








Acid Leaching-Based Production of Triple Superphosphate (TSP) Fertilizer from Burenkhaan Phosphorite, Khuvsgul, Mongolia

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Abstract. Mongolia possesses over 3.6 billion metric tons of phosphate resources, predominantly located in Khuvsgul and Zavkhan Provinces. Despite this abundance, the country lacks industrial-scale phosphate beneficiation and fertilizer production, resulting in over 90% import dependency. Current national fertilizer consumption is estimated at 60,000–70,000 metric tons annually, whereas agronomic assessments indicate a requirement of 250,000–300,000 tons annually to meet domestic food production targets.

This research examined the composition and processing potential of phosphate concentrate obtained by flotation from the Burenkhaan phosphorite deposit. The concentrate contained 35.91% P₂O₅, 50.53% CaO, and 78.47% BPL, primarily composed of fluorapatite (77.1%). Acid leaching with 40–60% phosphoric acid (H₃PO₄) at 80–100°C for 5–20 minutes produced high-quality triple superphosphate (TSP) fertilizer, containing 42.85–55.28% total P₂O₅, with 100% plant-available phosphate and up to 100% water solubility. The chemical composition and physicochemical properties of the produced TSP fertilizer and phosphate concentrate were analyzed using XRD, XRF, ICP-OES, TGA/DTG, and FTIR spectroscopic techniques.

The results confirm the technical and economic feasibility of processing Burenkhaan phosphate to produce high-quality fertilizers, providing a pathway for import substitution and sustainable agricultural development while supporting Mongolia's strategic goal of fertilizer self-sufficiency.

Keywords: Phosphorite, Phosphate concentrate, Triple superphosphate (TSP), Acid leaching, Phosphorus fertilizer.

1 Introduction

Phosphorus scarcity represents one of the most critical constraints in global food security, with agricultural systems fundamentally dependent on phosphorus-based fertilizers to maintain crop yields and feed an expanding global population^{1,2}. Among phosphorus fertilizers, triple superphosphate (TSP) serves as the most concentrated and bioavailable form, containing 46–55% P_2O_5 and exhibiting superior water solubility characteristics that enable rapid nutrient uptake by plants^{3,4}. The strategic importance of TSP has intensified as global phosphate rock reserves face depletion pressures, with current extraction rates suggesting potential exhaustion of high-grade deposits within 50–100 years^{5,6}. This finite resource constraint, combined with the uneven geographical distribution of phosphate reserves, has created significant geopolitical vulnerabilities in fertilizer supply chains and prompted renewed interest in developing domestic processing capabilities⁷.

Mongolia presents a compelling case study in resource-utilization paradox, possessing an estimated 3.6 billion metric tons of phosphate resources concentrated primarily in the Khuvsgul and Zavkhan geological provinces, yet maintaining virtually no industrial-scale fertilizer production infrastructure^{8,9}. The Khuvsgul phosphorite basin alone encompasses approximately 30 deposits and occurrences, representing one of the world's largest untapped phosphate resources^{10,11}. This situation is particularly acute given Mongolia's current fertilizer consumption patterns, where annual usage of 60,000–70,000 metric tons represent less than 25% of the estimated agronomic requirement of 250,000–300,000 metric tons needed to achieve optimal agricultural productivity¹². Consequently, Mongolia maintains over 90% import dependency for fertilizers, creating substantial economic vulnerabilities related to price volatility, supply chain disruptions, and foreign exchange expenditures.

Previous research efforts on Mongolian phosphate utilization have primarily focused on mechanical activation¹³ and direct application of phosphate rock powder, with limited investigation of chemical processing routes for value-added fertilizer production. While mechanochemical activation can enhance phosphorus availability to some extent, the resulting products typically exhibit inferior solubility and bioavailability characteristics compared to chemically processed fertilizers¹⁴. Recent technological advances in TSP production from fluorapatite-rich feedstocks have demonstrated that optimized acid leaching processes can achieve superior product quality metrics, including enhanced P_2O_5 content, improved water solubility, and reduced impurity levels compared to conventional processing methods^{15,16}.

The technical feasibility of developing domestic TSP production in Mongolia is supported by favorable geological and mineralogical characteristics of local phosphate deposits. The Burenkhaan phosphorite deposit exhibits particularly promising attributes, with fluorapatite comprising the dominant phosphate phase (>75%) and relatively low concentrations of deleterious impurities such as heavy metals and radioactive elements¹⁷. Contemporary soil fertility assessments across Mongolia's agricultural regions have revealed widespread phosphorus deficiencies that significantly constrain crop productivity, with soil available phosphorus levels frequently below critical thresholds for optimal plant growth¹⁸. Field experiments in degraded agricultural lands have demonstrated dramatic responses to phosphorus

fertilization, with vegetation cover increases of 200–300% following phosphorus application, indicating that phosphorus availability represents a primary limiting factor in both crop production and ecosystem restoration efforts.

The specific objectives of this investigation encompass four interconnected research domains: (i) systematic optimization of acid leaching parameters for TSP production from Burenkhaan phosphate concentrate, with emphasis on maximizing P_2O_5 content and water solubility while minimizing processing costs, (ii) comprehensive physicochemical characterization of the produced TSP using multiple analytical techniques to elucidate structural transformations, phase compositions, and quality attributes, (iii) rigorous evaluation of product quality against internationally recognized fertilizer standards to establish commercial viability and regulatory compliance, and (iv) assessment of industrial-scale implementation potential, including economic feasibility analysis and strategic implications for Mongolia's fertilizer self-sufficiency objectives.

The findings of this research contribute to the broader scientific understanding of phosphate processing while addressing practical challenges related to resource utilization, agricultural sustainability, and economic development in resource-rich developing countries. The implications extend beyond Mongolia's specific context, providing valuable insights for similar geological settings and economic circumstances worldwide, particularly for countries seeking to develop domestic fertilizer industries from indigenous phosphate resources.

2 Materials and Methods

2.1 Materials

Mongolia is endowed with significant sedimentary marine phosphate resources, with over 60 deposits and occurrences identified to date. Geological exploration and prospecting have been conducted for approximately 50 deposits within two major phosphate basins—Khuvsgul and Zavkhan—which together contain an estimated 3.6 billion tons of natural phosphate reserves, including 2.4 billion tons in Khuvsgul Province and 1.2 billion tons in Zavkhan Province. In this study, phosphate concentrate (BPC) obtained by flotation from the Burenkhaan phosphorite (BP) deposit in Khuvsgul Province was used as the raw material (Table 1). Phosphoric acid (CAS No. 7664-38-2, H_3PO_4 , 85%, GOST 6552-80, analytical grade, Sigma Tek LLC, Russia) was used as the reagent for acid leaching. The decomposition of the phosphate concentrate by phosphoric acid proceeds as a heterogeneous reaction, as shown below (1):

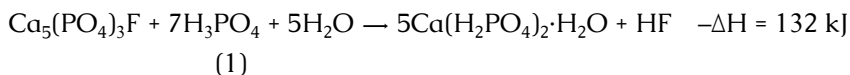


Table 1. Chemical composition of Burenkhaan Phosphorite (BP) and Phosphate Concentrate (BPC)(XRF,%)

Sample	CaO	P ₂ O ₅	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	Na ₂ O	MgO	LOI*
BP	40.89	29.45	20.68	2.21	1.45	0.37	0.1	0.37	2.24
BPC	50.62	35.91	7.16	0.76	0.64	0.05	0.32	0.19	1.45

Note: LOI* - Loss on Ignition determined at 1000 °C.

The phosphate concentrate primarily consisted of fluorapatite (Ca₅(PO₄)₃F), along with accessory minerals such as quartz, dolomite, albite, and calcite, as confirmed by XRD and XRF analyses.

2.2 Methods

TSP was synthesized via acid leaching using analytical grade phosphoric acid (50% H₃PO₄). Approximately 100 g of dried phosphate concentrate was reacted with phosphoric acid at a solid-to-liquid (S/L) ratio of 1:1.6 (g/mL) under continuous mechanical stirring at 90 °C. The reaction duration was optimized to 12.5 minutes, after which the slurry was cooled and dried at 60 °C to obtain the final product.

The mineral composition of the samples was determined using an X-ray diffractometer (XRD), model TD-3500 (Tongda). The diffraction measurements were employed using K α 1 (Cu) radiation with a wavelength of 1.540598 Å that generated by a copper anode X-ray source. The X-ray diffraction peaks were analyzed using the Rietveld refinement method. The wavelength dispersive X-ray fluorescence spectrometer PANalytical AxiosmAX (PW4400 spectrometer) fitted with a 4.0 KW Rh X-ray tube was applied to determine the samples' chemical composition. Analyses of major elements (SiO₂, Al₂O₃, P₂O₅, Fe₂O₃, MgO, CaO, Na₂O) was performed on fused-disks prepared from 1.2 g of calcined sample powder mixed with lithium-tetraborat. The loss of ignition was determined separately at 1000 °C (2h). The infrared spectra (IR) of the powder samples were obtained by Fourier transform infrared (FTIR) spectrometer ALPHA II (Bruker, Germany) in the middle – IR region with spectral range of 4000 to 400 cm⁻¹ with a resolution of 4 cm⁻¹. The powder sample was placed on the ZnSe crystal and pressed with a micrometer-controlled compression clamp. Elemental analysis of the phosphate samples was performed using an inductively coupled plasma optical emission spectrometer (ICP-OES, iCAP 7200, Thermo Scientific, USA). Thermogravimetric and differential thermogravimetric analyses (TGA/DTG) were conducted using a TG/DTA7300 thermal analyzer (Hitachi High-Tech, Japan). Approximately 10 mg of finely ground and dried phosphate sample was placed in a platinum crucible. The sample was heated continuously from 25 °C to 1000 °C under a nitrogen atmosphere with a flow rate of 100–200 mL/min. The heating rate was selected based on experimental requirements. Mass loss and its derivative (DTG) were recorded as a function of temperature and time. All measurements were digitally logged and analyzed using the instrument's proprietary thermal analysis software. The efficiency of fertilizers is mainly characterized by their solubility in citric acid and ammonium citrate solution¹⁹. The total, citric-soluble, and citric-ammonium-soluble phosphate contents were determined using the photocolometric method²⁰.

2.3 Process Optimization

The acid leaching parameters were systematically optimized using Design Expert software employing a Box-Behnken experimental design. Three key variables were investigated: phosphoric acid concentration (40-60%), reaction temperature (80-100°C), and reaction time (5-20 minutes). A total of 17 experiments were conducted with five center point replications to evaluate experimental error and ensure reproducibility. The optimization criteria focused on maximizing total P_2O_5 content (>50%), water-soluble P_2O_5 (>55%), and citrate-soluble P_2O_5 (>45%). Response surface methodology was employed to develop predictive models and identify optimal conditions. Statistical analysis revealed that the optimal conditions were: 50% H_3PO_4 concentration, 90°C reaction temperature, and 12.5 minutes reaction time, achieving the highest total P_2O_5 content (55.28%) with excellent water solubility (57.81%) and good reproducibility.

3 Results and Discussion

3.1 XRD Analysis

X-ray diffraction (XRD) analysis was performed to investigate the mineralogical composition of the phosphate concentrate and the synthesized triple superphosphate (TSP) product. The diffractograms are presented in Fig.1. The XRD pattern of the phosphate concentrate revealed that fluorapatite ($Ca_{10}(PO_4)_6F_2$) was the dominant crystalline phase, with strong peaks observed at characteristic 2θ positions around 31.8°, 32.2°, and 33.1°, indicating a highly crystalline and well-preserved phosphate matrix, consistent with previous studies on sedimentary phosphate ores. In addition to the major fluorapatite phase, several minor accessory phases were detected, including quartz (SiO_2), albite ($NaAlSi_3O_8$), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and trace amounts of hematite (Fe_2O_3). This mineral assemblage suggests that the ore body is a typical sedimentary phosphorite enriched with accessory silicate and carbonate minerals^{21,22}.

Upon acid leaching with 50% phosphoric acid under optimized conditions (90°C, 12.5 minutes, S/L ratio 1:1.6), the product underwent substantial mineralogical transformation. The XRD pattern of the synthesized TSP clearly showed a complete shift in dominant phases. The major reflections corresponded to monocalcium phosphate monohydrate (MCPM, $Ca(H_2PO_4)_2 \cdot H_2O$) and dicalcium phosphate dihydrate (DCPD, $CaHPO_4 \cdot 2H_2O$), with strong and sharp peaks at approximately 26°, 29°, and 31° 2θ , confirming successful conversion of the apatite structure into water-soluble phosphate compounds^{23,24}.

The complete disappearance of fluorapatite peaks and the emergence of TSP-specific reflections indicate nearly quantitative decomposition of the original phosphate mineral, consistent with previous studies on acid-induced recrystallization during TSP production^{23,25}. The residual presence of minor quartz and hematite phases suggests that these minerals remained inert during acid treatment, persisting through the process as undissolved phases. Such mineralogical transformation pathways during acid leaching are consistent with mechanisms described in earlier studies on phosphate ore processing²⁵. This phase transformation demonstrates the

high efficiency of phosphoric acid leaching for producing TSP fertilizer from indigenous phosphate concentrates, in line with recent findings on crystalline TSP products²⁴.

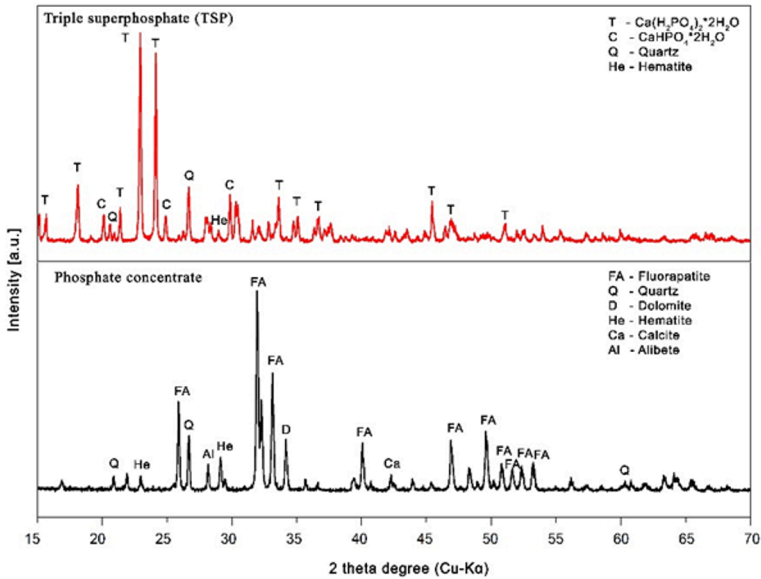


Fig.1. XRD patterns of the phosphate concentrate and the synthesized triple superphosphate (TSP) fertilizer

3.2 FTIR Analysis

Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted on both samples (Fig.2). The FTIR spectrum of the phosphate concentrate exhibited characteristic absorption bands associated with phosphate and carbonate minerals. Prominent bands appeared at 1092.44 cm^{-1} , 1031.57 cm^{-1} , and 963.23 cm^{-1} , corresponding to P–O stretching vibrations of the PO_4^{3-} groups. These bands are typical of fluorapatite-rich phosphate rocks and are consistent with literature values^{26,27}.

After chemical treatment, the FTIR spectrum of the TSP product revealed strong absorption bands at 1156.48 cm^{-1} , 1080.14 cm^{-1} , 955.38 cm^{-1} , and 857.28 cm^{-1} . Sharp bands at 3460.45 cm^{-1} and 1651.89 cm^{-1} indicate the presence of O–H stretching and H–O–H bending, confirming the presence of water of hydration. Peaks at 670.25 cm^{-1} , 568.54 cm^{-1} , and 483.87 cm^{-1} correspond to Ca–O and P–O bonding vibrations, confirming the formation of calcium phosphate hydrate phases, specifically monocalcium and dicalcium phosphate hydrates²⁸.

These spectral characteristics align closely with the XRD results and confirm the successful transformation of a low-solubility phosphate concentrate into a more soluble and hydrated TSP product. The combination of strong phosphate and

water-associated vibrational modes demonstrates the structural and chemical changes induced by acid treatment, which are desirable for enhanced plant nutrient availability

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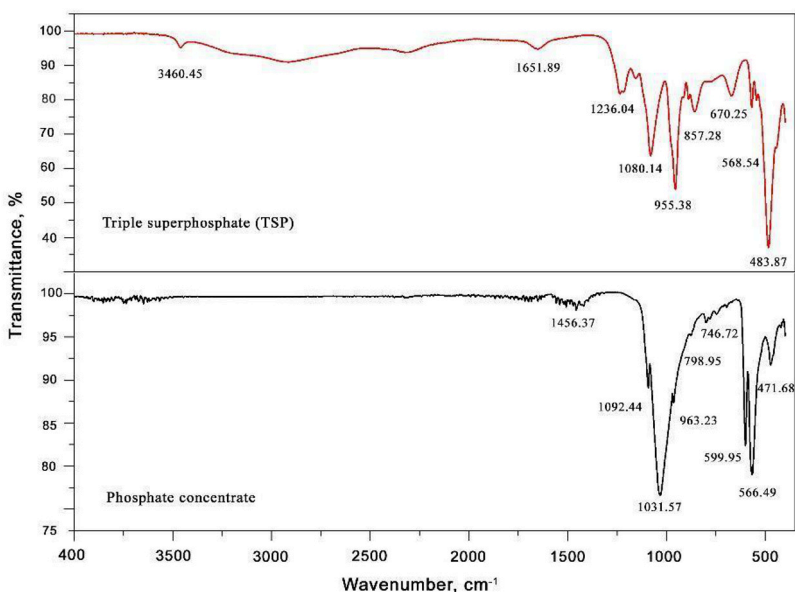


Fig.2. FTIR spectra of the phosphate concentrate and the synthesized TSP fertilizer

3.3 TGA/DTG Analysis

Thermogravimetric analysis (TGA) coupled with derivative thermogravimetry (DTG) was conducted to comprehensively evaluate the thermal stability, decomposition behavior, and structural transformations of both the raw phosphate concentrate and the synthesized triple superphosphate (TSP) fertilizer. The obtained TGA/DTG curves are presented in Fig.3a and Fig.3b, respectively, providing valuable insight into the distinct thermal responses of the mineral-based raw material and the chemically modified fertilizer product.

The phosphate concentrate (Fig.3a) exhibited exceptional thermal stability across the entire temperature range from ambient conditions up to 1100 °C, as evidenced by a minimal overall weight loss of approximately 1.3%. This negligible mass loss indicates the absence of volatile impurities, organic matter, or thermally unstable phases within the concentrate, confirming its high purity and mineralogical robustness. A noticeable DTG peak was observed around 760 °C, which corresponds to the decomposition of carbonate phases inherently present in the phosphate ore, primarily calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$). The decomposition of these minerals leads to the evolution of carbon dioxide (CO_2), a well-documented phenomenon during high-temperature treatment of phosphate rocks. Interestingly, a slight mass gain was detected above 950 °C, which can be attributed to the formation of pyrophosphate phases, particularly calcium pyrophosphate ($\text{Ca}_2\text{P}_2\text{O}_7$). Such high-temperature transformations are characteristic of phosphate-containing materials

and are often associated with structural reorganization and densification processes occurring under elevated thermal conditions³⁰.

In contrast to the phosphate concentrate, the TSP fertilizer (Fig.3b) displayed significant mass loss, amounting to approximately 20.5% over the investigated temperature range. The decomposition profile of TSP occurred in two clearly defined stages, as confirmed by both TGA and DTG data:

- First Stage (150–300 °C): The initial mass loss is primarily associated with the release of physically adsorbed water and crystallization water contained within the TSP matrix. The sharp DTG peak observed at approximately 150 °C supports the occurrence of dehydration processes, which are typical for hydrated phosphate-based fertilizers.
- Second Stage (300–500 °C): The subsequent, more pronounced weight loss corresponds to the thermal decomposition of monocalcium phosphate monohydrate (MCPM, $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$), a major component of TSP. This stage is also associated with the evaporation of residual free phosphoric acid (H_3PO_4) and sulfuric acid (H_2SO_4) that are commonly present in the final product due to incomplete reaction during synthesis. The distinct DTG peak around 250 °C further confirms the decomposition and volatilization processes³¹.

The absence of significant mass changes beyond 500 °C indicates that the remaining material undergoes minimal structural modification at higher temperatures, consistent with the formation of more thermally stable phosphate phases.

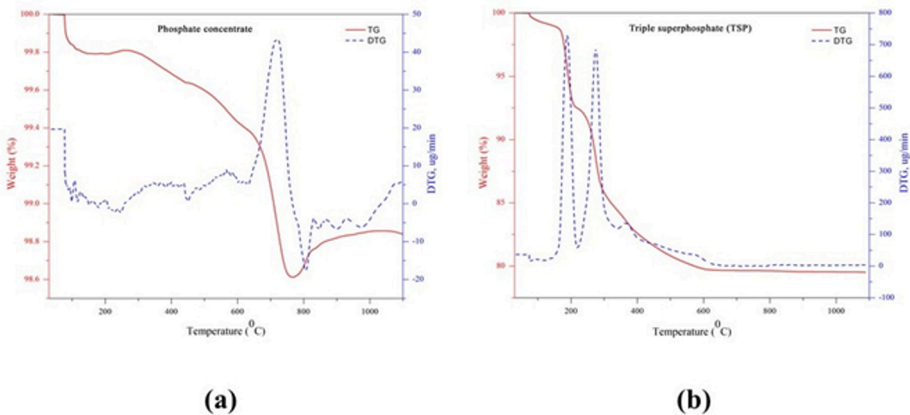


Fig.3. TG (a) and DTG (b) curves of the phosphate concentrate and the synthesized TSP fertilizer.

The marked difference in thermal behavior between the phosphate concentrate and the TSP product highlights the influence of chemical processing on material stability. The phosphate concentrate, composed predominantly of inert mineral phases such as

fluorapatite, demonstrates superior thermal resistance with minimal decomposition. In contrast, the acid-treated TSP exhibits multi-stage degradation, characteristic of hydrated, reactive, and partially amorphous structures introduced during fertilizer production. These findings are consistent with previous studies³⁰ reporting that natural phosphate ores generally exhibit higher thermal stability compared to processed phosphate fertilizers, owing to their crystalline mineral framework and lower content of volatile or labile species³².

Overall, the TGA/DTG results provide critical insight into the compositional and structural evolution of phosphate-based materials under thermal stress, offering valuable information for optimizing production processes, ensuring product quality, and predicting material performance during storage, handling, and application.

3.4 Chemical Analysis

X-ray fluorescence (XRF) analysis determined the elemental oxide composition before and after TSP synthesis (Table 2). In the phosphate concentrate, CaO (50.62%) and P₂O₅ (35.91%) were dominant, consistent with fluorapatite. After acid leaching, P₂O₅ increased to 55.28% in TSP, while CaO reduced to 24.98%, confirming conversion to soluble phosphates. SiO₂, Al₂O₃, and Fe₂O₃ contents decreased, indicating removal of inert gangue materials. Fluorine dropped from 2.91% to <0.05%, significantly improving product safety. The shift in oxide profile supports effective purification and fertilizer-grade enhancement.

Table 2. Chemical composition (major elements) of the Phosphate Concentrate (BPC) and as synthesized TSP fertilizer (XRF,%)

Sample	SiO ₂	Al ₂ O ₃	ΣFe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	P ₂ O ₅	F
BPC	7.16	0.76	0.64	50.62	0.19	0.32	0.09	0.028	35.91	2.91
TSP	3.27	0.35	0.34	24.98	0.06	0.33	0.05	0.022	55.28	<0.05

Table 3 shows the concentrations of selected trace and potentially toxic elements in the phosphate concentrate (BPC) and the synthesized triple superphosphate (TSP) fertilizer, determined by ICP-OES. The results indicate a significant reduction in most trace elements, including Cd, Pb, Cr, Cu, Ni, Sr, V, Zn, As, Mo, and U, during the acid leaching and TSP production process. For instance, cadmium content decreased from 1.36 ppm in the concentrate to 0.83 ppm in the TSP fertilizer, while uranium content reduced from 14.9 ppm to 6.25 ppm. The reduction of these elements demonstrates that the applied processing conditions effectively lower the concentrations of harmful trace elements in the final TSP product, contributing to its environmental safety and suitability for agricultural use.

Table 3. Trace elements composition of the Phosphate Concentrate (BPC) and as synthesized TSP fertilizer (ICP-OES, PPM).

Sample	Cd	Pb	Cr	Cu	Ni	Sr	V	Zn	Co	As	Mo	Th	U
BPC	1.36	4.3	28	64.2	27	1060	98	51	2.3	8	4.58	0.6	14.9
TSP	0.83	1.9	15	16.9	15	601	50	27	1.0	3	2.59	0.7	6.25

3.5 TSP Quality Evaluation

The quality of the synthesized triple superphosphate (TSP) fertilizer was assessed in comparison with standard technical requirements. The results showed that the product meets commercial fertilizer standards, with total P_2O_5 content $\geq 43.0\%$, water-soluble phosphate /WSP/ content $\geq 83.0\%$, plant-available phosphate content (Citric-soluble /CSP/, and citric-ammonium-soluble phosphate /CASP/) $\geq 96.0\%$, and moisture content $\leq 4.0\%$ (Table 4).

Table 4. Quality evaluation of the synthesized TSP fertilizer (ICP-OES, PPM)

№	Parameter	TSP	GB/T 21634-2020 ³³	GOST 16306-80 ³⁴
1	Total P_2O_5 , %	55.3	≥ 46.0	43.0-46.0
2	CSP, %	100.0	≥ 44.0	43.0-46.0
3	CASP, %	100.0	(96.0)	(100.0)
4	WSP, %	100.0	≥ 38.0 (83.0)	-
5	Moisture, %	1.0	≤ 4.0	3.0

4 Conclusion

This study successfully demonstrated the feasibility of producing high-grade triple superphosphate (TSP) fertilizer from Mongolian phosphate concentrate sourced from the Burenkhaan deposit using an acid leaching approach. The optimized process conditions—phosphoric acid concentration of 50%, a solid-to-liquid ratio of 1:1.6, reaction temperature of 90 °C, and a leaching time of 12.5 minutes—enabled efficient conversion of fluorapatite-rich concentrate into a highly soluble TSP product containing 55.28% total P_2O_5 with 100% plant-available phosphorus and complete water solubility.

Comprehensive characterization confirmed the structural transformation of the raw material, evidenced by the disappearance of fluorapatite phases and the formation of water-soluble calcium phosphate compounds (monocalcium phosphate monohydrate and dicalcium phosphate dihydrate). Thermal analysis (TGA/DTG) revealed distinct differences in thermal stability between the raw phosphate concentrate and the synthesized TSP, highlighting the influence of chemical processing on product behavior. The substantial reduction of fluorine (from 2.91% to <0.05%) and hazardous trace elements, such as cadmium and uranium, further demonstrates the effectiveness of the applied process in enhancing product safety and environmental compatibility. The synthesized TSP met and exceeded internationally recognized quality benchmarks, with superior levels of total, water-soluble, and plant-available phosphorus, combined with low moisture content and minimal impurity levels. These attributes confirm the suitability of the produced fertilizer for agronomic use under Mongolian conditions.

Importantly, this work provides a scalable, site-specific pathway for converting Mongolia's abundant but underutilized phosphate resources into value-added fertilizer products. By reducing reliance on imports and advancing domestic fertilizer self-sufficiency, this research aligns with Mongolia's strategic priorities for strengthening national food security, improving soil fertility, and promoting sustainable agricultural development. The findings not only contribute to bridging critical knowledge gaps regarding phosphate processing in Mongolia but also establish a scientific foundation for future industrial-scale production of high-efficiency phosphorus fertilizers from local raw materials.

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