite use:

- Elimination of 10% weight loss from dehydration
- Improved furnace charge stability
- Higher silicon recovery rates
- Reduced energy consumption

4.2.2 Iron Oxide Pigments

The global iron oxide pigment market offers significant opportunities [16]. Production routes from magnetite include:

- Red oxide (α-Fe_2O_3): Thermal oxidation at 600-900°C
- Black oxide (Fe_3O_4): Direct utilization after grinding to <1 μm
- Yellow oxide (α-FeO(OH)): Controlled precipitation from ferrous sulfate

Recent studies demonstrate successful pigment synthesis, achieving color specifications for architectural and industrial applications [17].

4.2.3 Cement Applications

Iron oxide serves as an essential component (2-5%) in Portland cement production [18]. Magnetite additions provide:

- Reduction in clinkering temperature by 50-100°C
- Improved raw meal burnability
- Enhanced early strength development
- Substitution for imported iron correctives

Sri Lanka's cement industry, producing over 6 million tonnes annually, represents a substantial domestic market (Table 5).

4.2.4 Ceramic Tile Manufacturing

Iron ore can comprise up to 40 wt% of ceramic tile formulations [19]. Applications include:

- Dark-colored architectural tiles
- Wear-resistant industrial flooring
- Electromagnetic shielding tiles

Studies show successful incorporation, achieving water absorption <0.1% and flexural strength >60 MPa.

4.2.5 Emerging Applications

Recent research demonstrates potential for:

- Nanoparticle synthesis: Hematite nanoparticles for gas sensors, photocatalysts, and biomedical applications [20]
- Environmental remediation: Heavy metal adsorbents and water treatment materials
- Energy storage: Battery materials and supercapacitors

Table 5 - Summary of value addition pathways and market potential

Application	Product	Market Size (LKR/yr)	Import Substitution Potential
Ferrosilicon	FeSi75	300-400 million	High
Pigments	Fe_2O_3, Fe_3O_4	150-200 million	Medium
Cement	Iron corrective	100-150 million	High
Ceramics	Black tiles	50-100 million	Medium
Nanotechnology	Various	Emerging	Currently Low

4.3 Economic and Environmental Implications

The conversion process enables the utilization of resources previously considered waste, including low-grade lateritic ores containing 30-40% Fe, iron-stained quartz rejects from gem mining operations, and weathered surface deposits that are typically discarded.

Local processing offers significant environmental and economic benefits by reducing transportation emissions from imports, decreasing foreign exchange expenditure, and minimizing mining waste accumulation at extraction sites.

Most of the value addition processes favor small-scale operations due to the relatively low conversion temperature (450°C compared to >1500°C for steel production) and availability of local reductants, making it accessible to local entrepreneurs and small mining operations.

5 Conclusion

This study demonstrates that goethite to magnetite conversion is essential for value addition of Sri Lanka's low-grade iron ore resources. Thermal treatment at 450°C for 4 hours successfully transformed goethite to magnetite with phase conversion efficiencies of 85-90% (Dela) and 70-75% (Pelpitigoda). The conversion enhanced iron content from 58.52% to 64.83% for Dela samples through structural water removal, while Pelpitigoda samples showed minimal change due to high gangue content. Both converted materials exhibited strong ferromagnetic behaviour crucial for downstream processing.

The converted magnetite enables multiple value addition pathways, with ferrosilicon production offering immediate import substitution potential worth $953,280 annually. Iron oxide pigments, cement applications, and ceramic manufacturing provide established markets, while emerging applications in nanotechnology represent future opportunities.

Implementation of goethite-to-magnetite conversion technology can transform Sri Lanka's underutilized iron ore resources into valuable industrial feedstock, supporting sustainable economic development. Future work should focus on pilot-scale demonstrations, optimization of conversion parameters for different ore types, and techno-economic assessments for integrated processing facilities.

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