ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№3
2026

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

3 (477)

JUNE – JULY 2026

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2026

The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

EDITOR-IN-CHIEF

ZHURINOV Murat Zhurinovich, Doctor of Chemical Sciences, Professor, Academician of IAAS and NAS RK, General Director of the Research Institute of Petroleum Refining and Petrochemicals (Almaty, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=6602177960; https://www.webofscience.com/wos/author/record/2017489

DEPUTY EDITOR-IN-CHIEF

ABSADYKOV Bakhyt Narikbayevich, Doctor of Technical Sciences, Professor, Academician of NAS RK, Satbayev University (Almaty, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=6504694468; https://www.webofscience.com/wos/author/record/2411827

EDITORIAL BOARD:

ABSAMETOV Malis Kudysovich, Doctor of Geological and Mineralogical Sciences, Professor, Academician of NAS RK, Director of the U.M. Akhmedsafin Institute of Hydrogeology and Geoecology (Almaty, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=56955769200; https://www.webofscience.com/wos/author/record/1937883

ZHOLTAEV Geroy Zholtaevich, Doctor of Geological and Mineralogical Sciences, Professor, Honorary Academician of NAS RK (Almaty, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=57112610200; https://www.webofscience.com/wos/author/record/1939201

SNOW Daniel, PhD, Associate Professor, Director, Aquatic Sciences Laboratory, University of Nebraska (Nebraska, USA), https://www.scopus.com/authid/detail.uri?authorId=7103259215; https://www.webofscience.com/wos/author/record/1429613

SELTMANN Reimar, PhD, Head of Petrology and Mineral Deposits Research in the Earth Sciences Department, Natural History Museum (London, Great Britain), https://www.scopus.com/authid/detail.uri?authorId=55883084800; https://www.webofscience.com/wos/author/record/1048681

PANFILOV Mikhail Borisovich, Doctor of Technical Sciences, Professor at the University of Nancy (Nancy, France), https://www.scopus.com/authid/detail.uri?authorId=7003436752; https://www.webofscience.com/wos/author/record/1230499

SHEN Ping, PhD, Deputy Director of the Mining Geology Committee of the Chinese Geological Society, Member of the American Association of Economic Geologists (Beijing, China), https://www.scopus.com/authid/detail.uri?authorId=57202873965; https://www.webofscience.com/wos/author/record/1753209

FISCHER Axel, PhD, Associate Professor, Technical University of Dresden (Dresden, Germany), https://www.scopus.com/authid/detail.uri?authorId=35738572100; https://www.webofscience.com/wos/author/record/2085986

AGABEKOV Vladimir Enokovich, Doctor of Chemical Sciences, Academician of NAS of Belarus, Honorary Director of the Institute of Chemistry of New Materials (Minsk, Belarus), https://www.scopus.com/authid/detail.uri?authorId=7004624845

CATALIN Stefan, PhD, Associate Professor, Technical University of Dresden (Dresden, Germany), https://www.scopus.com/authid/detail.uri?authorId=35203904500; https://www.webofscience.com/wos/author/record/1309251

JAY Sagin, PhD, Associate Professor, Nazarbayev University (Astana, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=57204467637; https://www.webofscience.com/wos/author/record/907886

FRATTINI Paolo, PhD, Associate Professor, University of Milano - Bicocca (Milan, Italy), https://www.scopus.com/authid/detail.uri?authorId=56538922400

NURPEISOVA Marzhan Baysanovna, Doctor of Technical Sciences, Professor of Satbayev University (Almaty, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=57202218883; https://www.webofscience.com/wos/author/record/AAD-1173-2019

RATOV Boranbay Tovbasarovich, Doctor of Technical Sciences, Professor, Head of the Department of Geophysics and Seismology, Satbayev University (Almaty, Kazakhstan), https://www.scopus.com/authid/detail.uri?authorId=55927684100; https://www.webofscience.com/wos/author/record/1993614

RONNY Berndtsson, Professor, Director of the Centre for Advanced Middle Eastern Studies, Lund University (Lund, Sweden), https://www.scopus.com/authid/detail.uri?authorId=7005388716; https://www.webofscience.com/wos/author/record/1324908

MIRLAS Vladimir, PhD, Professor, Eastern R&D Center, Ariel University (Ariel, Israel), https://www.scopus.com/authid/detail.uri?authorId=8610969300; https://www.webofscience.com/wos/author/record/53680261

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

© «Central Asian Academic Research Center» LLP, 2026.

БАС РЕДАКТОР

ЖҰРЫНОВ Мұрат Жұрынұлы, химия ғылымдарының докторы, профессор, ХҒАҚ және ҚР ҰҒА академигі, Мұнай өңдеу және мұнай-химиясы ғылыми-зерттеу институтының бас директоры (Алматы, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=6602177960; https://www.webofscience.com/wos/author/record/2017489

БАС РЕДАКТОРДЫҢ ОРЫНБАСАРЫ:

АБСАДЫҚОВ Бақыт Нәрікбайұлы, техника ғылымдарының докторы, профессор, ҚР ҰҒА академигі, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті (Алматы, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=6504694468; https://www.webofscience.com/wos/author/record/2411827

РЕДАКЦИЯ АЛҚАСЫ:

ӘБСӘМЕТОВ Мәліс Құдысұлы, геология-минералогия ғылымдарының докторы, профессор, ҚР ҰҒА академигі, У.М. Ахмедсафин атындағы Гидрогеология және геоэкология институтының директоры (Алматы, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=56955769200; https://www.webofscience.com/wos/author/record/1937883

ЖОЛТАЕВ Герой Жолтайұлы, геология-минералогия ғылымдарының докторы, профессор, ҚР ҰҒА құрметті академигі (Алматы, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=57112610200; https://www.webofscience.com/wos/author/record/1939201

СНОУ Дэниел, PhD, қауымдастырылған профессор, Небраска университетінің Су ғылымдары зертханасының директоры (Небраска, АҚШ), https://www.scopus.com/authid/detail.uri?authorId=7103259215; https://www.webofscience.com/wos/author/record/1429613

ЗЕЛЬТМАНН Раймар, PhD, Жер туралы ғылымдар бөлімінің петрология және пайдалы қазбалар кен орындары саласындағы зерттеулерінің жетекшісі, Табиғи тарих мұражайы (Лондон, Ұлыбритания), https://www.scopus.com/authid/detail.uri?authorId=55883084800; https://www.webofscience.com/wos/author/record/ 1048681

ПАНФИЛОВ Михаил Борисович, техника ғылымдарының докторы, Нанси университетінің профессоры (Нанси, Франция), https://www.scopus.com/authid/detail.uri?authorId=7003436752; https://www.webofscience.com/wos/author/record/1230499

ШЕН Пин, PhD, Қытай геологиялық қоғамының Тау-кен геологиясы комитеті директорының орынбасары, Американдық экономикалық геологтар қауымдастығының мүшесі (Бейжің, Қытай), https://www.scopus.com/authid/detail.uri?authorId=57202873965; https://www.webofscience.com/wos/author/record/ 1753209

ФИШЕР Аксель, PhD, қауымдастырылған профессор, Дрезден техникалық университеті (Дрезден, Германия), https://www.scopus.com/authid/detail.uri?authorId=35738572100; https://www.webofscience.com/wos/author/record/2085986

АГАБЕКОВ Владимир Енокович, химия ғылымдарының докторы, Беларусь ҰҒА академигі, Жаңа материалдар химиясы институтының құрметті директоры (Минск, Беларусь), https://www.scopus.com/authid/detail.uri?authorId=7004624845

КАТАЛИН Стефан, PhD, қауымдастырылған профессор, Дрезден Техникалық университеті (Дрезден, Германия), https://www.scopus.com/authid/detail.uri?authorId=35203904500; https://www.webofscience.com/wos/author/record/1309251

САҒЫНТАЕВ Жанай, PhD, қауымдастырылған профессор, Назарбаев университеті (Астана, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=57204467637; https://www.webofscience.com/wos/author/record/907886

ФРАТТИНИ Паоло, PhD, қауымдастырылған профессор, Бикокк Милан университеті (Милан, Италия), https://www.scopus.com/authid/detail.uri?authorId=56538922400

НҰРПЕЙІСОВА Маржан Байсанқызы, техника ғылымдарының докторы, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университетінің профессоры (Алматы, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=57202218883; https://www.webofscience.com/wos/author/record/AAD-1173-2019

РАТОВ Боранбай Товбасарович, техника ғылымдарының докторы, профессор, «Геофизика және сейсмология» кафедрасының меңгерушісі, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті (Алматы, Қазақстан), https://www.scopus.com/authid/detail.uri?authorId=55927684100; https://www.webofscience.com/wos/author/record/1993614

РОННИ Берндтссон, профессор, Таяу Шығысты заманауи зерттеу орталығының директоры, Лунд университеті (Лунд, Швеция), https://www.scopus.com/authid/detail.uri?authorId=7005388716; https://www.webofscience.com/wos/author/record/1324908

МИРЛАС Владимир, PhD, профессор, Ариэль университетінің Шығыс ғылыми-зерттеу орталығы (Ариэль, Израиль), https://www.scopus.com/authid/detail.uri?authorId=8610969300; https://www.webofscience.com/wos/author/record/53680261

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

© «Орталық Азия академиялық ғылыми орталығы» ЖШС, 2026,

ГЛАВНЫЙ РЕДАКТОР

ЖУРИНОВ Мурат Журинович, доктор химических наук, профессор, академик МААН и НАН РК, Генеральный директор НИИ нефтепереработки и нефтехимии (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=6602177960; https://www.webofscience.com/wos/author/record/2017489

ЗАМЕСТИТЕЛЬ ГЛАВНОГО РЕДАКТОРА

АБСАДЫКОВ Бахыт Нарикбаевич, доктор технических наук, профессор, академик НАН РК, Казахский национальный исследовательский технический университет им. К.И. Сатпаева (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=6504694468; https://www.webofscience.com/wos/author/record/2411827

РЕДАКЦИОННАЯ КОЛЛЕГИЯ:

АБСАМЕТОВ Малис Кудысович, доктор геолого-минералогических наук, профессор, академик НАН РК, директор Института гидрогеологии и геоэкологии им. У.М. Ахмедсафина (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=56955769200; https://www.webofscience.com/wos/author/record/1937883

ЖОЛТАЕВ Герой Жолтаевич, доктор геолого-минералогических наук, профессор, почетный академик НАН РК (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=57112610200; https://www.webofscience.com/wos/author/record/1939201

СНОУ Дэниел, PhD, ассоциированный профессор, директор Лаборатории водных наук Университета Небраски (Небраска, США), https://www.scopus.com/authid/detail.uri?authorId=7103259215; https://www.webofscience.com/wos/author/record/1429613

ЗЕЛЬТМАНН Раймар, PhD, руководитель исследований в области петрологии и месторождений полезных ископаемых в Отделе наук о Земле Музея естественной истории (Лондон, Великобритания), https://www.scopus.com/authid/detail.uri?authorId=55883084800; https://www.webofscience.com/wos/author/record/ 1048681

ПАНФИЛОВ Михаил Борисович, доктор технических наук, профессор Университета Нанси (Нанси, Франция), https://www.scopus.com/authid/detail.uri?authorId=7003436752; https://www.webofscience.com/wos/author/record/1230499

ШЕН Пин, PhD, заместитель директора Комитета по горной геологии Китайского геологического общества, член Американской ассоциации экономических геологов (Пекин, Китай), https://www.scopus.com/authid/detail.uri?authorId=57202873965; https://www.webofscience.com/wos/author/record/1753209

ФИШЕР Аксель, PhD, ассоциированный профессор, Технический университет Дрезден (Дрезден, Берлин), https://www.scopus.com/authid/detail.uri?authorId=35738572100; https://www.webofscience.com/wos/author/record/2085986

АГАБЕКОВ Владимир Енокович, доктор химических наук, академик НАН Беларуси, почетный директор Института химии новых материалов (Минск, Беларусь), https://www.scopus.com/authid/detail.uri?authorId=7004624845

КАТАЛИН Стефан, PhD, ассоциированный профессор, Технический университет Дрезден (Дрезден, Германия), https://www.scopus.com/authid/detail.uri?authorId=35203904500; https://www.webofscience.com/wos/author/record/ 1309251

САГИНТАЕВ Жанай, PhD, ассоциированный профессор, Назарбаев университет (Астана, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=57204467637; https://www.webofscience.com/wos/author/record/907886

ФРАТТИНИ Паоло, PhD, ассоциированный профессор, Миланский университет Бикокк (Милан, Италия), https://www.scopus.com/authid/detail.uri?authorId=56538922400

НУРПЕИСОВА Маржан Байсановна, доктор технических наук, профессор Казахского национального исследовательского технического университета им. К.И. Сатпаева (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=57202218883; https://www.webofscience.com/wos/author/record/AAD-1173-2019

РАТОВ Боранбай Товбасарович, доктор технических наук, профессор, заведующий кафедрой «Геофизика и сейсмология», Казахский национальный исследовательский технический университет им. К.И. Сатпаева (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=55927684100; https://www.webofscience.com/wos/author/record/1993614

РОННИ Берндтссон, профессор, Директор Центра современных ближневосточных исследований, Лундский университет (Лунд, Швеция), https://www.scopus.com/authid/detail.uri?authorId=7005388716; https://www.webofscience.com/wos/author/record/1324908

МИРЛАС Владимир, PhD, профессор, Восточный научно-исследовательский центр, Университет Ариэля, (Ариэль, Израиль), https://www.scopus.com/authid/detail.uri?authorId=8610969300; https://www.webofscience.com/wos/author/record/53680261

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.
Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*
Периодичность: 6 раз в год.
http://www.geolog-technical.kz/index.php/en/

© ТОО «Центрально-Азиатский академический научный центр», 2026.

CONTENTS

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 3.
Number 477 (2026), 104–118

https://doi.org/10.32014/2026.2518-170X.643

UDC: 622.341.1
IRSTI: 53.31.19

©Eshonkulov U.[1*], Umirzokov A.[2], Nosirov N.[3], Ruziyev U.[1], Karimov M.[2], 2026.
[1]Karshi State Technical University, Karshi, Uzbekistan;
[2]Tashkent State Technical University, Tashkent, Uzbekistan;
[3]Almalyk branch of the Tashkent State Technical University named after Islam Karimov, Almalyk, Uzbekistan.
*E-mail: uchqun.eshonqulov91@mail.ru

OXIDATION AND REDUCTION DYNAMICS IN PYRITE ROASTING FOR POROUS IRON PRODUCTION

Eshonkulov Uchkun — PhD, Associate Professor, Karshi State Technical University, Karshi, Uzbekistan,
E-mail: uchqun.eshonqulov91@mail.ru, https://orcid.org/0009-0002-8415-7218;
Umirzokov Azamat — PhD, Associate Professor, Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan,
E-mail: a_umirzoqov@mail.ru, https://orcid.org/0000-0002-9609-179X;
Nosirov Nurzod — PhD, Associate Professor, Almalyk branch of the Tashkent State Technical University named after Islam Karimov, Almalyk, Uzbekistan,
E-mail: nurzod2016@yandex.ru, https://orcid.org/0000-0003-0886-9336;
Ruziyev Ulugbek — Assistant, Karshi State Technical University, Karshi, Uzbekistan,
E-mail: ulugruziyev2@gmail.com, https://orcid.org/0009-0001-9533-3603;
Karimov Maruf — PhD, Associate Professor, Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan,
E-mail: maruf.karimov.1991@bk.ru, https://orcid.org/0009-0004-8100-7219.

Abstract. *Relevance.* Iron-containing technogenic waste generated during flotation beneficiation and metallurgical processing represents not only a serious environmental burden but also a valuable secondary resource for metal recovery. The growing demand for resource-efficient and environmentally sustainable metallurgical technologies has intensified interest in integrated roasting–reduction methods for producing porous metallic iron from sulfide-containing industrial waste. In particular, pyrite concentrates and iron-bearing residues formed during copper–molybdenum ore processing contain significant amounts of iron compounds suitable for secondary extraction. *Objective.* The aim of this study was to investigate the oxidation and reduction behavior during thermal treatment of pyrite concentrate and to evaluate the efficiency of magnetic separation for metallic iron recovery. *Methods.* Oxidation roasting was carried out at 500 °C for 30 min, followed by solid-phase reduction at 950 °C for 90 min using 15 wt.% Angren brown coal as a reducing agent. Structural and physicochemical characterization of the obtained products was performed using X-ray diffraction (XRD), chemical composition analysis, scanning electron microscopy (SEM), optical microscopy, and magnetic separation analysis. *Results.* XRD analysis confirmed the transformation of iron sulfides into Fe_2O_3 and Fe_3O_4 during oxidative roasting and their subsequent reduction to metallic iron during high-temperature treatment. The reduction process proceeded through the sequential $Fe_2O_3 \rightarrow FeO \rightarrow Fe$ pathway controlled by carbon monoxide formation via the Boudouard reaction. The metallization degree reached 70%, while the magnetic fraction yield ranged from 50 to 55%, indicating effective recovery of metallic iron from technogenic waste. Microstructural investigations revealed the formation of porous metallic iron with a developed pore structure, which enhanced reduction kinetics and magnetic separation efficiency. The use of locally available Angren coal provided additional technological and economic advantages due to its high volatile matter content and lower cost compared with imported metallurgical coke. *Conclusions.* The obtained results demonstrate that oxidation–reduction treatment followed by magnetic separation enables efficient recovery of metallic iron from pyrite-containing technogenic waste. The proposed approach can be applied for secondary processing of mining and metallurgical residues and contributes to resource conservation and reduction of environmental impact.

Keywords: pyrite roasting, iron oxide reduction, porous iron, magnetic separation, technogenic waste, metallization degree

For citations: *Eshonkulov U., Umirzokov A., Nosirov N., Ruziyev U., Karimov M. Oxidation and Reduction Dynamics in Pyrite Roasting for Porous Iron Production. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences. 2026. No.3. Pp. 104–118. DOI: https://doi.org/10.32014/2026.2518-170X.643*

©Эшонқұлов У.[1]*, Өмірзақов А.[2], Носиров Н.[3], Рузиев У.[1], Каримов М.[2], 2026.
[1]Каршы мемлекеттік техникалық университеті, Қарши, Өзбекстан;
[2]Ташкент мемлекеттік техникалық университеті, Ташкент, Өзбекстан;
[3]Ислам Каримов атындағы ташкент мемлекеттік техникалық университетінің Алмалық филиалы, Алмалық, Өзбекстан.
*E-mail: uchqun.eshonqulov91@mail.ru

КЕУЕКТІ ТЕМІР АЛУ МАҚСАТЫНДА ПИРИТТІ КҮЙДІРУ БАРЫСЫНДАҒЫ ТОТЫҒУ ЖӘНЕ ТОТЫҚСЫЗДАНУ ҮДЕРІСІНІҢ ДИНАМИКАСЫ

Ешонқұлов Учкун — PhD, доцент, Қарши мемлекеттік техникалық университеті, Қарши, Өзбекстан,
E-mail: uchqun.eshonqulov91@mail.ru, https://orcid.org/0009-0002-8415-7218;
Өмірзақов Азамат — PhD, доцент, Ислам Каримов атындағы Ташкент мемлекеттік техникалық университеті, Ташкент, Өзбекстан;
E-mail: a_umirzoqov@mail.ru, https://orcid.org/0000-0002-9609-179X;
Носиров Нұрзод — PhD, доцент, Ислам Каримов атындағы Ташкент мемлекеттік техникалық университетінің Алмалық филиалы, Алмалық, Өзбекстан;
E-mail: nurzod2016@yandex.ru, https://orcid.org/0000-0003-0886-9336;
Рузиев Ұлықбек — ассистент, Қарши мемлекеттік техникалық университеті, Қарши, Өзбекстан,
E-mail: ulugruizyev2@gmail.com, https://orcid.org/0009-0001-9533-3603;
Каримов Маруф — PhD, доцент, Ислам Каримов атындағы Ташкент мемлекеттік техникалық университеті, Алмалық, Өзбекстан,
E-mail: maruf.karimov.1991@bk.ru, https://orcid.org/0009-0004-8100-7219.

Аннотация. *Өзектілігі.* Флотациялық байыту және металлургиялық өңдеу барысында түзілетін темірқұрамды техногендік қалдықтар қоршаған ортаға айтарлықтай қауіп төндірумен қатар, металдарды қайта алуға мүмкіндік беретін құнды екінші реттік шикізат көзі болып табылады. Ресурсты үнемдейтін және экологиялық тұрғыдан тиімді металлургиялық технологияларға деген сұраныстың артуы сульфидқұрамды өндірістік қалдықтардан кеуекті металдық темір алу үшін кешенді күйдіру–тотықсыздандыру әдістеріне қызығушылықты күшейтті. Әсіресе, мыс–молибден кендерін өңдеу кезінде түзілетін пирит концентраттары мен темірқұрамды қалдықтар құрамында қайта өңдеуге жарамды темір қосылыстарының едәуір мөлшері кездеседі. *Мақсат.* Зерттеудің мақсаты пирит концентратын термиялық өңдеу кезінде жүретін тотығу және тотықсыздану процестерін зерттеу және магниттік сепарация арқылы металдық темірді бөліп алу тиімділігін бағалау болды. *Әдістері.* Тотықтырушы күйдіру 500 °C температурада 30 минут жүргізілді, одан кейін тотықсыздандыру 950 °C температурада 90 минут бойы 15 масс.% Ангрен қоңыр көмірін тотықсыздандырғыш ретінде пайдалану арқылы орындалды. Алынған өнімдердің құрылымдық және физика-химиялық сипаттамалары рентгендік фазалық талдау (XRD), химиялық құрамды талдау, сканерлеуші электрондық микроскопия (SEM), оптикалық микроскопия және магниттік сепарация әдістерімен зерттелді. *Нәтижелер.* XRD нәтижелері тотығу күйдіруі кезінде темір сульфидтерінің Fe_2O_3 және Fe3O4 қосылыстарына айналғанын, ал жоғары температуралық өңдеу барысында олардың металдық темірге дейін тотықсызданғанын растады. Тотықсыздану процесі Бодуар реакциясы нәтижесінде түзілетін көміртек оксидінің әсерімен $Fe_2O_3 \rightarrow FeO \rightarrow Fe$ тізбегі бойынша жүрді. Металдану дәрежесі 70%-ға жетті, ал магниттік фракция шығымы 50–55% аралығында болды, бұл техногендік қалдықтардан металдық темірді тиімді бөліп алуға мүмкіндік беретінін көрсетті. Микроқұрылымдық зерттеулер дамыған кеуекті құрылымы бар кеуекті металдық темірдің түзілгенін көрсетті, бұл тотықсыздану кинетикасын және магниттік сепарация тиімділігін арттырды. Жергілікті Ангрен көмірін пайдалану оның ұшқыш заттарының жоғары мөлшері мен импорттық металлургиялық кокспен салыстырғандағы төмен құнына байланысты қосымша технологиялық және экономикалық артықшылықтар берді. *Тұжырымдар.* Алынған нәтижелер тотығу–тотықсыздандыру өңдеуі мен кейінгі магниттік сепарацияның пиритқұрамды техногендік қалдықтардан металдық темірді тиімді алуға мүмкіндік беретінін көрсетті. Ұсынылған әдіс тау-кен және металлургиялық қалдықтарды екінші реттік өңдеуде қолданылып, ресурстарды үнемдеуге және қоршаған ортаға түсетін жүктемені азайтуға ықпал етеді.

Түйін сөздер: темір кенін пайдалану, пирометаллургиялық өндіру, қара металдарды алу, темір оксидтерін қалпына келтіру, қалдықтарды қайта өңдеу технологиясы, металлургиялық қалдықтарды өңдеу

© Эшонкулов У.[1*], Умирзоков А.[2], Носиров Н.[3], Рузиев У.[1],
Каримов М.[2], 2026.
[1]Каршинский государственный технический университет, Карши, Узбекистан;
[2] Ташкентский государственный технический университет,
Ташкент, Узбекистан;
[3]Алмалыкский филиал Ташкентского государственного технического
университета имени Ислама Каримова, Алмалык, Узбекистан.
*E-mail: uchqun.eshonqulov91@mail.ru

ДИНАМИКА ОКИСЛЕНИЯ И ВОССТАНОВЛЕНИЯ ПРИ ОБЖИГЕ ПИРИТА ДЛЯ ПОЛУЧЕНИЯ ПОРИСТОГО ЖЕЛЕЗА

Эшонкулов Учкун — кандидат технических наук, доцент, Каршинский государственный технический университет, Карши, Узбекистан,
E-mail: uchqun.eshonqulov91@mail.ru, https://orcid.org/0009-0002-8415-7218;
Умирзоков Азамат — кандидат технических наук, доцент, Ташкентский государственный технический университет имени Ислама Каримова, Ташкент, Узбекистан,
E-mail: a_umirzoqov@mail.ru, https://orcid.org/0000-0002-9609-179X;
Носиров Нурзод — кандидат технических наук, доцент, Алмалыкский филиал Ташкентского государственного технического университета имени Ислама Каримова, Алмалык, Узбекистан,
E-mail: nurzod2016@yandex.ru, https://orcid.org/0000-0003-0886-9336;
Рузиев Улугбек — ассистент, Каршинский государственный технический университет, Карши, Узбекистан,
E-mail: ulugruizyev2@gmail.com, https://orcid.org/0009-0001-9533-3603;
Каримов Маруф — кандидат технических наук, доцент, Ташкентского государственного технического университета имени Ислама Каримова, Алмалык, Узбекистан,
E-mail: maruf.karimov.1991@bk.ru, https://orcid.org/0009-0004-8100-7219.

Аннотация. *Актуальность.* Железосодержащие техногенные отходы, образующиеся при флотационном обогащении и металлургической переработке, представляют собой не только серьезную экологическую проблему, но и ценный вторичный ресурс для извлечения металлов. Рост потребности в ресурсосберегающих и экологически безопасных металлургических технологиях усиливает интерес к комплексным методам обжига и восстановления для получения пористого металлического железа из сульфидсодержащих промышленных отходов. В частности, пиритовые концентраты и железосодержащие остатки, образующиеся при переработке медно-молибденовых руд, содержат значительное количество соединений железа, пригодных для вторичного извлечения. *Цель.* Изучить процессы окисления и восстановления при термической обработке пиритового концентрата, а также оценить эффективность магнитной сепарации для извлечения металлического железа. *Методы.* Окислительный обжиг проводили при температуре 500 °C в течение 30 минут, после чего осуществляли твердофазное восстановление при 950 °C в течение 90 минут с использованием 15 масс.% ангренского бурого угля в качестве восстановителя. Структурные и физико-химические характеристики полученных продуктов исследовали методами рентгенофазового анализа (XRD), химического анализа состава, сканирующей электронной микроскопии (SEM), оптической микроскопии и магнитной сепарации. *Результаты и выводы.* Результаты XRD подтвердили превращение сульфидов железа в Fe_2O_3 и Fe_2O_3 в процессе окислительного обжига и их последующее восстановление до металлического железа при высокотемпературной обработке. Процесс восстановления протекал по последовательной схеме $Fe_2O_3 \rightarrow FeO \rightarrow Fe$ под воздействием монооксида углерода, образующегося в результате реакции Будуара. Степень металлизации достигла 70%, а выход магнитной фракции составил 50–55%, что свидетельствует об эффективном извлечении металлического железа из техногенных отходов. Микроструктурные исследования показали образование пористого металлического железа с развитой поровой структурой, что способствовало повышению кинетики восстановления и эффективности магнитной сепарации. Использование местного ангренского угля обеспечило дополнительные технологические и экономические преимущества благодаря высокому содержанию летучих веществ и более низкой стоимости по сравнению с импортным металлургическим коксом. Полученные результаты подтверждают, что окислительно-восстановительная обработка с последующей магнитной сепарацией обеспечивает эффективное извлечение металлического железа из пиритсодержащих техногенных отходов. Предложенный подход может быть использован для вторичной переработки горно-металлургических отходов, способствуя ресурсосбережению и снижению экологической нагрузки.

Ключевые слова: обжиг пирита, восстановление оксидов железа, пористое железо, магнитная сепарация, техногенные отходы, степень металлизации

Introduction. The sustainable development of the metallurgical industry requires efficient utilization of mineral resources and secondary raw materials.

In recent decades, the rapid growth of construction, mechanical engineering, energy production, and high-technology sectors has significantly increased the global demand for ferrous metals. However, conventional beneficiation processes, including flotation of sulfide copper–molybdenum ores and magnetic separation of iron ores, generate substantial volumes of technogenic waste containing oxidized iron compounds (Bulayani et al., 2024). These wastes represent both an environmental burden and a valuable secondary resource for metal recovery.

In many processing plants, tailings, clinker residues, slags, and gas-cleaning dust contain iron predominantly in the form of hematite (Fe_2O_3), magnetite (Fe_3O_4), wüstite (FeO), fayalite, and other iron-bearing phases (Pilchin, 2011). The presence of such compounds creates opportunities for secondary extraction; however, their strong association with silicate matrices and complex mineralogical composition complicate efficient recovery. Traditional hydrometallurgical methods often face limitations due to poor filtration properties of pulps and high reagent consumption, while pyrometallurgical approaches require optimization to reduce energy demand and environmental impact.

Recent studies emphasize the importance of integrated waste processing and direct reduction technologies to improve metal recovery efficiency while minimizing CO_2 emissions and raw material losses. In this context, low-temperature sulfation roasting, selective leaching, and solid-phase reduction using carbonaceous reducing agents have attracted particular attention. The optimization of temperature regimes, reducing agent dosage, and gas composition plays a decisive role in achieving high iron extraction rates.

Consequently, the aim of this study is to investigate the oxidation and reduction dynamics of iron-containing technogenic waste during pyrite roasting and subsequent reduction processes, to determine optimal technological parameters, and to evaluate the feasibility of replacing imported coke with locally available reducing agents (Sahu et al., 2020). The study provides experimental data on the roasting and reduction behavior of pyrite-containing materials and evaluates the possibility of using local reducing agents for iron recovery.

Literary Review. The processing of iron-bearing technogenic waste has become increasingly relevant in the context of global efforts toward circular economy and sustainable industrial development. According to recent estimates, the Almalyk Mining and Metallurgical Complex alone generates hundreds of thousands of tonnes of sulfide-bearing tailings annually, creating both environmental challenges and opportunities for secondary resource utilization (Yessengaliev et al., 2023). Integrated pyrometallurgical processing of such waste materials is increasingly studied as a practical method for recovering valuable components from technogenic raw materials.

Pyrite concentrate, as a by-product of copper–molybdenum ore beneficiation, contains substantial amounts of iron in the form of sulfides and oxides. The thermal decomposition of pyrite (FeS_2) proceeds through intermediate phases, including pyrrhotite ($Fe_{1-x}S$), before complete oxidation to hematite (Fe_2O_3) and magnetite (Fe_3O_4) (Strezov et al., 2011). The temperature and atmosphere during roasting critically determine the phase composition of the calcine and, consequently, its suitability for subsequent reduction treatment. It has been established that oxidative roasting at temperatures between 450–600 °C effectively removes sulfur while preserving iron in a highly reactive oxide form favorable for further processing (Gomes et al., 2022).

The thermodynamic basis of iron oxide reduction in carbon-rich environments is well established. The Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$) plays a central role in controlling the partial pressure of CO at elevated temperatures, thereby governing the reduction potential of the gas phase. At temperatures above 900 °C, equilibrium strongly favors CO formation, creating conditions suitable for the sequential reduction of $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$ (Peng et al., 2017). The kinetics of this process are strongly influenced by the porosity of the iron oxide particles, the reactivity of the carbonaceous reductant, and the contact efficiency between solid and gas phases. Studies have shown that the use of brown coal, with its higher volatile content compared to coke, can accelerate the initial stages of reduction by providing additional reactive gases at lower temperatures (Yuan et al., 2020).

The use of locally available carbonaceous reductants as alternatives to imported metallurgical coke has attracted considerable attention in recent years. Angren brown coal, characterized by relatively high volatile matter content and moderate fixed carbon, has been identified as a technically viable reducing agent for direct reduction processes in Central Asian industrial contexts (Sahu et al., 2020). Its availability and low cost provide significant economic advantages over conventional coke-based processes, particularly for small- and medium-scale operations focused on secondary raw material processing.

Magnetic separation following reduction roasting represents a well-established and efficient method for concentrating metallic iron from complex multi-component mixtures. The effectiveness of separation depends primarily on the degree of metallization achieved during reduction, the grain size of the metallic iron particles, and the intensity of the applied magnetic field. Several studies have confirmed that metallization degrees exceeding 60–65% are generally sufficient to achieve satisfactory iron recovery rates through low-intensity magnetic separation (Yu et al., 2020; Zhang et al., 2022). Furthermore, the formation of porous metallic iron during solid-phase reduction is known to enhance both the surface area available for reaction and the liberation of iron particles from the silicate matrix, thereby improving separation performance (Strezov et al., 2011).

Materials and methods. Iron-containing technogenic waste generated at the Almalyk Mining and Metallurgical Complex was used as the primary research material. The investigated materials included flotation tailings from the copper beneficiation plant, pyrite concentrate obtained from Kalmakyr ore, and iron-bearing slag formed during smelting operations (Yessengaliev et al., 2023).

Chemical analysis showed that cyclone dust contained 52.5 wt.% Fe, 13.0 wt.% SiO_2, 3.12 wt.% Al_2O_3, 0.30 wt.% CaO, 0.10 wt.% MgO, 0.35 wt.% Cu, 0.30 wt.% Zn, and 1.64 wt.% total sulfur. After roasting, the calcine exhibited 18.0 wt.% Fe and 52.84 wt.% SiO_2. Granulometric analysis indicated that approximately 73% of the material belonged to the fraction below 0.061 mm, ensuring sufficient reaction surface during thermal processing. Angren brown coal was used as the reducing agent. The coal was dried, crushed, and sieved prior to mixing.

The raw material was mixed with 3.5 wt.% bentonite binder and granulated in a laboratory drum granulator (diameter 0.75 m; side wall height 0.13 m; productivity 50 kg/h). The moisture content during granulation was maintained at 30–31%. The main operating parameters of the granulation and drying stages are summarized in Table 1.

Table 1. Operating parameters of granulation and thermal drying stages.

Parameter	Value
Binder addition	Bentonite – 3.5 wt.% of the granulated material mass
Moisture content in granulator	30–31 %
Granulator capacity (0.75 m diameter; 0.13 m side height)	50 kg/h
Drying agent (air) temperature	600–700 °C
Fluidized bed drying layer temperature	200–220 °C
Air velocity during drying	0.20 m/s
Drying furnace productivity (0.02 m² area)	15 kg/h
Residual moisture content of pellets	0.5–1.0 %

The prepared pellets were subsequently transferred to the reduction furnace for thermal treatment.

Pellets were dried using hot air at 600–700 °C. The fluidized bed drying layer temperature was controlled within 200–220 °C. Air velocity was maintained at 0.20 m/s. The drying furnace (effective area 0.02 m²) provided a productivity of 15 kg/h. Residual pellet moisture was reduced to 0.5–1.0%.

Oxidation roasting of pyrite concentrate was carried out at 500 °C for 30 min. Subsequent reduction was performed at 950 °C for 90 min using 15 wt.% reducing agent relative to the charge mass.

Experiments were conducted in a laboratory rotary tube furnace under controlled temperature conditions. The heating rate was maintained at 10 °C/min. Samples (100–200 g per batch) were reduced and cooled inside the furnace to prevent rapid oxidation.

Each experiment was repeated three times to ensure reproducibility. The average values were calculated, and deviation did not exceed ±3%.

After reduction, the product was subjected to magnetic separation using a laboratory magnetic separator. The magnetic field intensity was set to approximately 0.2–0.3 T to ensure effective recovery of metallic iron.

Phase composition was determined using X-ray diffraction (XRD). Microstructural analysis was performed using scanning electron microscopy (SEM). Chemical composition was analyzed by atomic absorption spectroscopy (AAS) and X-ray fluorescence (XRF). Statistical processing was performed using standard deviation analysis.

Results and Discussion. The oxidation and reduction behavior of iron-bearing pyrite concentrate was systematically investigated under controlled laboratory conditions. The experimental results demonstrate significant phase transformation during both roasting and reduction stages (Quast, 2018).

Oxidative roasting at 500 °C for 30 minutes resulted in effective sulfur removal and partial conversion of iron sulfides into iron oxides. The mass loss observed during roasting is attributed to sulfur oxidation and SO_2 evolution.

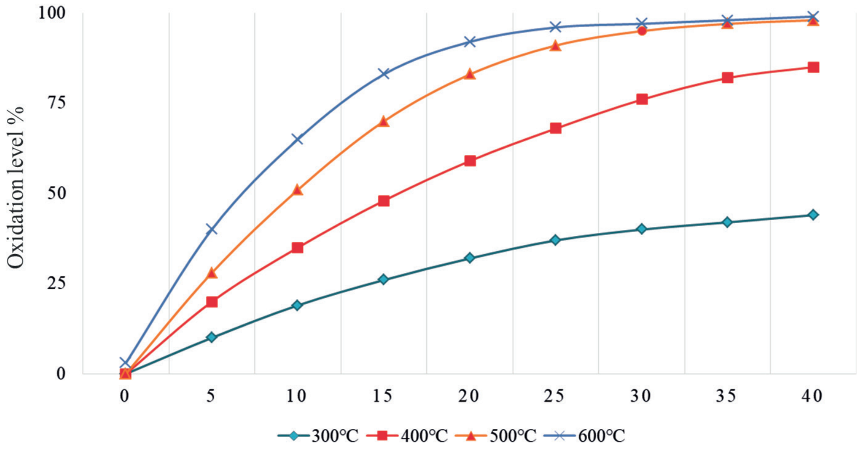

Figure 1. Oxidation kinetics of pyrite concentrate during roasting at different temperatures.

The oxidation behavior observed during roasting can be explained by the multistage thermal decomposition mechanism of pyrite. Initially, pyrite (FeS_2) undergoes partial sulfur removal with the formation of intermediate pyrrhotite phases ($Fe_{1-x}S$), which are subsequently oxidized into magnetite and hematite. At temperatures near 500 °C, sulfur oxidation becomes thermodynamically favorable, resulting in intensive SO_2 evolution and progressive destruction of sulfide structures. The selected roasting temperature ensured efficient sulfur removal while preventing excessive sintering of oxide particles, which is important for maintaining high porosity and reactivity during the subsequent reduction stage. Similar oxidation behavior of pyrite concentrates has been reported in previous studies, where roasting within the range of 450–600 °C promoted effective transformation of iron sulfides into reactive iron oxide phases suitable for further reduction treatment. The results show that controlled oxidation roasting promotes the formation of porous iron oxide phases that are favorable for subsequent reduction and metallization.

Table 2. Chemical composition of cyclone dust and calcine obtained from the fluidized bed furnace at Copper Beneficiation Plant No. 1.

Component	Cyclone Dust (wt.%)	Calcine (wt.%)
Fe	52.5	18.0
Cu	0.35	-
Zn	0.30	-
S (total)	1.64	0.84
S (sulfide)	1.08	-
SiO_2	13.0	52.84
CaO	0.30	-
MgO	0.10	-
Al_2O_3	3.12	-

Subsequent reduction at 950 °C for 90 minutes using 15 wt.% Angren coal resulted in the formation of metallic iron. The reduction process required higher temperature and longer duration compared to oxidation, confirming thermodynamic expectations.

Based on the obtained experimental results, the main kinetic relationships were plotted. The dependence of the reduction degree of iron oxide in the iron-bearing material on the isothermal holding time at a reducing agent consumption of 15 wt.% is presented in figure 2.

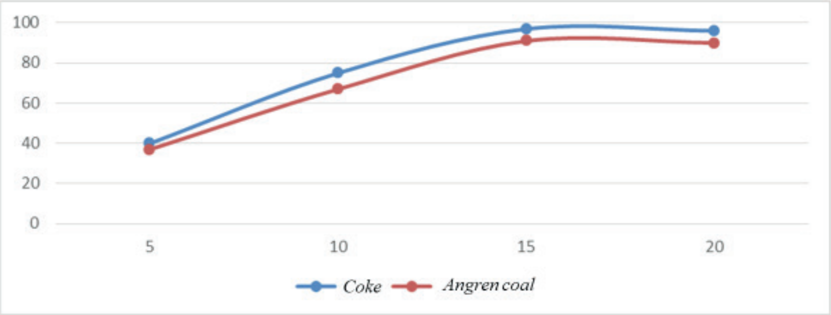

Figure 2. Reduction kinetics of iron oxide during pyrite calcine reduction at 950 °C.

The reduction kinetics presented in Figure 2 indicate that temperature and gas-phase composition strongly influence the metallization process. At elevated temperatures, the Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$) shifts toward carbon monoxide generation, increasing the reducing potential of the gaseous atmosphere. The produced CO actively participates in the sequential reduction pathway $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$. The accelerated reduction observed at 950 °C confirms that the thermodynamic conditions at this temperature are favorable for metallic iron formation. In addition, the porous structure formed during oxidative roasting enhanced gas diffusion and improved contact between reducing gases and iron oxide particles. The use of Angren brown coal also contributed significantly to the reduction efficiency due to its relatively high volatile matter content. During thermal decomposition, volatile compounds released from coal generated additional reducing gases, intensifying the initial stages of reduction and improving overall reaction kinetics. Similar reduction behavior has been reported by Peng et al. (2017) and Yuan et al. (2020), who demonstrated that carbon-based reduction systems achieve higher metallization efficiency under CO-rich conditions. Compared with conventional coke-based reduction, the use of locally available Angren coal provides additional economic and technological advantages while maintaining satisfactory reduction performance.

After reduction, the product was subjected to magnetic separation. The magnetic fraction yield ranged between 50–55%, confirming efficient recovery of metallic iron.

Table 3. Chemical composition and metallization parameters of the magnetic fraction after reduction roasting.

Number of experiments	Number of samples	Fe_{total}	Fe_{met}	FeO→Fe conversion	Cu	C	SiO_2	Reduction degree, %
1	1 sample	62.1	37.8	-	0.71	4.2	17.40	61.0
	2 sample	58.2	37.8	-	0.65	3.8	18.76	65.0
	3 sample	60.9	41.7	-	0.66	3.54	18.76	68.80
	4 sample	64.4	42.0	-	0.74	2.65	16.0	65.50
2	5 sample	61.1	36.5	23.5	-	-	-	60.0
	6 sample	61.6	38.1	24.7	0.86	1.6	21.8	62.0
	7 sample	68.5	47.9	21.3	0.93	1.5	16.9	70.0

The obtained metallization degree of 60–70% demonstrates the effectiveness of the proposed roasting–reduction technology for secondary iron recovery from pyrite-containing technogenic waste. The highest metallization level achieved in sample 7 indicates that optimized reduction conditions significantly enhance the transformation of iron oxides into metallic iron. Similar metallization ranges have been reported in previous studies involving magnetization roasting and coal-based reduction of refractory iron ores. However, the present results demonstrate that pyrite-derived materials can also serve as effective feedstock for porous iron production when appropriate thermal treatment conditions are applied. The relatively high magnetic fraction yield further confirms the feasibility of subsequent magnetic separation for iron concentration. In addition, the residual non-magnetic fraction was composed mainly of silicate phases, indicating satisfactory liberation of metallic iron particles from the gangue matrix during reduction. These findings highlight the potential of integrated roasting–reduction treatment as an environmentally sustainable alternative for valorization of mining and metallurgical waste streams.

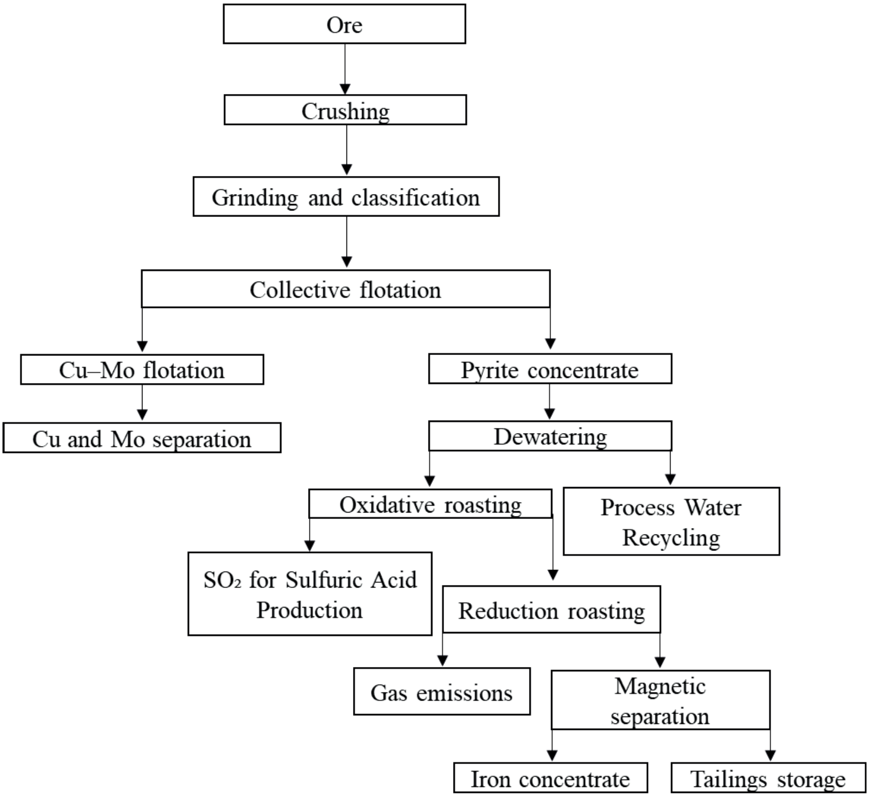

Figure 3. Technological flow diagram for iron recovery from Kalmakkir ore.

According to the scheme, the ore undergoes crushing, grinding and classification followed by bulk flotation at pH 11. The Cu–Mo–pyrite concentrate is subjected to selective flotation at pH 8.5–9 to obtain pyrite concentrate. The pyrite concentrate is oxidatively roasted to remove sulfur, with SO_2 directed to sulfuric acid production. The calcine is then reduced at elevated temperature using a carbonaceous reductant, followed by magnetic separation to obtain iron concentrate, while non-magnetic fractions are discharged as tailings.

The chemical analysis of the magnetic fraction revealed a substantial increase in iron content compared to the initial material. Non-magnetic fractions were primarily composed of silicate phases and were directed to tailings.

SEM analysis demonstrated the formation of porous metallic iron structure after reduction. The porous morphology enhances reactivity and improves subsequent processing characteristics.

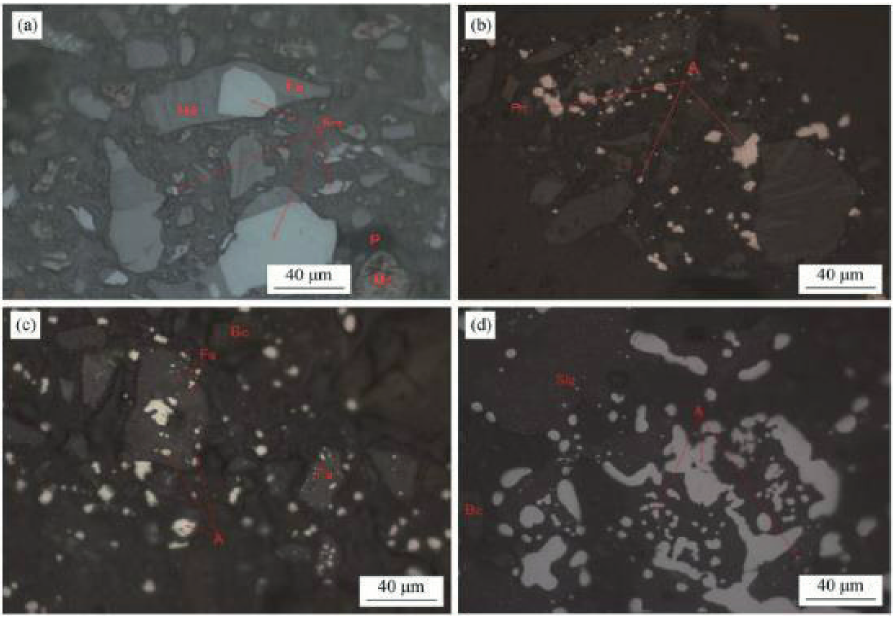

Figure 4. Optical micrographs of reduced granulated particles at different temperatures: (a) 800 °C; (b) 850 °C; (c) 950 °C; (d) 1000 °C. A – metallic phase; Bc – coal; Frr – ferrite; Fa – fayalite; P – pores; Slg – slag; Hd – hedenbergite.

Microstructural observations revealed that the reduction process was accompanied by intensive pore formation within the metallic phase. The development of porous iron structure can be associated with sulfur removal, gas evolution, and volume changes occurring during oxide reduction. As reduction progresses, oxygen removal from iron oxides creates internal voids and channels, improving gas permeability inside the particles. Such porous morphology significantly enhances diffusion of reducing gases and facilitates further metallization of the inner particle regions. In addition, the formation of porous metallic iron improves liberation of metallic particles from silicate phases, thereby increasing magnetic separation efficiency. The observed structural transformation confirms that controlled reduction conditions promote not only chemical conversion of iron oxides but also favorable microstructural evolution. Similar porous structures have been reported in studies on solid-phase reduction of iron-bearing materials, where pore development was identified as one of the key factors governing reduction kinetics and separation performance.

Conclusion. The conducted study confirms that iron-containing technogenic waste, particularly pyrite concentrate and roasting residues, represents a viable secondary resource for porous iron production through controlled oxidation–reduction treatment. The experimental results demonstrated that oxidation roasting at 500 °C for 30 minutes ensures effective sulfur removal and transformation of iron sulfides into Fe_2O_3 and Fe_3O_4 phases, while subsequent reduction at 950 °C for 90 minutes using 15 wt.% Angren coal promotes the formation of metallic iron. X-ray diffraction analysis verified the sequential phase transformation pathway Fe_2O_3→FeO→Fe, governed by CO generation through the Boudouard reaction. The metallization degree reached 70%, and the magnetic fraction yield ranged between 50–55%, confirming the efficiency of the proposed reduction–magnetic separation route. Microstructural analysis revealed the formation of porous metallic iron with a developed pore network, which enhances both reactivity and separation performance. Beyond confirming the thermodynamic feasibility of the process, the obtained results highlight the technological and environmental relevance of integrated roasting–reduction treatment. The use of locally available Angren coal as a reducing agent improves economic feasibility while reducing dependence on imported coke. In conclusion, the findings of this study establish a technically sound and economically feasible framework for the secondary recovery of iron from technogenic waste streams generated at copper–molybdenum processing facilities. The optimized combination of oxidative roasting, carbon-based solid-phase reduction, and magnetic separation demonstrates clear potential for industrial implementation, particularly in regions where locally available carbonaceous reductants can replace conventional metallurgical coke. Beyond the immediate technological implications, the proposed approach aligns with broader objectives of sustainable resource management and circular economy principles, offering a replicable model for the valorization of iron-bearing industrial residues in the mining and metallurgical industry.

References

Adamaev M., Kuttybaev A., & Auezova A. (2015) Dynamics of dry grinding in two-compartment separator mills (2015) New Developments in Mining Engineering. Theoretical and Practical Solutions of Mineral. Resources Mining. – No. 435-439. (in Eng.).

Bulayani, M. M., Raghupatruni, P., Mamvura, T., & Danha, G. (2024). Exploring low-grade iron ore beneficiation techniques: a comprehensive review. Minerals. – No. 14(8). – P. 796. https://doi.org/10.3390/min14080796 (in Eng.).

Gomes T., da Rosa R., Cargnin M., Quadri M.B., Peterson M., de Oliveira C.M., ... & Angioletto E. (2022). Pyrite roasting in modified fluidized bed: Experimental and modeling analysis. Chemical Engineering Science. – No. 261. – P. 117977. (in Eng.).

Junhui X., Kai Z., & Zhen W. (2020). Studying on mineralogical characteristics of a refractory high-phosphorous oolitic iron ore. SN Applied Sciences. – No. 2(6). – P. 1051. https://doi.org/10.1007/s42452-020-2871-4 (in Eng.).

Makhmarezhabov, D., Matkarimov, S., Yavkochiva, D., & Yuldasheva, N. (2024). Flocculation of Sulfide Minerals with a Mixture of Potassium Xanthate Butyl and Water-Soluble Polymer. Engineering Proceedings. – No. 63(1). – P. 27. (in Eng.).

Ngoma E. I. (2025). Optimization of pilot bioleaching for enhanced metal recovery: scale-up bioreactor, comparative bio-oxidation analysis, and advancing the continuous pyrrhotite bioleaching process (Doctoral dissertation, Laurentian University Library & Archives). (in Eng.).

Peng T., Gao X., Li Q., Xu L., Luo L., & Xu L. (2017). Phase transformation during roasting process and magnetic beneficiation of oolitic-iron ores. – Vacuum. – No. 146. – P. 63-73. https://doi.org/10.1016/j.vacuum.2017.09.029 (in Eng.).

Pilchin, A. N. (2011). Magnetite: the story of the mineral's formation and stability. Magnetite: structure, properties and applications. – P. 1-99. (in Eng.).

Quast, K. (2018). A review on the characterisation and processing of oolitic iron ores. Minerals Engineering. – No. 126. – P. 89-100. https://doi.org/10.1016/j.mineng.2018.06.018 (in Eng.).

Sahu S.N., Baskey P.K., Barma S.D., Sahoo S., Meikap B.C., & Biswal S.K. (2020). Pelletization of synthesized magnetite concentrate obtained by magnetization roasting of Indian low-grade BHQ iron ore. Powder Technology. – No. 374. – P. 190-200. https://doi.org/10.1016/j.powtec.2020.07.004 (in Eng.).

Strezov V., Evans T.J., Zymla V., & Strezov L. (2011). Structural deterioration of iron ore particles during thermal processing. International Journal of Mineral Processing. – No. 100(1-2). – P. 27-32. https://doi.org/10.1016/j.minpro.2011.04.005 (in Eng.).

Tang Z., Gao P., Sun Y., Han Y., Li E., Chen J., & Zhang Y. (2020). Studies on the fluidization performance of a novel fluidized bed reactor for iron ore suspension roasting. Powder Technology. – No. 360. – P. 649-657. https://doi.org/10.1016/J.POWTEC.2019.09.092 (in Eng.).

Umarova I.K., Amindjanova S.I., Salidjanova G.K., Bekpulatov J.B., & Djumaeva K.Y. (2023). Hydrometallurgical processing of pyrite concentrates from Yoshlik deposits. In E3S Web of Conferences. EDP Sciences. – Vol. 389. – P. 01079. (in Eng.).

Yessengaliev D., Mukhametkhan M., Mukhametkhan Y., Zhabalova G., Kelamanov B., Kolesnikova O., ... & Kuatbay Y. (2023). Studies of the Possibility of Improving the Quality of Iron Ores and Processing of Technogenic Composite Iron-Containing Waste of Metallurgical Production. Journal of Composites Science. – No. 7(12). – P. 501. https://doi.org/10.3390/jcs7120501 (in Eng.).

Yu J., Han Y., Li Y., & Gao P. (2020). Recent advances in magnetization roasting of refractory iron ores: A technological review in the past decade. Mineral Processing and Extractive Metallurgy Review. – No. 41(5). – P. 349-359. https://doi.org/10.1080/08827508.2019.1634565 (in Eng.).

Yuan S., Zhou W., Han Y., & Li Y. (2020). Selective enrichment of iron particles from complex refractory hematite-goethite ore by coal-based reduction and magnetic separation. Powder Technology. – No. 367. – P. 305-316. https://doi.org/10.1016/j.powtec.2020.04.004 (in Eng.).

Zhang Q., Sun Y., Han Y., Li Y., & Gao P. (2022). Effect of thermal oxidation pretreatment on the magnetization roasting and separation of refractory iron ore. Mineral Processing and Extractive Metallurgy Review. – No. 43(2). – P. 182-187. https://doi.org/10.1080/08827508.2020.1837126 (in Eng.).

Zhienbayev A., Takhanov D., Zharaspaev M., Kuttybayev A., Rakhmetov B., & Ivadilinova D. (2025). Identifying rational locations for field mine workings in the zone influenced by minedout space during repeated mining of pillars. Mining of Mineral Deposits. – No. 19 (1). – P. 1, 12. (in Eng.).

Publication Ethics and Publication Malpractice in the journals of the Central Asian Academic Research Center LLP

For information on Ethics in publishing and Ethical guidelines for journal publication see http://www.elsevier.com/publishingethics and http://www.elsevier.com/journal-authors/ethics.

Submission of an article to the journals of the Central Asian Academic Research Center LLP implies that the described work has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis or as an electronic preprint, see http://www.elsevier. com/postingpolicy), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder. In particular, translations into English of papers already published in another language are not accepted.

No other forms of scientific misconduct are allowed, such as plagiarism, falsification, fraudulent data, incorrect interpretation of other works, incorrect citations, etc. The Central Asian Academic Research Center LLP follows the Code of Conduct of the Committee on Publication Ethics (COPE), and follows the COPE Flowcharts for Resolving Cases of Suspected Misconduct (http://publicationethics. org/files/ u2/New_Code.pdf). To verify originality, your article may be checked by the Cross Check originality detection service http://www.elsevier.com/editors/plagdetect.

The authors are obliged to participate in peer review process and be ready to provide corrections, clarifications, retractions and apologies when needed. All authors of a paper should have significantly contributed to the research.

The reviewers should provide objective judgments and should point out relevant published works which are not yet cited. Reviewed articles should be treated confidentially. The reviewers will be chosen in such a way that there is no conflict of interests with respect to the research, the authors and/ or the research funders.

The editors have complete responsibility and authority to reject or accept a paper, and they will only accept a paper when reasonably certain. They will preserve anonymity of reviewers and promote publication of corrections, clarifications, retractions and apologies when needed. The acceptance of a paper automatically implies the copyright transfer to the Central Asian Academic Research Center LLP.

The Editorial Board of the Central Asian Academic Research Center LLP will monitor and safeguard publishing ethics.

Requirements for articles design for publication in the journal are available on the websites:
www:nauka-nanrk.kz
http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Managing Editor: *T. Apendiev*
Editors: *D.S. Alenov, A.Shormakova*
Computer layout: *G.D. Zhadyranova*

Signed for print: July 10, 2026
Format: 70×90 1/16. 26.5 printed sheets. Order No. 3.

«Central Asian Academic Research Center» LLP
Almaty, Shevchenko Street, 28