International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2025: 7.089

Geochemical, Mineralogical and Thermal Characterization of Paleoproterozoic Phosphorites from the Hirapur-Mardeora Belt, Central India: Implications for Agronomic Safety and Utilization

Rahul Kumar Jain[1], Sukhchand Adey[2], Shailendra Rajpoot[3], Dr. Diwa Mishra[4]

[1]Department of Chemistry, Govt. Geetanjali Girls P.G. College, Barkatullah University, Bhopal, Madhya Pradesh, India
Email: *rahul003.jain[at]yahoo.in*

[2, 3, 4]Department of Chemistry, Govt. Geetanjali Girls P.G. College, Barkatullah University, Bhopal, Madhya Pradesh, India

Abstract: ***Phosphate rock is a vital raw material for the manufacture of fertilizers, agrochemicals, animal feed supplements, water purification agents, and various chemical industries. In the present study, the thermal and geochemical characteristics of Hirapur phosphate rock samples were systematically investigated to evaluate their mineralogical composition and resource potential. Powder X-ray diffraction (XRD) analysis confirmed apatite as the principal ore mineral, predominantly in the form of fluorapatite. Fourier transform infrared (FTIR) spectroscopy further substantiated the presence of characteristic functional groups associated with hydroxyapatite. Thermogravimetric analysis (TGA) demonstrated favorable thermal stability and provided insights into the geological origin of the deposit. Chemical composition and elemental concentrations were determined using X-ray fluorescence (XRF), enabling precise quantification of both ore and associated gangue minerals. The P_2O_5 content was found to be 21.70%, indicating moderate-grade phosphate. Quartz constitutes approximately 30.7% of the sample, while hematite content (0.861 wt.%) remains within acceptable limits for fertilizer-grade phosphate. Although silica and iron contents are relatively higher, these characteristics may contribute to gradual phosphorus release under suitable soil conditions, supporting sustained nutrient availability for crops.***

Keywords: Geochemistry, Phosphate rock; fluorapatite; XRD; FTIR; XRF; TGA; beneficiation; P_2O_5; hematite; quartz.

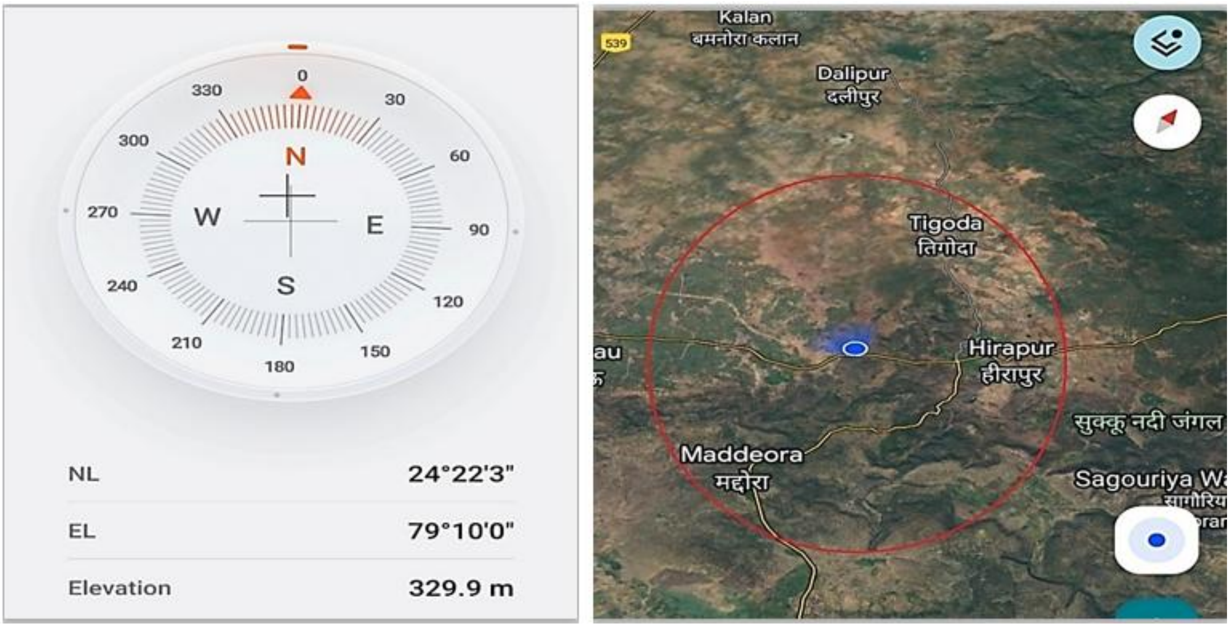
1. Introduction

Sedimentary phosphorites constitute the principal global source of phosphorus fertilizers and have formed episodically throughout Earth's history under specific oceanographic, geochemical, and biological conditions (Cook, 1984; Lucas & Prevot, 1980; Pufahl & Groat, 2017). India hosts several Precambrian phosphorite provinces, among which the Bijawar Group of central India is recognized as a major Paleoproterozoic phosphogenic system (Banerjee et al., 1982; Choudhuri, 1990; Sahu & Jain, 2021).

Phosphorus is a critical nutrient for plant growth, playing a fundamental role in various essential biochemical processes within plants, including photosynthesis, energy transfer, and nucleic acid synthesis (Holford, 1997). However, the limited solubility of phosphorus in soil often restricts its availability to plants, leading to reduced crop yields and the need for external supplementation (Tisdale et al., 1985). To address this limitation, synthetic phosphate fertilizers have been widely employed in agriculture, providing an accessible source of phosphorus for plants (Smit et al., 2019). Nevertheless, the excessive and indiscriminate use of these fertilizers has raised environmental concerns, including water pollution and resource depletion (Cordell et al., 2009). In response to these challenges, there has been growing interest in exploring alternative sources of phosphorus that are more sustainable and environmentally friendly. Phosphate rocks, which naturally contain high levels of phosphorus, have emerged as a promising alternative to synthetic fertilizers (Frossard et al., 2000). Most phosphate deposits are of sedimentary origin, typically consisting of an apatite matrix that contains considerable amounts of impurities such as carbonates and silicates (Abouzeid, 2008). Consequently, the growing demand for high-grade material has intensified the need for beneficiation techniques to address the inherent complexity of sedimentary ores (Cordell et al., 2009). These deposits generally exhibit low to medium concentrations of P_2O_5. Phosphate rocks are essential components in agriculture due to their phosphorus content, a vital nutrient for plant growth. Traditionally, the focus has primarily been on the phosphorus content of these rocks. Agronomic implications of phosphate rocks of the Hirapur Area in District Sagar, Madhya Pradesh, are of paramount importance. Given the likelihood of mineralogical heterogeneity within these rocks, understanding their specific mineral composition becomes imperative. Without such knowledge, it would be challenging to design effective and sustainable fertilizer application strategies for local agricultural practices. In this context, the present study aims to comprehensively evaluate the geochemical composition, mineralogical constitution, spectroscopic features, and thermal behavior of Paleoproterozoic phosphorites from the Hirapur–Mardeora Belt using a multi-analytical approach involving WD-XRF, XRD, FTIR spectroscopy, and thermogravimetric analysis (TGA). By integrating these datasets, the study seeks to provide a scientifically robust basis for assessing phosphate mineral quality, physicochemical stability, trace-element safety, and the sustainable agronomic utilization potential of these indigenous phosphorites.

2. Geology of Hirapur Phosphorite

The Proterozoic phosphorite deposits of the Hirapur–Mardeora area, located within the Sagar and Chhatarpur districts of



NL	24°22'3"
EL	79°10'0"
Elevation	329.9 m

Figure 1 & 2: Location and Satellite map of sampling area.

Madhya Pradesh (latitude 24°19′–24°23′ N and longitude 79°09′–79°14′ E), are associated with the Gangau ferruginous and phosphatic formations of the Bijawar Group (Mathur and Mani, 1978; Banerjee et al., 1982). The Bijawar Basin has sustained geological interest since the nineteenth century due to its stratigraphy and economic significance. Medlicott (1859) originally introduced the term *Bijawar Series* to describe the sedimentary succession resting unconformably on the Bundelkhand Granite Complex and underlying the Lower Vindhyan Supergroup. The Bijawar Group comprises Gangau iron formations deposited over the Archean Bundelkhand granitic basement. lithological units: shale-phosphorite, secondary phosphorite, ironstone-phosphorite, and quartz-breccia phosphorite. Subsequent advancements in the geological understanding of the basin were achieved through systematic mapping and investigation by Wilson (1877), Kedar Narain (1954), Mathur (1960), Mani (1970), Halder and Ghosh (1978), and Binod Kumar et al. (1985). During uranium exploration in 1976, the Atomic Minerals Division first reported the occurrence of phosphorite in the Hirapur area. A preliminary evaluation of the deposit was conducted in 1977 by N. Subramaniam of the Geological Survey of India. Further detailed exploration carried out between 1978 and 1984 by A. Sonakia and Binod Kumar led to the estimation of in situ reserves of approximately 18.66 million tonnes with an average grade of about 23% P_2O_5, along with an additional inferred reserve of nearly 22 million tonnes grading 7–10% P_2O_5 in and around the Hirapur–Mardeora sector (Binod Kumar, 1984).

Figure 2: Stratigraphic succession of the Hirapur- Maedeora Area, Sagar and Chhatarpur, Central India.

3. Sampling and Material Methods

3.1. Sample Collection and preparation

For the present study, samples were systematically collected from various locations of Mardeora-Tigoda, Hirapur. Sampling was carried out from pits, trenches, and stream sediments to ensure comprehensive coverage of the study area. Representative specimens of all encountered lithologies were obtained, including samples from contact zones between contrasting rock types. Approximately 500 gm to 1 kg samples were collected and stored in polythene bags and properly labeled for subsequent analysis.

The particle sieve size analysis done by HAVER EML digital plus made in Germany, all samples were subjected to Grinding, crushing and sieving, with the fine fraction separated using a <180-micron sieve size to obtain material suitable for detailed study.

3.2 X-ray diffraction

The X-ray diffraction of phosphate powders was obtained with a Bruker D8 advance, with CuKα radiation (λ = 1.5406 Å), a Bragg-Brentano setup and a graphite back monochromator. It is operated at a voltage of 40 kV, and the intensity of 50 mA. The scan range was from 5◦ to 90◦ of 2θ. The identification of the phases was carried out using the standard database ICDD-PDF2004, (Khan et.al.2018).

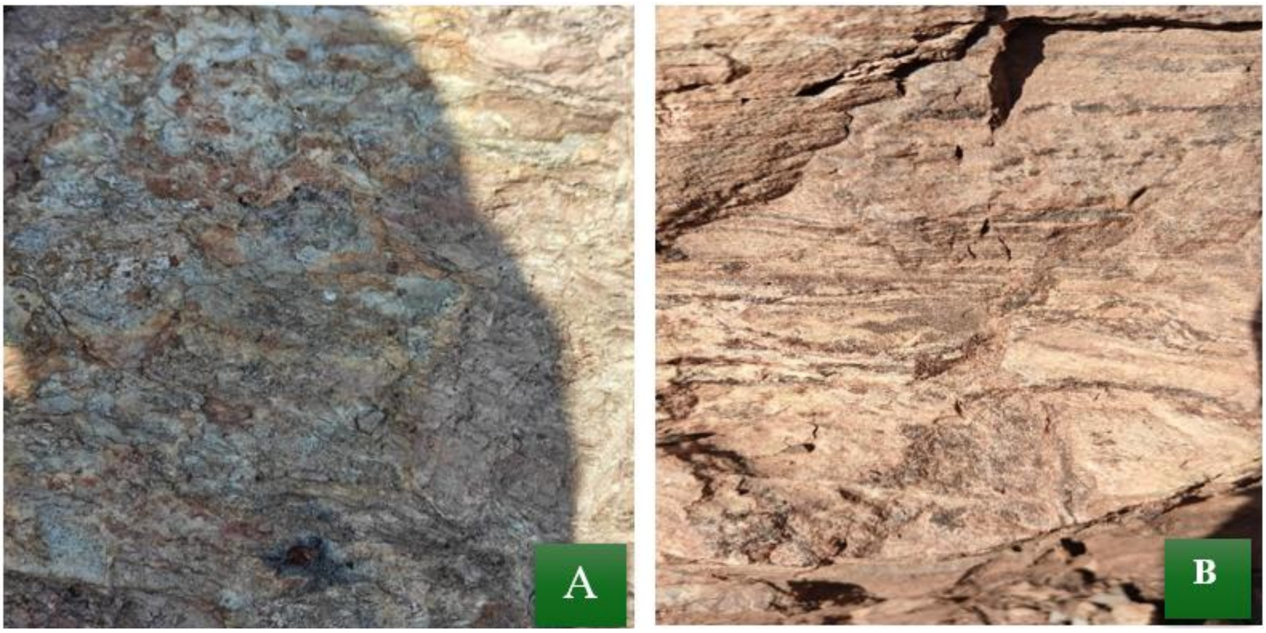


Figure 3: (A&B): - Brownish, reddish, rock of phosphate is showing massive & fragmental Structure, having the different mineralogy such as hematite and chert with content P2O5 in major of Bijawar Group Phosphorite Beds (Hirapur–Mardeora).

3.3 Fourier Transform Infrared Spectroscopy (FTIR)

The ATR-FTIR (Attenuated Total Reflection – Fourier Transformation Infrared Analyzes) were performed on a Perkin Elmer Spectrum Two Spectrometer. The finely ground powders were deposited directly on the diamond objective of the apparatus. The powder deposited on the crystal is then subjected to a uniform and small pressure, allowing it to be maintained in the form of a pellet. The IR data were collected by scanning in the range of 400–4000 cm^{-1} with a resolution of 2 cm^{-1} and a number of 64 steps. (Khan et.al.2018).

3.4 Thermogravimetric analysis (TGA)

Thermal Stability and Proximate analysis of rock phosphate was carried out using a LECO TGA-701 system. Approximately 0.5–1.0 g of sample was analyzed under an inert nitrogen (N_2) atmosphere using controlled heating programs to determine inherent moisture, volatile components primarily released as carbon dioxide and other thermally labile constituents and ash content, (Bachouâ et al.2014).

3.5 X-Ray Fluorescence (XRF)

Elemental composition of the phosphate samples was determined using a Rigaku ZSX Primus IV X-ray fluorescence (XRF) spectrometer. X-ray fluorescence is generated when a material is excited by bombardment with high-energy X-rays or gamma rays, causing the emission of characteristic secondary (fluorescent) X-rays specific to the elements present. This analytical technique is widely employed for qualitative and quantitative elemental analysis and chemical characterization, particularly in studies of metals, glass, ceramics, and building materials, as well as in geochemical, forensic, and archaeological investigations. In the present study, XRF analysis was applied to evaluate the major and trace elemental composition of the phosphate samples **(Hassan et. al.2013)**

4. Results

4.1 Field Sampling and Sample Representativeness.

Phosphorite samples investigated in the present study were collected from a single, well-defined stratigraphic horizon within the Hirapur–Mardeora Belt of the Bijawar Group, Central India. Focusing on one representative location minimized lithological and geochemical variability, ensuring that the analytical results reflect intrinsic mineralogical and geochemical characteristics of the deposit rather than spatial heterogeneity. The selected sample (MRD) is massive to nodular in texture, compact, and moderately ferruginous, consistent with earlier petrographic and geological descriptions of Bijawar phosphorites (Banerjee et al., 1982; Khan et al., 2012; Sahu & Jain, 2021). This targeted sampling strategy enhances the agronomic relevance of the study by representing a realistic, utilization-ready ore material, rather than an averaged regional composite.

4.2 Fourier transform infrared Spectroscopy (FTIR)

Fourier Transform Infrared (FTIR) spectroscopy was employed to characterize the mineralogical composition of rock phosphate samples collected from the Hirapur–Mardeora area. FTIR spectra of minerals exhibit distinctive absorption features that are qualitatively related to variations in their constituent mineral phases. These absorption bands arise from vibrational modes, including lattice vibrations and molecular group vibrations. Owing to the presence of characteristic absorption bands in the mid-infrared region (4000–400 cm^{-1}). FTIR spectroscopy enables effective qualitative identification of mineral phases present in the rock phosphate samples. Moreover, quantitative assessment is possible, as in simple two-component systems the intensity of absorption features is proportional to the concentration of individual components, in accordance with Beer's law (Griffiths, 1986; Smith, 1995). The bands observed in spectrogram are shown in table No.1.

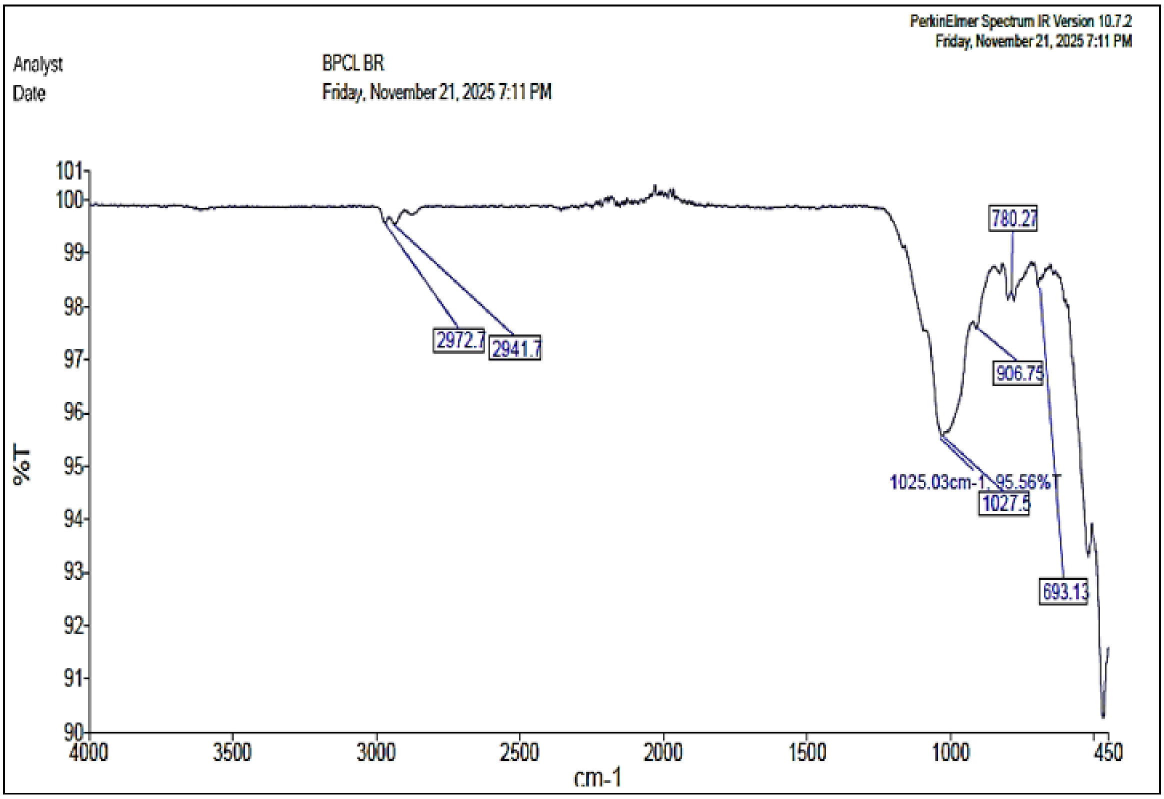


Figure 4: FTIR analysis of phosphorite rock of Maddeora, Hirapur Phosphorites deposits.

Table 1: FTIR Absorption Bands and Vibrational Assignments for MRD Phosphorite Sample

Observed Band (cm^{-1})	Vibrational Mode	Assigned Group / Phase	Interpretation
2972, 2941	ν(C–H) stretching	Aliphatic C–H	Trace organic matter in sedimentary phosphorite
~1025–1027	ν_3 asymmetric stretching	PO_4^{3-} (apatite)	Dominant phosphate framework
~906	ν_1 symmetric stretching	PO_4^{3-}	Confirms crystalline apatite
~780	Lattice / bending mode	PO_4^{3-} / minor silicates	Phosphate bending, accessory phases
~693	ν_4 bending	PO_4^{3-}	Characteristic apatite vibration
600–450	ν_2, ν_4 bending / lattice modes	PO_4^{3-}	Well-developed apatite lattice
Absence at 3570–3400	—	OH^-	Indicates Absence of Water Molecule
Overlapping carbonate features	ν_2, ν_3 CO_3^{2-}	Carbonate-substituted apatite	Enhanced agronomic reactivity

Accordingly, FTIR analysis was carried out in the present investigation to identify specific functional groups and to evaluate the degree of mineralogical alteration of the Hirapur–Mardeora rock phosphate. Fourier transform infrared (FTIR) analysis reveals that hydroxyapatite is characterized by the presence of several functional groups, primarily phosphate (PO_4^{3-}), carbonate (CO_3^{2-}), hydroxyl (OH^-), and hydrogen phosphate (HPO_4^{2-}), as reported by Eisa et al. (2015). The absorbance spectrum is typically recorded within the mid-infrared region, ranging from 400 to 4000 cm^{-1}. In this range, the bands observed at 2971 and 2941.3 cm^{-1} correspond to the stretching vibrations of hydroxyl groups, while the band at 780.27 cm^{-1} is attributed to their vibrational modes. The most intense absorption bands, appearing at 906.75, 1025.03, and 1027.5 cm^{-1}, are associated with the vibrational modes of phosphate (PO_4^{3-}) ions. Due to the stoichiometric composition of hydroxyapatite, the O–H stretching vibrations exhibit lower intensity compared to the strong P–O stretching vibrations, a behavior consistently observed in both synthetic and natural hydroxyapatite

(Marković et al., 2004, Eisa Y. Mohammed et al., 2015 and Bachouâ et al., 2014).

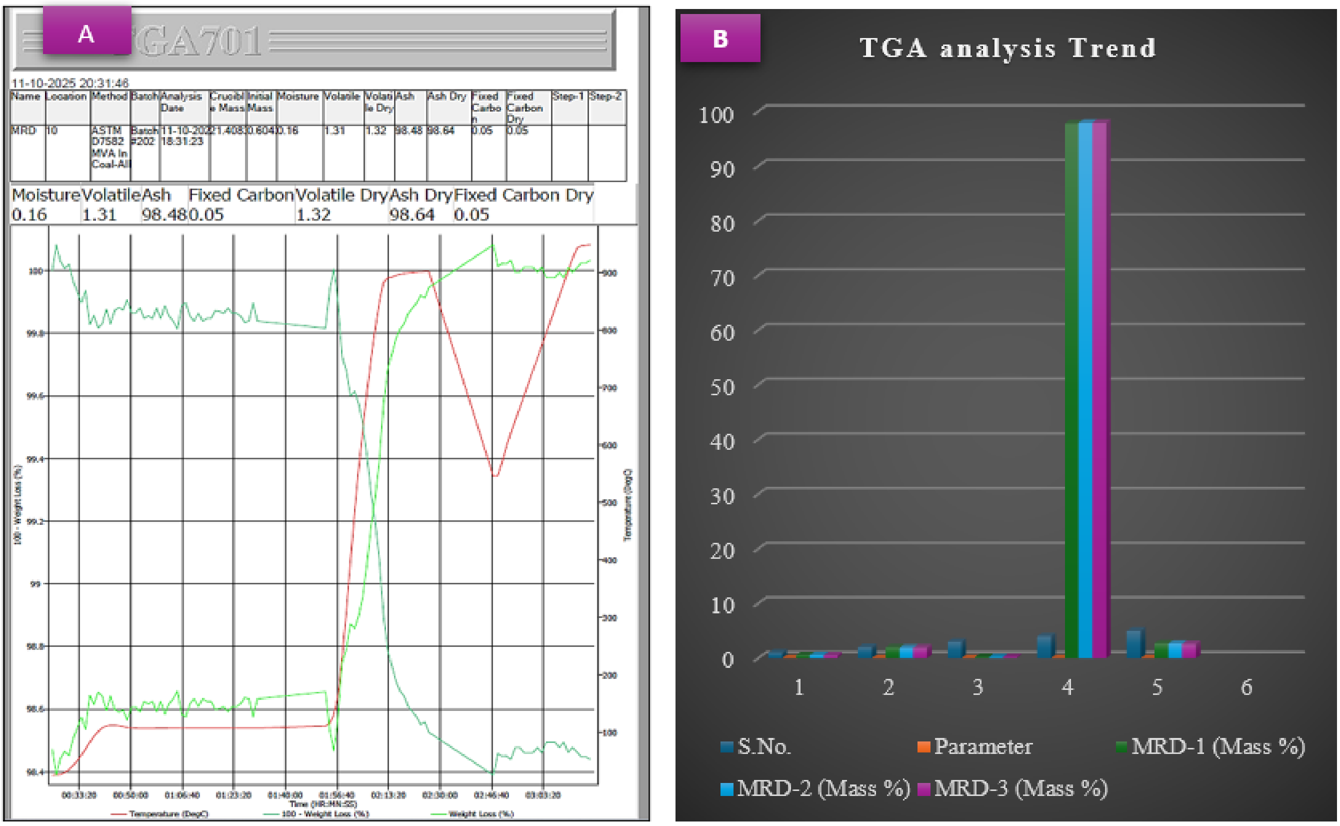
4.3 Thermal Behavior and Carbonate Stability

Rock phosphate (RP) is a naturally occurring mineral resource composed predominantly of apatite [$Ca_5(PO_4)_3$ (F, Cl, OH)], accompanied by minor amounts of gangue minerals such as silicates, carbonates, and oxides. It serves as the primary raw material for the production of phosphoric acid and phosphate fertilizers. Comprehensive characterization of RP is essential to evaluate its chemical composition, thermal behavior, and overall suitability for agricultural and industrial applications.

Thermal analysis, particularly thermogravimetric analysis (TGA), is extensively used to assess parameters such as moisture content, volatile matter, and residual inorganic fraction (ash). Although proximate analysis using TGA was initially developed for fuels and carbonaceous materials, it has increasingly been applied to mineral characterization. This technique provides valuable information on water content, decomposition behavior, and inorganic purity, which directly influence downstream processes including acidulation, calcination, and beneficiation. In the present study, The Hirapur–Mardeora rock phosphate exhibits very low volatile matter content (approximately 2.0%), indicating a predominantly inorganic origin and suggesting that biological processes played a minimal role in its formation. The Hirapur–Mardeora phosphate rock samples show LOI values of 1.53–2.56%, markedly lower than the typical range for sedimentary phosphorites (5–15%) (McClellan & Gremillion, 1980). Such low values reflect minimal volatile matter and indicate high mineralogical purity, with limited carbonate, organic, or clay content. This agrees with studies on Indian Proterozoic phosphorites that highlight their suitability for fertilizer production (Banerjee & Majumder, 1999 & Singh & Choudhary, 2000). Reduced volatile fractions enhance acidulation efficiency and support direct agronomic use, particularly in wheat cultivation. Geologically, the low LOI suggests restricted organic input and limited carbonate replacement, consistent with global models of Proterozoic phosphorite genesis (Altschuler, 1980). Overall, the Hirapur–Mardeora deposit represents a high-quality resource with strategic importance for sustainable fertilizer and energy security in India. The TGA gives idea about the major losses of rocks in higher temperature, but the Hirapur Mardeora.

Table 2: TGA Results of phosphorite rock of Maddeora, Hirapur Phosphorites deposits.

S. No.	Parameter	Mass %		
-	-	MRD-1	MRD-2	MRD-3
1	Moisture @ 105°C	0.16	0.13	0.26
2	Volatile Matter @ 900 °C	1.32	1.92	2.42
3	Fixed Carbon (loss Based)	0.05	0.14	0.18
4	Ash >950 °C	98.48	97.81	97.93
5	LOI @ 950°C	1.53	2.19	2.56
6	pH	6.6	6.7	6.6



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Name	Location	Method	Batch	Analysis Date	Crucible Mass	Initial Mass	Moisture	Volatile	Volatile Dry	Ash	Ash Dry	Fixed Carbon	Fixed Carbon Dry	Step-1	Step-2
MRD	10	ASTM D7582 MVA In Coal-All	Batch #202	11-10-202 18:31:23	21.4083	0.6040	0.16	1.31	1.32	98.48	98.64	0.05	0.05		

Moisture	Volatile	Ash	Fixed Carbon	Volatile Dry	Ash Dry	Fixed Carbon Dry
0.16	1.31	98.48	0.05	1.32	98.64	0.05

Figure 4: TGA Results of phosphorite rock of Maddeora, Hirapur Phosphorites deposits

The TGA curve of the phosphate rocks analysis indicates first weight loss of 0.56% between 25°C and 105°C corresponding to the desorption of water. A second mass loss of 1.95% occur between 900°C which corresponds to the elimination of organic matter (Bachouâ et al., 2014), The weight loss of 0.22 % at 900°C is attributed to the decomposition of mineral carbon or carbonate species and also some time is dolomitic nature of rocks the Hirapur Mardeora RP generally not support the dolomitic nature, it is related to apatite nature (Eisa et al., 2015) associated with hard rocks present in the phosphate as indicated by FTIR and XRD.

The loss of 0.56% at 105°C, indicated the RP sample contains very low physically adsorbed water, Low moisture minimizes handling issues, microbial growth, and moisture-induced variability in chemical analysis. Dried RP improves reproducibility in acidulation and other chemical processes. In second step the loss weight at the temperature between 900°C is due to the low value of 1.95% volatile fraction represents minor decomposition of hydrous minerals and residual organics, Sedimentary RP may contain organics, clays, or carbonates; the low value here indicates either an igneous or beneficiated sedimentary ore, Low volatiles ensure thermal stability during calcination or acid treatment, (Bachouâ et al., 2014). Thermal analysis suggests that the Bijawar Group was formed during the Paleoproterozoic and consists of volcano-sedimentary successions of both clastic and chemogenic origin, deposited under marine conditions. The lithological assemblage includes conglomerates, basaltic intrusions, carbonates, sandstones, shales, phosphorites, and ferruginous sandstones (Rajiv et al., 2022).

4.4. Major Oxides and Geochemistry of phosphorite rock

Major oxide composition of the representative phosphorite sample (MRD) from the Hirapur–Mardeora Belt was determined using WD-XRF to evaluate phosphate grade, gangue mineral association, and suitability for agronomic utilization. The oxide data (Table 3) show that MRD is characterized by moderate P_2O_5 content (21.70 wt.%) and substantial CaO (31.6 wt.%), confirming the dominance of calcium phosphate minerals. The calculated CaO/P_2O_5 ratio of 1.456 is indicative of carbonate–fluorapatite (francolite) with relatively low carbonate dilution, a mineralogical attribute associated with enhanced phosphate reactivity and agronomic effectiveness (Altschuler et al., 1956; McClellan & Lehr, 1969; Syers et al., 1986).

Table 3: Major Oxides of phosphorite rock of Maddeora, Hirapur Phosphorites deposits.

S. No	Component	Result (Mass%)	El. Line	Intensity	w/o normal
1	**SiO_2**	30.700	Si-KA	152.0537	9.7743
2	**CaO**	31.600	Ca-KA	154.1588	9.9756
3	**P_2O_5**	21.700	P2-KA	111.0409	6.8632
4	**Al_2O_3**	8.240	AL-KA	40.6347	2.6015
5	**K_2O**	5.520	K2-KA	36.488	1.7433
6	**Fe_2O_3**	0.861	Fe-KA	11.5004	0.2718
7	**TiO_2**	0.682	Ti-KA	0.9188	0.2155
8	**MgO**	0.493	Mg-KA	0.8124	0.1558
9	**SO_3^-**	0.116	SO-KA	0.7035	0.0367
10	**$Cr_2O_3^-$**	0.053	Cr-KA	0.2538	0.0168
11	**Na_2O**	0.047	Na-KA	0.0355	0.0148
12	**ZrO_2**	0.023	Zr-KA	5.9924	0.0071
13	**RbO_2**	0.017	Rb-KA	3.7642	0.0055
14	**ZnO**	0.012	Zn-KA	0.7085	0.0038
15	**CuO**	0.010	Cu-KA	0.0588	0.0038
16	**Cl^-**	0.012	Cl-KA	0.4375	0.0033

Silica (SiO_2) constitutes 30.70 wt.%, reflecting quartz-rich gangue material derived from siliciclastic input during phosphorite deposition, a characteristic feature of Precambrian sedimentary phosphorites of the Bijawar Group (Banerjee et al., 1982; Ghosh et al., 2024). Moderate concentrations of Al_2O_3 (8.240 wt.%) and K_2O (5.520 wt.%) suggest minor aluminosilicate contributions, likely from illite or mica phases, while MgO (0.493 wt.%) points to limited dolomitic association within the host carbonate strata. The presence of Fe_2O_3 (0.861 wt.%) indicates Minor ferruginous coatings and Fe-oxyhydroxide phases formed under fluctuating redox conditions, consistent with shallow-marine phosphogenic environments (Dar et al., 2025).

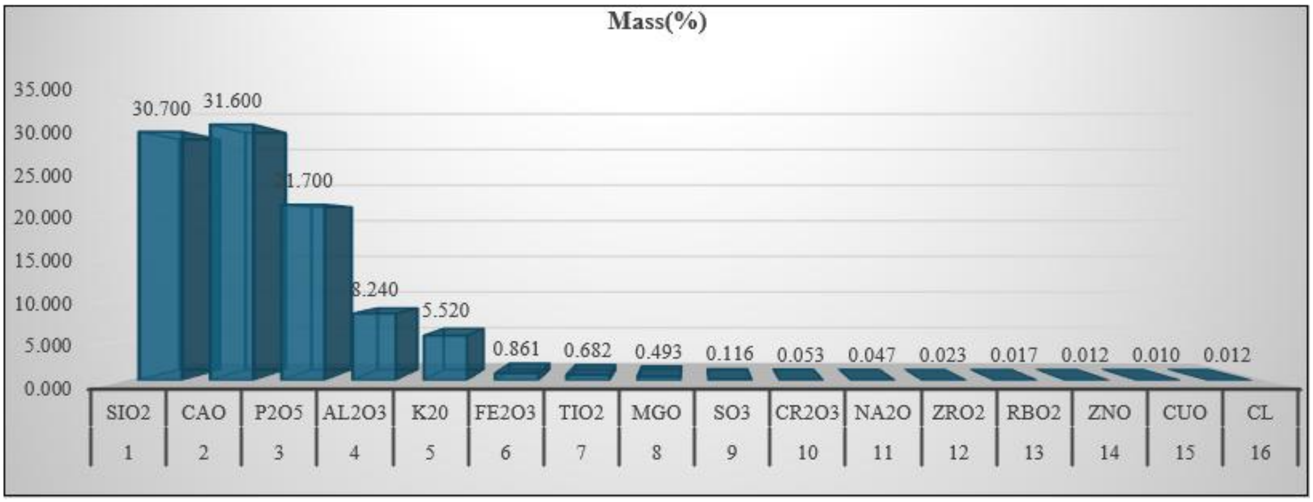

Figure 6: Major oxides of phosphorite rock of Maddeora, Hirapur.

Importantly, the major oxide profile lacks any environmentally deleterious oxide enrichment, and the high P_2O_5 coupled with a favorable CaO/P_2O_5 ratio places MRD within the category of agronomically valuable medium-grade phosphorite, well suited for direct soil application, phosphate rock–enriched compost, and sustainable phosphorus-release strategies (Bolan et al., 1990; Safi et al., 2006).

4.1. Mineralogical Composition

Table 4: Major Mineral Phases in MRD Phosphorite by XRD Analysis

2θ Peak (°)	Identified Mineral Phase	Probable Chemical Formula	Interpretation
26.1–26.3	Quartz	SiO_2	Siliceous detrital gangue
31.7–33.2	Carbonate–fluorapatite (Francolite)	Ca5(PO4)2.5(CO3)0.5F	Major P-bearing mineral
34.0–34.2	Apatite (secondary)	$Ca_5(PO_4)_3(F/OH)$	Confirms apatite dominance
39.5–40.0	Calcite/Dolomite	$CaCO_3$ / $CaMg(CO_3)_2$	Carbonate matrix
49.3–49.7	Francolite/Apatite	—	Strong secondary reflection
62.0–62.3	Goethite/Hematite	$FeO(OH)$ / Fe_2O_3	Minor iron oxides

X-ray diffraction (XRD) analysis of the representative phosphorite sample MRD from the Hirapur–Mardeora Belt was carried out to determine its crystalline mineral assemblage and validate bulk geochemical observations. The corresponding XRD diffractogram is presented in Figure 2, illustrating the dominant and accessory mineral phases identified in the sample. The XRD pattern is dominated by intense reflections at 2θ ≈ 31.7–33.2°, 34.0°, 39.5°, 46.9°, 49.5°, and 53.1°, which correspond closely to carbonate–fluorapatite (francolite). This confirms francolite as the principal phosphorus-bearing mineral phase. Francolite, a carbonate-substituted apatite, is characteristic of marine sedimentary phosphorites and is consistent with the elevated CaO and P_2O_5 contents obtained from WD-XRF analysis. Its presence implies moderate reactivity and favorable phosphorus release behavior under acidic soil conditions.

Subordinate peaks at 2θ ≈ 26.2° indicate quartz (SiO_2), reflecting siliceous detrital input during deposition. Weak reflections between 2θ ≈ 28–30° and 39–40° are attributable to calcite and dolomite, representing carbonate gangue minerals. Minor peaks near 2θ ≈ 35° and **62°** suggest trace iron oxide phases (goethite/hematite), consistent with moderate Fe enrichment. The principal mineral phases identified in MRD phosphorite sample, along with their characteristic 2θ peak positions and mineralogical assignments, are summarized in Table 3. Overall, the mineralogical simplicity and dominance of carbonate–fluorapatite highlight the agronomic suitability and mineralogical uniformity of the MRD phosphorite, supporting its potential for direct application and compost-based phosphorus enrichment

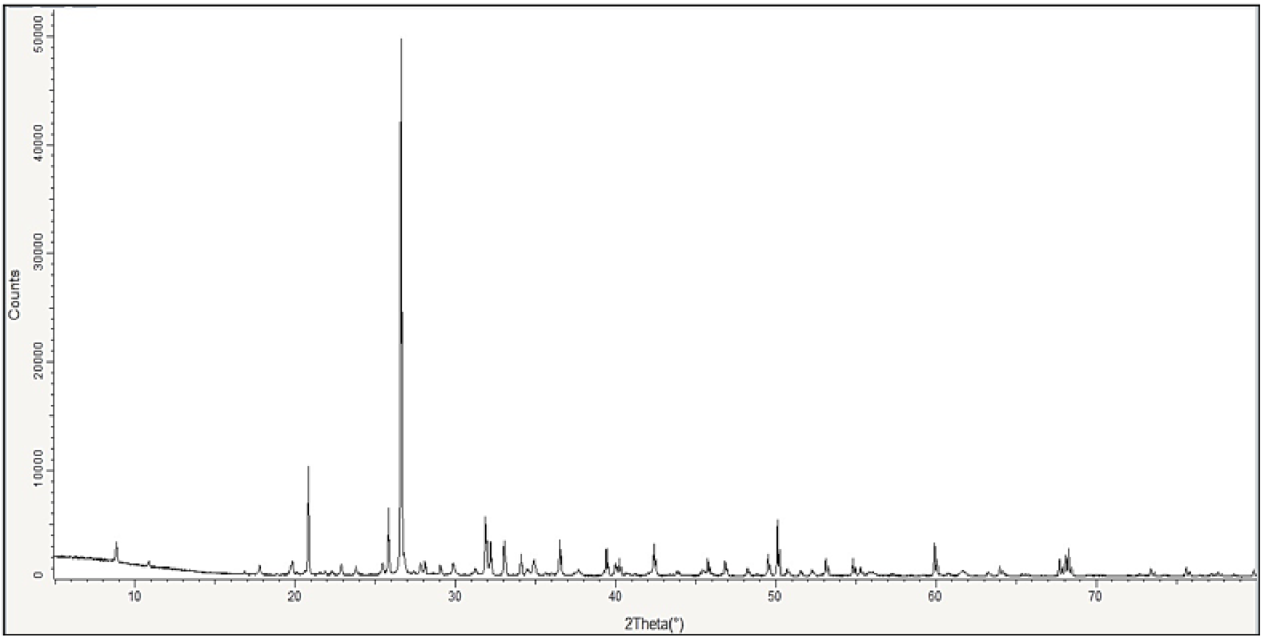

Figure 7: XRD Diffractogram of Representative Phosphate Rock Sample MRD (Hirapur– Maddeora Region)

5. Discussion

The combined geochemical, mineralogical, spectroscopic, and thermal datasets collectively indicate that the MRD phosphorite from the Hirapur– *Maddeora* Belt represents an agronomically viable and environmentally safe indigenous phosphorus resource. The relatively medium P_2O_5 content (21.70 wt.%) together with a low CaO/P_2O_5 ratio (1.456) reflects a carbonate–fluorapatite–dominated mineralogy with limited gangue dilution, a compositional feature widely associated with improved phosphate reactivity and gradual phosphorus release under soil conditions (Syers et al., 1986; Hammond et al., 1986; Bolan et al., 1990). Mineralogical confirmation of francolite through XRD and FTIR, along with evidence of carbonate substitution within the apatite lattice, further supports enhanced solubility in acidic soils and under biologically mediated processes such as composting and microbial solubilization (Chien et al., 2011; Eisa et al., 2015; Ptáček, 2016. The high thermal stability, low volatile content, and minimal loss-on-ignition values demonstrated by TGA confirm a chemogenic origin and structural robustness of the phosphate mineral phase, attributes favorable for processing, storage, and formulation into phosphate rock–enriched composts and controlled-release fertilizers (Mostert, 2019; Notholt, 1980). Collectively, these characteristics position the MRD phosphorite as a sustainable alternative to imported phosphate fertilizers, supporting region-specific phosphorus management and long-term soil fertility enhancement.

6. Conclusion

The present study provides an integrated geochemical, mineralogical, spectroscopic, and thermal evaluation of Paleoproterozoic phosphorite from the Hirapur–Mardeora Belt of the Bijawar Group, central India. The deposit is characterized by moderate P_2O_5 content and a favorable CaO/P_2O_5 ratio, making it suitable for the production of single superphosphate (SSP) and triple superphosphate (TSP) fertilizers. The predominance of carbonate–fluorapatite confirms its classification as a medium-grade phosphate rock with significant agronomic potential. Confirmation of carbonate substitution within the apatite lattice, coupled with high crystallinity, suggests favorable phosphorus release behavior under acidic soil conditions and biologically mediated processes such as composting. The absence of hazardous elements ensures compliance with agronomic and environmental safety standards. Furthermore, high thermal stability and low volatile content indicate robust mineral structure suitable for handling, processing, and fertilizer formulation. Overall, the Hirapur–Mardeora phosphorite represents a safe, sustainable, and underutilized indigenous phosphorus resource with strong potential to reduce dependence on imported fertilizers and support long-term soil fertility management in Indian agroecosystems.

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